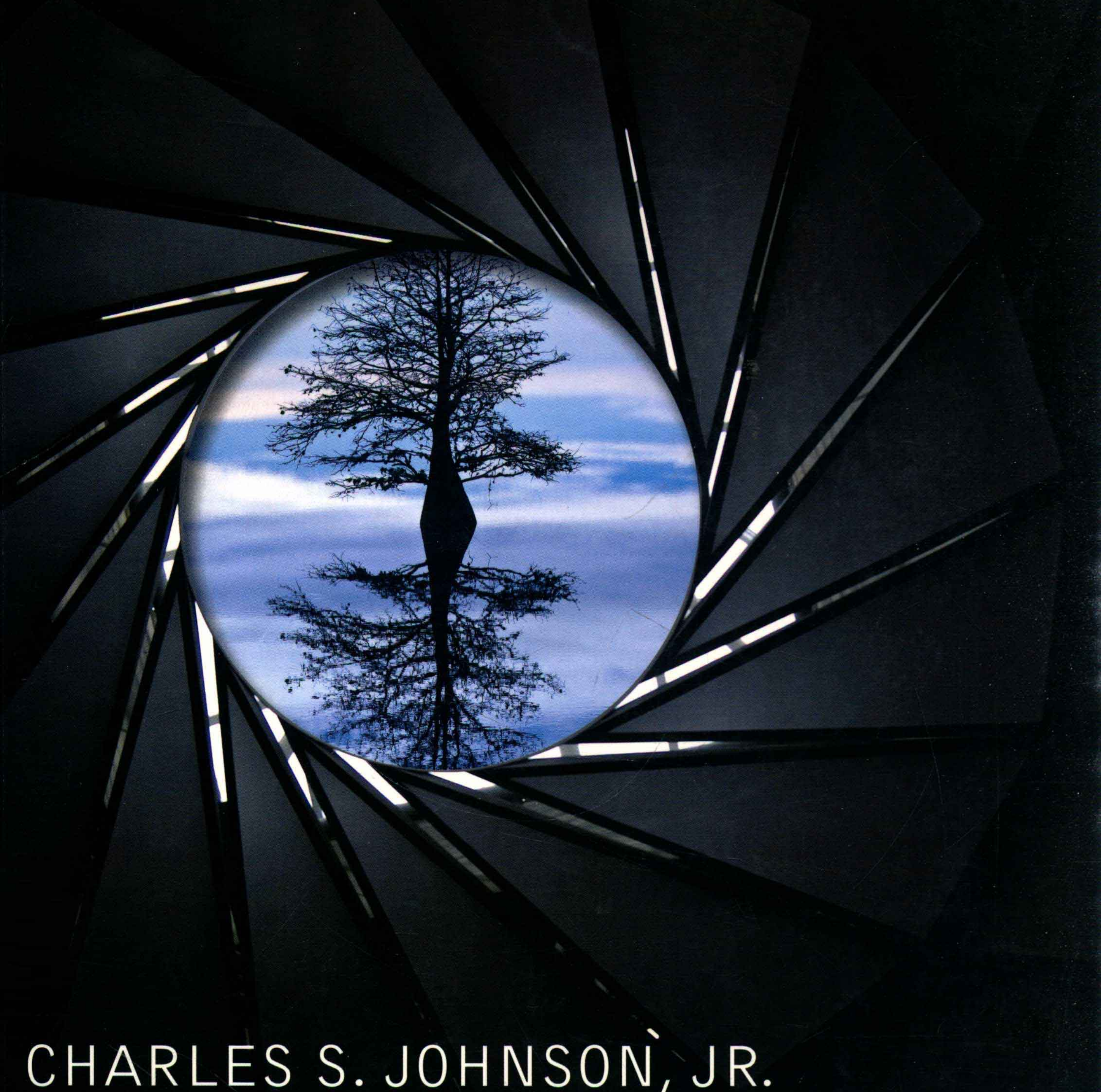
SCIENCE FOR THE CURIOUS PHOTOGRAPHER



CHARLES S. JOHNSON, JR.

Science for the Curious Photographer

An Introduction to the Science of Photography

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To Ellen, my wife and best friend

Preface

My love of photography started very early. As a teenager I worked in a small full-service photography shop. Portraits were made, events were photographed, snapshots were developed and printed, and equipment was sold. From that experience, I learned about photographic techniques and the value of quality cameras and lenses. I started developing and enlarging my own photographs, and I searched for ways to learn more. Fortunately, I found the book *Lenses in Photography* by Rudolf Kingslake in the photography shop, and I studied it diligently. I still have that book and refer to it frequently. At that time (the 1950s), my uncle was serving with the Air Force in Germany, and he was able to buy fine cameras for me. First, I got a Zeiss Ikonta 35. It was bare bones, with no rangefinder or light meter, but it had a wonderful Zeiss Tessar $f/2.8$ lens. It was great for documenting sports and other high school events. Later, when I started doing freelance photography (while still in high school), I ordered a Rolleicord III medium format camera. It served me well and is still functional.

From the beginning I was fascinated by all aspects of photography. I love the equipment, the techniques, the processing of images, and, of course, the chance to photograph interesting things. Photography also provided a summer job and a doorway to business and social interactions. Photographs documenting those years reveal small-town life in the 1950s and a few cheesecake pictures as well. My career as a scientist and a university professor took me away from photography for many years, but in the past decade I have returned to that early love. I spend a lot of time on nature photography now, and I enjoy photo shoots with the Carolinas' Nature Photographers Association (CNPA). Of course, everything is digital, so the chemical darkroom is no longer necessary. This has given me a new world of opportunities and an array of new subjects to understand.

In my case, understanding the way photography works has increased enjoyment of it. Each new question is a challenge. The process of working through the concepts of photography from basic optics and image sensors to human perception of color and the appreciation of beauty was an exhilarating experience for me. I have written this book for those who also enjoy photography, and who want to know more about their photographic equipment and the operation of their eyes and brain as well. The book is specifically aimed at those who enjoy science and are not afraid of a little math. Of course, perfectly good photographs can be made by those who have no interest in the scientific side of photography. They see a clean separation between the scientific part and the artistic part, and they reject the scientific part. On the other hand, some great photographers and other artists as well have benefited from a knowledge of their media and ways to get the most out of it: Ansel Adams comes to mind. In addition to making awe-inspiring photographs, Adams wrote technical books on cameras, negatives, and prints. To each his/her own, but I believe that in photography, as elsewhere, knowledge is power.

I have worked on this book for four years, trying the patience of my wife and friends. I appreciate comments from all those who have read sections of it at various stages of its gestation. I am sure to leave out some generous and helpful people, but here is at least a partial list of those who have contributed at various times with corrections and advice: John Fowler, Archibald Fripp, Richard Jarnagin, and Calvin Wong.

—CHARLES S. JOHNSON, JR.

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CHAPTER 1

What Is Photography?

The painter constructs,
the photographer discloses.

—SUSAN SONTAG

You don't take a photograph,
you make it.

—ANSEL ADAMS

There are two sides to photography. First, photography is the capture and display of images by means of film or an electronic sensor, and, second, photography is the art of taking and presenting photographs. As commonly practiced, photography is inseparable from cameras. Of course, *photography* means "writing with light" and *writing* is really the operative word. When photography was invented in 1839, the thing that was discovered was the means for permanently capturing images. Cameras of various kinds had, in fact, been available for centuries.

The original camera, known as the *camera obscura* (see Figure 1.1), was nothing more than a dark room with a small hole (aperture) in one wall and an inverted image on the opposite wall created by light rays passing through the aperture. The wonderful image-forming property of a small aperture was noted by the philosophers Mo-Ti in China and Aristotle in Greece in the 5th and 4th centuries BCE, respectively, although apparently without an understanding of how it was accomplished. It is clear that scientists in the Western world from at least the time of Leonardo da Vinci (*c.* 1490) were aware of the camera obscura, and at some point it was discovered that the image

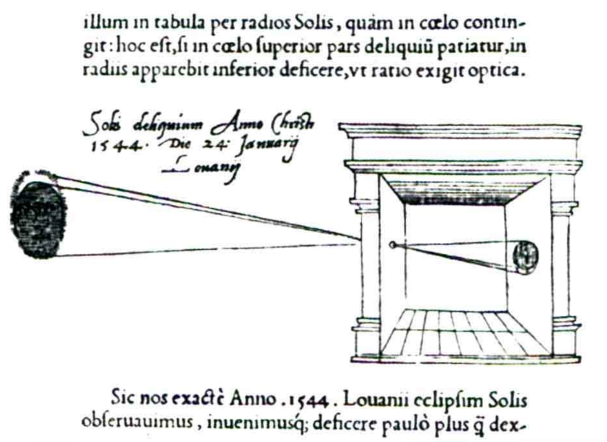

FIGURE 1.1. The camera obscura was used by Reinerus Gemma-Frisius in 1544 to observe an eclipse of the sun.

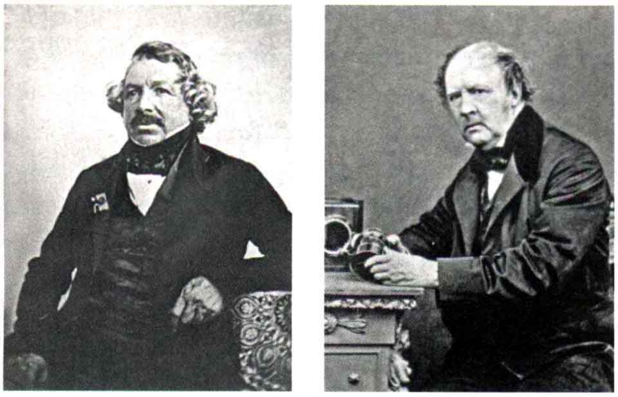

FIGURE 1.2. Louis Mandé Daguerre (left) and Henry Fox Talbot (right).

quality and intensity could be improved by enlarging the aperture and inserting a convex lens of the appropriate focal length. The portable camera obscura, a box with a lens on one side and some means of viewing the image, became popular with artists as an aid in representing perspective in paintings. For example, the 16th-century Dutch painter Johannes Vermeer (1632–1675) almost certainly used a camera obscura to see the correct representation of perspective for his paintings. By the 19th century these devices were essentially box cameras without photographic film.

In the early 19th century, many individuals were experimenting with sensitized materials that darkened when exposed to light and produced fleeting images, so proper credit for the invention of photography is diffuse and controversial. Photography as we know it dates from 1839 when two men independently reported processes for capturing images in the camera obscura. Their disclosures initiated explosive developments in image-making around the world. The Frenchman Louis Mandé Daguerre discovered a method for producing a permanent image on a silver surface; while, in England, Henry Fox Talbot created permanent images on paper treated with a mixture containing silver chloride. In Daguerre's images, the areas exposed to light and properly processed were highly reflecting; and, therefore, there was a natural (positive) appearance though, of course, without color (monochrome). These images, which were called daguerreotypes, unfortunately, could not easily be reproduced. The striking images obtained by Daguerre were an instant hit, however, and most contemporaries considered him to be the inventor of photography. (See Figure 1.2.)

In marked contrast, Talbot's images were initially unpleasing because the (bright) exposed areas were found to be dark on the paper. In other words, a negative image was produced. That turned out to be a great advantage, however, because the negative could be combined with another sheet of sensitized paper and exposed to light to produce a positive copy, and that procedure could be repeated to produce multiple copies. Of course, paper is translucent rather than transparent, and it was not until the 1850s that transparent negatives could be obtained. The terms *photography* and *photograph* are usually attributed to Sir John Herschel, who included them in a paper that he read to the Royal Society of London in 1839. Herschel also deserves credit for advancing photographic science by discovering how to stabilize silver images; however, credit for the name *photography* is controversial. The term photography may actually have been introduced earlier by an artist named Hercules Florence working in Brazil in 1833. Florence, who used sensitized paper to copy drawings, did not report his work, and as a consequence, he had little influence on the development of photography.

For the next 160 years, silver-sensitized paper and film coupled with the negative/positive process, dominated photography; and it was only after the year 2000 that photoelectric detectors and powerful, yet inexpensive, computers challenged film-based photography. Replacing film with sensors and computer memory has not yet basically changed photography; however, computer manipulation of images has turned out to be a revolutionary development. Even images captured on film are now routinely scanned into computers and digitized so that they are also subject to modification. If computer image manipulations were limited to the types of things that photographers were already doing in the dark room to correct exposure, hold back or burn in areas, change contrast, etc., there would be no fundamental change in photography. But now the changes can be so extensive and subtle that the boundaries of photography are continuously being tested.

It has been said that photographers reveal while artists create. Software for manipulating photographic images and even creating realistic images from scratch is fundamentally changing this equation. Illustrators using computer graphics have almost unlimited ability to produce realistic images of any type. Photojournalists, on the other hand, must have their creative inclinations severely limited by a code of professional ethics and perhaps by authentication software that can spot even microscopic changes in digital images.

Anyone who has viewed recent movies knows that amazing things can be done to produce realistic images of things that never existed. The opening scenes in *Day After Tomorrow* show a flight over ocean, ice, and cliffs in Antarctica. It is beautiful and impressive. How was it done? A helicopter flight over those remote areas would be costly and dangerous, so the producer decided to create the scenes entirely with computer graphics. And what about the magnificent scenes in the epic *Troy*? Does anyone believe that 1000 or even 100 ships were constructed, or that 75,000 Greek warriors took part in the battle? We can all enjoy the endless possibilities for image-making, but we can no longer (if ever we did) believe in what the images show.

So, ultimately, what is photography? Does it matter that wrinkles can be removed from faces and heads can be switched? Do we care if it is easy to move an alligator from a zoo to a natural area or a hummingbird from a feeder to a flower? These tricks are still rare enough that gullible observers may marvel at how such "difficult" photographs could be obtained. I think we are seeing the emergence of a new art form, but I am not sure where that leaves photography. Will "pure" photography remain when everyone has an incentive to improve the images they obtain and it is so easy to do? Is there any merit in maintaining photography with minimum manipulation for recording the world as it is? The future will tell. In fact, "truth" is found in some novels and paintings and in some photographs, but it must be tested and verified by wise readers and observers.

Questions raised by the concepts of reality and truth in visual images are much more complex than may be thought. Later in the book I discuss the operation of the human visual system and its relation to our awareness of the world. It is fair to say that our eyes and brain create the illusion of a full-color, three-dimensional world. It is an illusion, because the images projected on the retinas of our eyes do not provide enough information for the construction of a unique worldview. The brain fills in details based on a sort of automatic inference system that is influenced by both the evolution of the human brain and the experience of the individual. The result is that we see, at first glance, petty much what we expect to see. One should also realize that digital cameras basically compute pictures from captured light. The computation is not straightforward, and there is a lot of room for "enhancement" of the final image. The new field of computational photography is influencing the images produced by our cameras and the special effects we see in movies. It is an interesting time to be alive and maybe a little disturbing as well.

Further Reading

N. Rosenblum. *World History of Photography, Third Edition.* New York: Abbeville Press, 1997. (This is a tour of photography from 1839 through the film era, including both art and the technical details.)

M. R. Peres (Editor). *Focal Encyclopedia of Photography, Fourth Edition.* Amsterdam: Elsevier, 2007. (Although it is uneven and already somewhat dated, this text provides extensive coverage of theory, applications, and science.)

CHAPTER 2

What Is Light?

The study of light has resulted in achievements of insight, imagination, and ingenuity unsurpassed in any field of mental activity; it illustrates, too, better than any other branch of physics, the vicissitudes of theories.

—SIR J.J. THOMPSON

All the fifty years of conscious brooding have brought me no closer to the answer to the question, "What are light quanta?" Of course today every rascal thinks he knows the answer, but he is deluding himself.

—ALBERT EINSTEIN

We can wax eloquent: Light is universally revered. It represents illumination and understanding. It represents our greatest treasure, as in the "light of our lives." We believe that bad things happen under cover of darkness, and evil works cannot stand the light of day. Light sets the pattern of our days. When light goes away, we sleep. Photography involves writing with light, and it uses the information in light to capture moments in our lives so that they are preserved and can be replayed. In this way photography brings light to our past.

But here we need useful rather than poetic definitions that can help us understand photography. We all know the difference between light and dark, but what is light? The problem is that most definitions introduce other words that need to be defined. I will start with several ideas that are correct but not complete as a step toward understanding what we mean by *light*. First, light is a form of energy that comes to us from some source and can make our environment visible to us. Of course, even with our eyes closed we can tell the difference between bright light and no light. Another useful statement is that light is a kind of radiation that is visible to us. Again this implies energy, the ability to do work and affect change.

All of our energy, other than that associated with radioactivity, comes to us directly or indirectly from the sun, and the sun is our major source of light. The sun provides bright white light in the middle of the day and less intense yellow and red shades

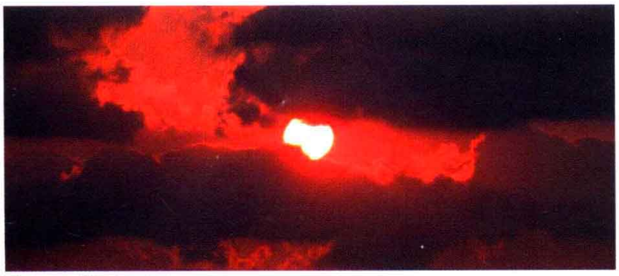

FIGURE 2.1. The sun, primary source of light and energy.

in the early morning and late afternoon, at least as seen from the surface of the Earth (Figure 2.1). This sentence brings up the concepts of intensity and color, both of which are related to human perceptions. Therefore, the study of light in photography requires not only precise mathematical definitions of brightness and color, but also methods of quantifying perceptions of brightness and color. The latter gets us into the realm of psychophysics.

Later chapters will be devoted to the measurement of light, the manipulation of light, and the recording of light. Here I consider only the primary physical properties of light, starting with a bit of history. In the 4th and 5th centuries BCE, the ancient Greeks speculated extensively about the nature of light. Some (Empedocles, Euclid, and Plato) thought that light is projected from the eye. Lucretius believed that particles of light are sent out from the sun, while Pythagoras held that light particles are emitted by objects. Aristotle even offered a theory of wave propagation of light. Some of these ideas have elements of truth, but they were not particularly useful and did not advance knowledge because they were not based on a consistent theoretical framework and were not tested. In fact, these ideas only provided a set of possibilities.

There were, of course, some observations and insights in the antique world that carry over into the scientific study of light. For example Euclid (4th and 3rd centuries BCE) noted that light appears to travel in a straight line, and Hero (1st century BCE) concluded from the study of reflections that light follows the shortest path between two points. However, modern ideas about the nature of light and optics have their origin in the 17th century. At that time, two ideas dominated theory and experiment: first, that light is a propagating wave and, second, that light consists of streams of particles (corpuscles).

One of the most influential scientists of that period was Sir Isaac Newton (1642–1727, Figure 2.2), who had carried out exquisite optical experiments to determine the nature of color; and who developed a theory of color we still use. He concluded that light rays consist of particles rather than waves because light travels in a straight line. Anyone who has played with a laser pointer might reach the same conclusion. Now we know that this view is incomplete because, among other things, shadows do not have sharp edges, and there is much evidence of diffraction in the everyday world. I will treat diffraction in detail later; here it suffices to say that diffraction refers to the deflection and decomposition that occurs when light interacts with sharp edges of opaque objects, narrow slits, or collections of narrow slits (gratings). In fact, in 1663 James Gregory noticed that sunlight passing through a feather is diffracted into spots of different colors and he wrote, "I would gladly hear Mr. Newton's thoughts of it." Francesco Grimaldi even published a book in 1665 on the effects of small apertures on the passage of light beams that seemed to indicate wave-like properties for light. Apparently, Newton did not consider the possibility that light might be a wave with a very small wavelength so that it would indeed appear to travel in a straight line unless one looked very closely.

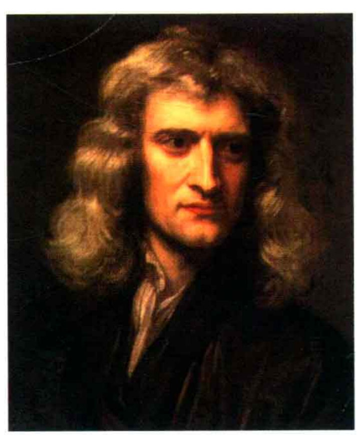

FIGURE 2.2. Sir Isaac Newton (1642–1727), who dispersed light with a prism and developed a theory of color.

The particle theory was, in fact, undermined by continuing observations of diffraction and the presentation of a wave theory of light by Christiaan Huygens in 1678 that explained such phenomena, albeit with certain unproved assumptions. According to the wave theory, diffracted intensity patterns, which consist of bright and dark lines, result from interference effects—that is to say, the addition of the amplitudes of waves. In this way, the positive and negative peaks can reinforce to give intensity maxima or cancel to produce the dark places. This process is shown in Figure 2.3.

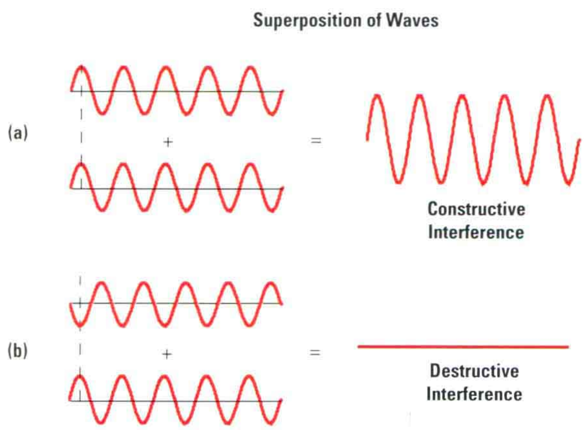

FIGURE 2.3. The (a) constructive and (b) destructive interference of waves.

The validity of the wave theory was confirmed by a number of scientists. Most notably, Thomas Young (1802), who demonstrated the interference (diffraction) of light by passing a light beam through two closely spaced slits in an opaque sheet and displaying the resulting pattern of bright and dark lines. Also, Joseph Fraunhofer and Augustine Fresnel investigated diffraction effects using small holes of different shapes and presented rigorous theories for calculating diffraction patterns, thus advancing the wave hypothesis. The diffraction of light from a compact disc (Figure 2.4) where there are 625 tracks per millimeter provides a beautiful example.

By the early 19th century, the wave properties of light were well known, and there was a practical understanding of the way light rays behave and of the basis of perceived color resulting from the

FIGURE 2.4. Diffraction of light from the surface of a compact disc. The pitch of the data tracks is 1.6 μm, and each angle of reflection selects a specific spectral color.

mixing of light beams. At that time, however, there was still the open question, "What is light?"

One line of evidence was provided by the speed of light. To casual observers, the speed of light appears to be infinite, but well-planned experiments show that is not the case. An early, approximate value of the speed of light had been determined from observations of eclipses of the moons of Jupiter by Olaf Romer (1676), and by 1860 there were measurements of the speed of light in air from the study of light pulses (Armand Fizeau) and rotating mirrors (J. L. Foucault). The conclusion of this part of the story was provided by James Clerk Maxwell's monumental achievements in the 1860s. Maxwell (see Figure 2.5) developed a set of partial differential equations to describe electric and magnetic fields. He concluded that oscillating electric fields are always accompanied by oscillating magnetic fields and together they propagate through space as electromagnetic waves. In 1862 he computed the velocity of electromagnetic waves and discovered

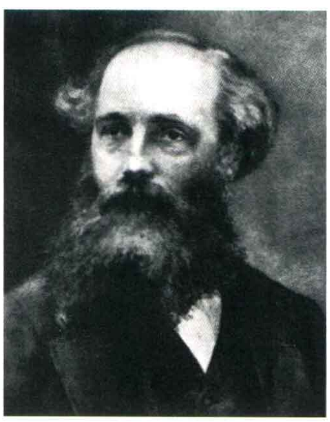

FIGURE 2.5. James Clerk Maxwell (1831–1879), who identified light as electromagnetic radiation.

that they have the same velocity as light. This revelation prompted him to write, in an 1864 paper, "The velocity is so nearly that of light that it seems we have strong reason to conclude that light itself (including radiant heat and other radiations) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws." So the simple answer to the question "What is light?" is that light is electromagnetic (EM) radiation.

But that is not the end of the story. In 1905 Albert Einstein (see Figure 2.6) showed that light is composed of quanta or particles of energy, and every experiment since that time confirms his conclusion. What he had discovered was that light quanta are necessary to explain the interaction of light with electrons in metals. For this amazing conceptual breakthrough Einstein was awarded the Nobel Prize in 1921. Newton was right, but for the wrong reasons. We always detect light quanta, now called *photons*, but the wave theory lets us compute the probability of finding a photon at a certain location. Each photon carries an amount of energy that depends on the frequency of the light, and the number of photons arriving each second determines the intensity. A few photons are required to activate a nerve in the eye, and the creation of a latent image in photographic film requires the absorption of photons by atoms in silver halide grains. By the late 20th century, instruments for counting photons were widely available.

So we have a beautiful and subtle story: Light is made of particles, and light is a wave. Maxwell's equations are sufficient for describing light when there are many photons and the quantum theory is necessary when there are only a few. It is no wonder that earlier scientists had such a hard time getting it straight.

FIGURE 2.6. Albert Einstein (1879–1955), who discovered that light is quantized.

In later chapters we will explore in detail how the nature of light is manifest in photography and especially digital photography. We will see how the wave nature of light ultimately determines the way lenses work but also limits the resolution of all lenses. For example, the size of the image of a distant star is determined by diffraction, a wave phenomenon, as well as by imperfections in the lens and the resolving power of film or an electronic sensor. Also, detection and recording of an image depends on the collection of photons in each picture element (pixel) of the detector or by grains of silver halide in a photographic film. When the light level is low, the number of photons in each pixel may be small, so that deviations from the average will be significant. Therefore, different pixels will receive different numbers of photons and the image will appear to be "noisy." We shall see that the laws of physics ultimately limit the quality of images and force us to make compromises in camera and lens designs. I expand on this topic and define the signal-to-noise ratio in Chapter 16.