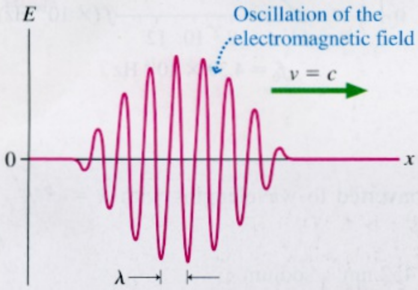
39.3 Photons

Einstein was awarded the Nobel prize in 1921 not for his theory of relativity, as many suppose, but for his explanation of the photoelectric effect. Although Planck had made the first suggestion, it was Einstein who showed convincingly that energy is quantized and that light, even though it exhibits interference, comes in some kind of particle-like packets of energy. These fundamental units of light energy were later given the name **photons.**

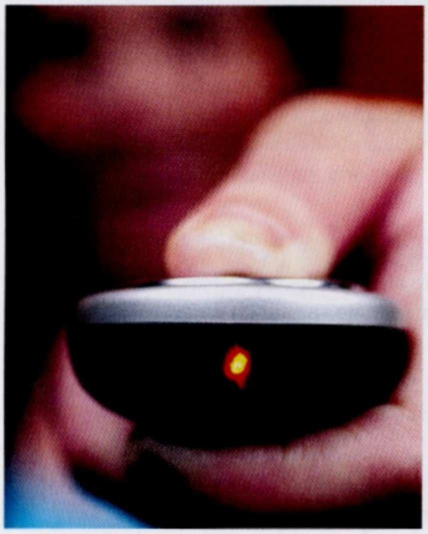
But just what are photons? Although particle-like, they clearly do not mesh with the classical idea of a particle. A classical particle, when faced with Young's double-slit apparatus, would go through one hole or the other. If light consisted of classical particles, we would see two bright spots on the screen. Instead, we see interference fringes behind a double slit. We even observed, in Chapter 25, that the interference pattern can be built up photon by photon if the light intensity is very low. This behavior indicates that a photon must, in some sense, go through *both* slits and interfere with itself! Photons seem to be both wave-like *and* particle-like at the same time.

FIGURE 39.11 A wave packet has wave-like and particle-like properties.



Photons are sometimes visualized as **wave packets.** The electromagnetic wave shown **FIGURE 39.11** has a wavelength and a frequency, yet it is also discrete and fairly localized. But this cannot be exactly what a photon is because a wave packet would take a finite amount of time to be emitted or absorbed. This is contrary to much evidence that the entire photon is emitted or absorbed in a single instant; there is no point in time at which the photon is "half absorbed." The wave packet idea, although useful, is still too classical to represent a photon.

The bottom line is that there simply is no "true" mental representation of a photon. Analogies such as raindrops or wave packets can be useful, but none is perfectly accurate. We can detect photons, measure the properties of photons, and put photons to practical use, but the ultimate nature of the photon remains a mystery. To paraphrase Gertrude Stein, "A photon is a photon is a photon."



Photodectors based on silicon can be triggered by photons with energy as low as 1.1 eV, corresponding to a wavelength in the infrared. The light-sensing chip in a digital camera can detect the infrared signal given off by a remote control. Press a button on your remote control, aim it at your digital camera, and snap a picture. The picture will clearly show the infrared emitted by the remote, even though this signal is invisible to your eye.

The Photon Rate

Light, in the raindrop analogy, consists of a stream of photons. For monochromatic light of frequency f, N photons have a total energy $E_{\text{light}} = Nhf$. We are usually more interested in the *power* of the light, or the rate (in joules per second, or watts) at which the light energy is delivered. The power is

$$P = \frac{dE_{\text{light}}}{dt} = \frac{dN}{dt}hf = Rhf \tag{39.10}$$

where $R = dN/dt$ is the *rate* at which photons arrive or, equivalently, the number of photons per second.

EXAMPLE 39.5 **The photon rate in a laser beam**

The 1.0 mW light beam of a helium-neon laser ($\lambda = 633$ nm) shines on a screen. How many photons strike the screen each second?

SOLVE The light-beam power, or energy delivered per second, is $P = 1.0\text{ mW} = 0.0010\text{ J/s}$. This is a realistic value. The frequency of the light is $f = c/\lambda = 4.74 \times 10^{14}$ Hz. The number of photons striking the screen per second, which is the *rate* of arrival of photons, is

$$R = \frac{P}{hf} = 3.2 \times 10^{15} \text{ photons per second}$$

ASSESS That is a lot of photons per second. No wonder we are not aware of individual photons!

Photodetectors

Modern photodetectors are descendants of the photoelectric effect. These range from simple "electric eyes" to the detector array in a video camera. Most detectors use what is called a *photodiode* in which the photoelectrons are emitted internally in a semiconductor. Even so, they still have a threshold frequency, a stopping potential, and other attributes of the photoelectric effect.

Very low light levels can be detected photon by photon with a device called a *photomultiplier tube,* or PMT. **FIGURE 39.12a** shows that a PMT consists of a cathode, an anode, and a number of intermediate electrodes sealed inside an evacuated glass tube. The cathode is coated with a low-work-function material, allowing it to respond to most visible wavelengths of light. The cathode is at a fairly high negative voltage and the anode, at the other end, is at essentially zero volts. Steadily descending potentials are applied to the intermediate electrodes.

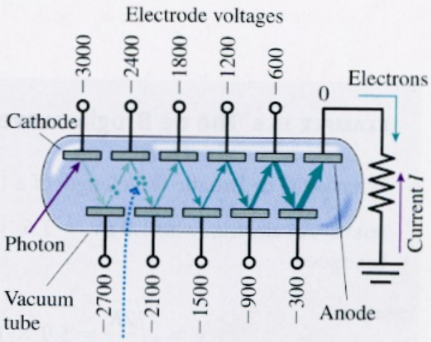
A photon of light ejects a photoelectron from the cathode. The electric field between the cathode and the first intermediate electrode accelerates that electron through a potential difference of about 300 V, and it then strikes this electrode at high speed. When a fast electron collides with a metal surface, it can kick out two or three other electrons called *secondary electrons.* The secondary electrons of the first electrode are accelerated to the second electrode, where they kick out more electrons. These are accelerated to the third electrode, where they kick out yet more electrons, and so on. There is a chain-reaction *multiplication* of electrons—1, 2, 4, 8, 16, . . . —as they move from the cathode toward the anode. For a typical PMT, a single photon at the cathode causes an electron bunch with 10^6 or 10^7 electrons to arrive at the anode.

The electrons are collected by the anode and flow through a resistor. Because these are negative charge carriers, we would say that a current pulse I travels upward through the resistor. This creates a *negative* voltage across the resistor, $\Delta V = IR$, for the length of time that the current lasts. **FIGURE 39.12b**, an actual measurement, shows a pulse generated by a single photon. The horizontal scale is 0.2 ns/division and the vertical scale is 20 millivolts (mV)/division. You can see that the width of the pulse is ≈0.3 ns and its height (measured downward from the baseline) is ≈120 mV = 0.12 V. This is not a large voltage, even after the multiplication, but it is a voltage easily detected with modern electronics.

NOTE ▶ The 0.3 ns pulse duration is *not* an indication of the duration of a photon. The photon absorption is instantaneous, but as the electron bunch grows in size, the electron-electron repulsion causes the bunch to spread out some. The observed pulse width is an artifact of the PMT, not a characteristic of the photon. ◀

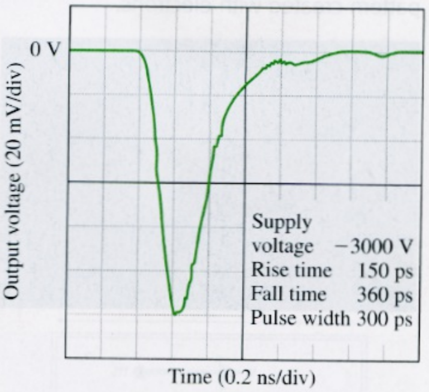
FIGURE 39.12 A photomultiplier tube can detect individual photons.

(a) A photomultiplier tube



The electron bunch grows after each collision with an electrode.

(b) The output signal from a single photon



STOP TO THINK 39.2 The intensity of a beam of light is increased but the light's frequency is unchanged. Which one (or perhaps more than one) of the following is true?

a. The photons travel faster.
b. Each photon has more energy.
c. The photons are larger.
d. There are more photons per second.

39.4 Matter Waves and Energy Quantization

Prince Louis-Victor de Broglie was a French graduate student in 1924. It had been 19 years since Einstein had shaken the world of physics by blurring the distinction between a particle and a wave. As de Broglie thought about these issues, it seemed that nature should have some kind of symmetry. If light waves could have a