Preface

Light is all around us. Vision is our dominant sense, and we are richly rewarded with a palette of colors from red to violet. Our eyes do not detect the low-energy, long-wavelength infrared (IR) radiation, but we know it exists from discussions of war applications and televised images of guided weapons targets. Our eyes do not detect the higher-energy (above visible light energies) and shorter-than-visible-wavelength ultraviolet radiation, and yet we know it is there from the sunburn we receive in Arizona. We also know that window glass can block ultraviolet rays so we don't get a burn while driving with the windows rolled up.

We know about radio waves from the little boxes that talk to us and x-rays from the dentist office. These waves and rays belong to the same family of light, often called photons (from the Greek *photos*, light), that describes the spectra of electromagnetic radiation over 10 orders of magnitude from very low-energy radio waves to very high-energy x-rays and gamma rays.

This book starts with the visible — the straight path of light — because what we can see is a good starting point. It continues with reflection as we look at ourselves in mirrors and storefront windows. It includes a chapter on refraction, its discovery and description, and a chapter on lenses, which are familiar to the myopic (eyeglasses) and the football fan (binoculars). Color is introduced with the query, Why is the sky blue? After answering that and other similar questions, the book goes beyond the visible to the infrared and ultraviolet. It ends with analysis of Mars using x-ray emission.

This is a descriptive book rather than a technical book. It is designed for the general reader with no background in science but who has an interest in the light around us. There is an Internet site associated with the text called Images of Nature (http://ion.eas.asu.edu). It provides optical and electron microscopy images that can be downloaded by the reader and student for free. The site also provides additional information on x-ray emission techniques and comparisons between optical and electron microscopy. For the educator or curious reader, exercises, solutions, and exams are available by writing to the publisher.

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James W. Mayer
Tempe
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Steve Beeson
Washington, DC
May 2007

2 The Reflection of Light

2.1 Reflections on the Past

Besides the occasional light bulb, electric eel or star, we see things because light is reflected from them, a statement profound in its simplicity. Imagine a sneaker. If there is no light, is the sneaker there? Of course it is. We can touch it, hear it if it drops, sometimes smell it. But it casts no light of its own; it needs a light source to illuminate it. The light is then reflected[1] from the sneaker into our eyes, and the sneaker information is transmitted into our brain: color (white with brown dirt spots and red markings); shape (oblong, flat-bottomed); texture (rough, synthetic). Like the proverbial falling tree in the forest, the sneaker needs a mechanism and a receiver in order to be perceived. The receiver is our eye, the mechanism is light. The tree (and the sneaker) just reflects the light.

The ancients did not know that objects simply reflect light. Three thousand years ago, Plato and Euclid believed light exited the eye and somehow illuminated the object like Superman's x-ray vision, thus allowing it to be perceived. Empedocles in the fifth century BCE theorized that objects emit rays of information, which our eyes received by sending out a similar "visual ray" to intercept the information, as in Fig. 2.1(b). Eyes were thought literally to shine. The combined visual ray and information were then thought to be somehow transmitted to the eye, and an image was created in the mind.

Others believed objects sent out ultra-thin, invisible images of themselves in all directions, and that those were then received by the eye. These ethereal object-ghosts were thought to be transmitted in a continuous manner so that we would perceive an unbroken image of the object. Figure 2.1(c) shows an image being emitted in all directions, with some of the images landing in the eye of the observer. Many of these theories lasted into the seventeenth century. Students today still have difficulty understanding the mechanism of light reflection and visual perception. Ask a fourth grader how we see objects and you will likely hear the Superman Theory.

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[1] Some is absorbed.

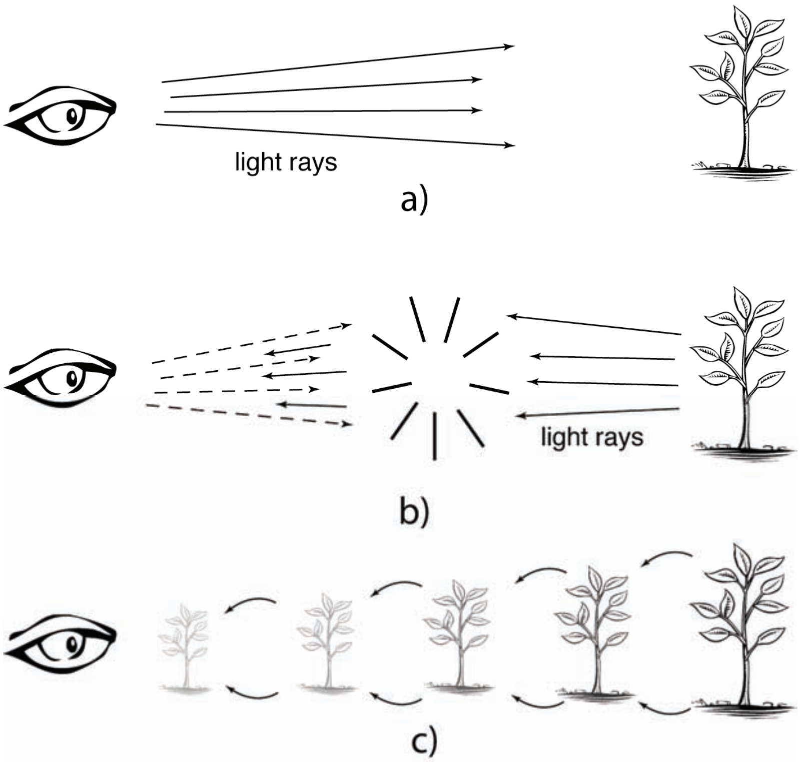

Fig. 2.1 An illustration of three theories of visual perception throughout history. **(a)** The Superman Theory, in which light is emitted from the eye, illuminating objects. **(b)** The object emits rays of information which the "visual rays" from the eye intercept and then transmit to the eye. **(c)** Ethereal images of an object are emitted in all directions — some land in the eye.

Not until Johannes Kepler in 1604 was the theory that light enters the eye simply as light treated in the proper scientific manner (i.e., based on an experimental process). Yet even after looking through the back of an eyeball and seeing an upside-down image, he still regarded light as a form of heat. After Kepler, most scientists agreed that light must only enter, not exit, the eye in order for an object to be visually perceived. Subsequently, it was the nature of light, not the mechanics of vision, which intrigued many physicists. We pause now to reflect on the behavior of light, and we'll defer the discussion of its nature to later chapters. As betrayed by our fascination, we are still searching for light's elusive definition.

2.2 All Things Equal

Though early philosophers lacked a fundamental understanding of how we see things and how to test their theories of light, several Greek and Arabic philosophers forged ahead in developing rigorous geometric theories about light and its interaction with the everyday world. Euclid is credited with developing the first and most sensible law of optics, called the *Law of Equal Angles*. Simply stated, the Law of Equal Angles says it doesn't matter what light is made of. If light shines on a surface at an angle, it will bounce off the surface at exactly the same angle.

If light comes in at 67º, it will leave at 67º. If it comes in straight down on the surface at 0º, it will bounce right back up. Figure 2.2 displays the simple relationship between an incoming ray of light, the surface it encounters, the *normal* (an imaginary line perpendicular to the surface), and the outgoing ray.

As anyone who has used a hand mirror to blind their little sister can attest, the Law of Equal Angles holds in every situation, even when the surface is not flat

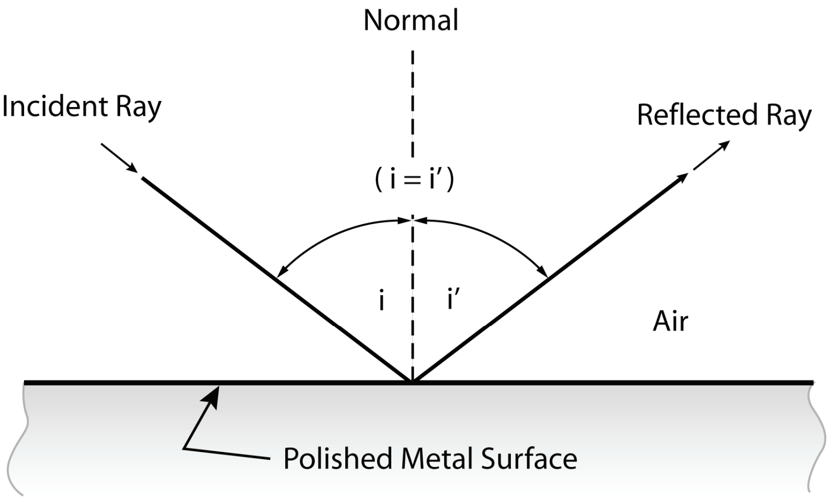

Fig. 2.2 The Law of Equal Angles. An incoming light ray incident on a surface at an angle *i* to the *normal* will reflect from the surface at an angle *i'*, which is equal to *i*. The normal is a line perpendicular to the surface at any point.

like a mirror. Have you ever tried frying an ant on the sidewalk with a curved mirror?[2] It's the Law of Equal Angles that focuses the sunlight to a point (or, if the mirror is turned around, sends all the light rays away from each other). Let's look a little more closely at how light is reflected from various surfaces.

2.3 From the Looking Glass

The Law of Equal Angles can be used in many different ways and is beautifully evident in nature. The most obvious use is the plane mirror. Like most useful tools humans have invented, the mirror's early history is lost in the fog of time; the first mirrors were simple pools of water. Pre-dynastic Egyptian cultures used slabs of slate and gypsum for mirrors up to 6500 years ago, as shown in Fig. 2.3. Ornate bronze and copper mirrors have been found in India dating to 3000 years BCE. Archimedes and the Greeks understood many of the properties of mirrors

Fig. 2.3 A hand mirror from Egypt, c.1400 BCE. (From Roche et al. *Mirrors*, Rizzoli, NY, 1985)

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[2] The authors neither condone nor admit to such an act, but the result is quite interesting.

and (according to legend) used polished and curved metal mirrors to focus the Sun’s light onto enemy ships advancing on Syracuse, burning an entire fleet in the process. As a scientific tool, the mirror’s heyday came in the eighteenth and nineteenth centuries: Newton borrowed an idea from seventeenth-century astronomer James Gregory and built the reflecting telescope, an improvement on long, unwieldy *refracting* telescopes. Jean Bernard Foucault in the 1850s and, later, Albert Michelson, used rotating mirrors to measure the speed of light.

In terms of its physical properties, a plane mirror is very simple: any flat reflecting surface will do. Its optical properties are just as simple: light is incident on the reflecting surface and is reflected at the same angle at which it arrives. The best plane mirrors are those that use highly polished silver (or aluminum) as the reflecting (or *first*) surface, since silver reflects almost 100% of the visible light incident on it. Silver’s downside as the first surface, however, is its tendency to tarnish and scratch easily. Most commercial mirrors are made with a glass plate over the silver to prevent tarnishing and scratching. The layer of glass, however, degrades the image somewhat because glass also reflects light.

Have you ever looked at yourself as you walked by a storefront window? The photograph of Misty (Fig. 2.4) demonstrates the reflectivity of glass, which is

Fig. 2.4 A glass window reflects 4% of the light incident upon it. If the light from the object hits the window at an oblique (i.e., large) angle, more than 4% of the light will be reflected. (Photo by J. Phillips)

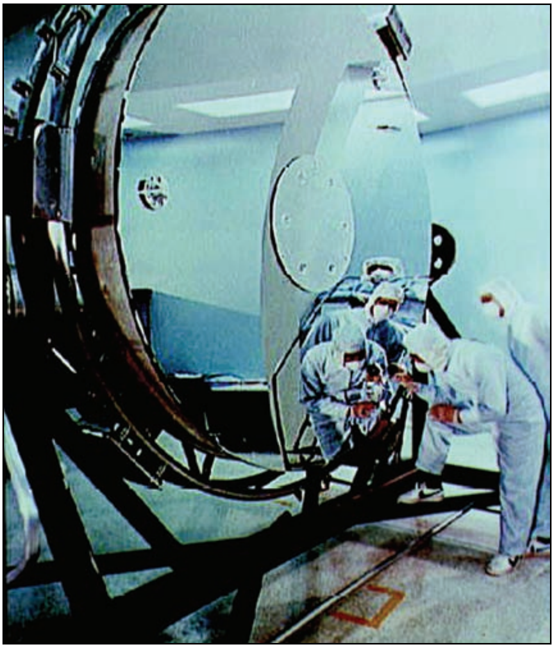

Fig. 2.5 The Hubble Space Telescope mirror, a concave mirror 2.4 meters (8 ft.) in diameter and weighing 1800 lbs. The curved surface of the mirror creates the large image of the technician. (Courtesy of NASA/STScI)

about 4% for most angles. At the *oblique* angle the photo was taken, even more reflection than normal occurs due to the light from the object (Misty, in this case) grazing the surface of the glass. At very large angles of incidence, as much as 100% of the light can be reflected at the surface.[3] You can also see instances of *grazing incidence* in smooth ponds or lakes and in wet streets.

Grazing incidence aside, if you look closely at a standard bathroom or decorative mirror, you'll see a dim, ghost-like secondary image of yourself in the glass. This secondary image is caused by the small amount of light reflection from the first surface of glass. For this reason, astronomers and aerospace engineers who need perfect light reflection without secondary images will use mirrors whose reflecting surface is only polished silver without the glass protection. The Hubble Space Telescope's mirror (Fig. 2.5) is a mirror of this type.

But the Hubble mirror is more than just a fancy reflector. At 2.4 meters in diameter and a cost of $300 million, the Hubble mirror is one of the largest and

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[3] In Chapter 3 we'll explore the concept of total internal reflection in substances such as water and diamond.

most expensive mirrors ever made (Chaisson 1998). More importantly, because its primary purpose is to investigate celestial objects billions of miles away, the Hubble Space Telescope, like our ant-frying mirror, needs to reflect light in order to focus it. In the next chapter we will look at how lenses use refraction to focus light. For now, however, we're interested in finding out how mirrors use reflection to focus light, and the only way to do this is to make the mirror curved.

2.4 The Curved Mirror

Let's face it, plane mirrors can be plain boring. Curvaceous mirrors have more fun. (Who hasn't had fun looking in the wavy mirrors at a carnival?) Many people use curved mirrors every day if they drive a car with a side view mirror that proclaims, "Objects in mirror are closer than they appear." Have you ever looked into a spoon? Polish one and you've got a wonderful two-sided curved mirror. The cosmetic mirror in your bathroom that lets you look so closely at your skin is a simple concave mirror, focusing light to create a magnified image of your face. The cosmetic mirror has a reflecting surface that curves inward, away from the object. As you might expect, a *convex* mirror bends outward, toward the object.

Other than physical traits, the major difference between concave and convex is the directions in which they reflect light. Since concave mirrors are curved inward, they *converge* light so that it's focused toward a point on the inside side of the curve, as in Fig. 2.6. Convex mirrors, as we'll see, *diverge* light — the opposite of focusing. But if mirrors obey the Law of Equal Angles, how can a curved mirror reflect light rays so they all end up at (or near) a focal point? Doesn't the focal property disobey the Law of Equal Angles?

If we look close enough at a curved mirror's surface, we can imagine the mirror as hundreds of flat surfaces lined up end to end, each placed at a slight angle to its neighbor. At each point on the surface, the mirror still obeys the Law of Equal Angles because, to a light beam, each point is just like a tiny flat mirror. Figure 2.6 shows us a close-up view of what happens to light beams that encounter these tiny flat mirrors: each light beam hits the surface and reflects, obeying the Law of Equal Angles. The trick is that each surface is angled slightly differently than its neighbors, so each light beam heads off in a slightly different direction. Viewed as a whole, all the light beams reflect differently from their neighbor, but all converge to a point, or diverge as if they were coming from a point.

The Hubble Space Telescope mirror in Fig. 2.5 is a *concave* mirror, one that focuses light to a point somewhere in front of the mirror's surface. Where exactly that point will be depends on the shape of the surface. Figure 2.7 shows the (exaggerated) difference between two concave mirrors that reflect light to the

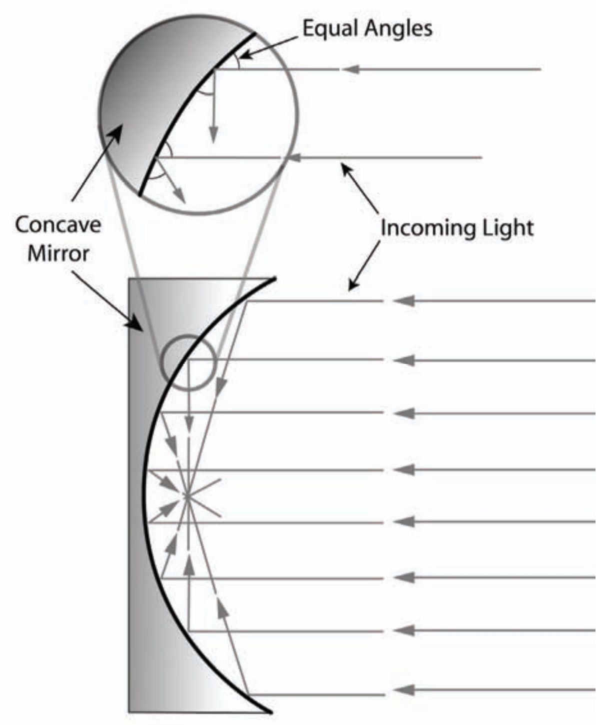

Fig. 2.6 Each point of the concave mirror is like a tiny flat mirror tilted slightly from its neighboring points. Each ray of light is reflected at an angle equal to its incoming angle.

focal point. In Fig. 2.7(a), the mirror is not sharply curved, so the light beams come to a focus far away from the mirror. When the mirror *is* sharply curved, as in Fig. 2.7(b), the light beams converge to a focal point much closer to the mirror. It is this difference that causes the differences in magnification between curved mirrors. As we'll see in Chapter 3, it is the difference between lenses as well.

2.5 Shaving and a Spoon

When we flip a spoon over, we find we're upside down and our heads have shrunk. Welcome to the weird world captured in a convex mirror. Figure 2.8(a) exhibits how light incident on the surface of a convex mirror will behave: instead of reflecting inward, the light rays reflect away from each other — they *di-*

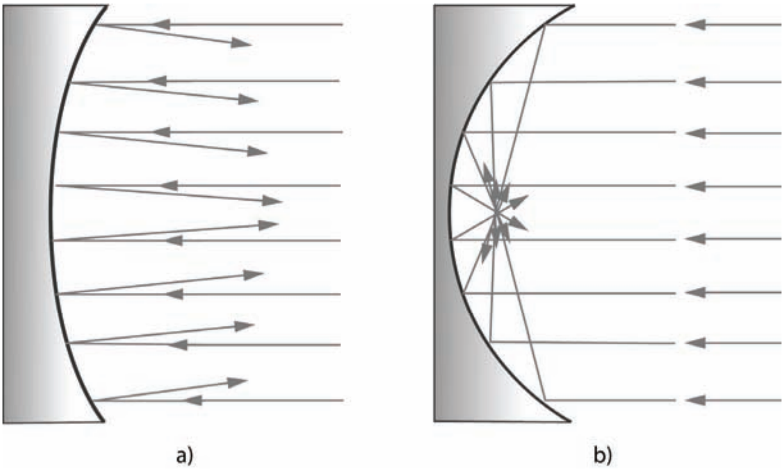

Fig. 2.7 Two concave mirrors reflecting incoming parallel light rays to a focus. **(a)** A shallow curved mirror has a focal point far from the mirror surface. **(b)** A steeply curved mirror has a focal point close to the mirror.

verge. Similarly to concave mirrors, the more a convex mirror is curved, the "faster" the light will diverge.

The tendency of light to diverge from a convex mirror makes for quite bizarre images. In Chapter 1 we found that the paths of light are reversible; a ray of light traveling in a certain direction will follow the exact same path backward if we reverse the process. Taking this concept to mirrors (and later, to lenses), we can imagine reversing the light rays in Fig. 2.8(a), having them come toward the mirror from divergent places. The light reflects off the mirror and leaves in an orderly fashion, in parallel as in Fig. 2.8(b). In this way, we see that objects far outside the view of a flat mirror can be seen quite clearly in a convex or wide-angle mirror. We mentioned the passenger-side mirror of an automobile: these are convex mirrors, which allow the driver to see objects outside the range of what a standard plane mirror would show. The downside is that it makes those objects look far away in the mirror, thus the warning written on the mirror.

One of the notable differences between images seen in a concave mirror versus a convex mirror is that the image sizes are generally not the same. Concave mirrors produce large images that are often upside down, depending on both the location of the object and of the observer relative to the focal point of the mirror. You can see this effect in a makeup or shaving mirror at home. Try viewing your image in the mirror when you stand very close to it (as you would when shaving or applying makeup). Then try looking at the mirror when standing a few feet away. Up close, you are standing between the focal point and the mirror, and your image is larger, or magnified. Far away, you are outside the focal point, and the image is still larger, but you are upside down, or inverted. As an

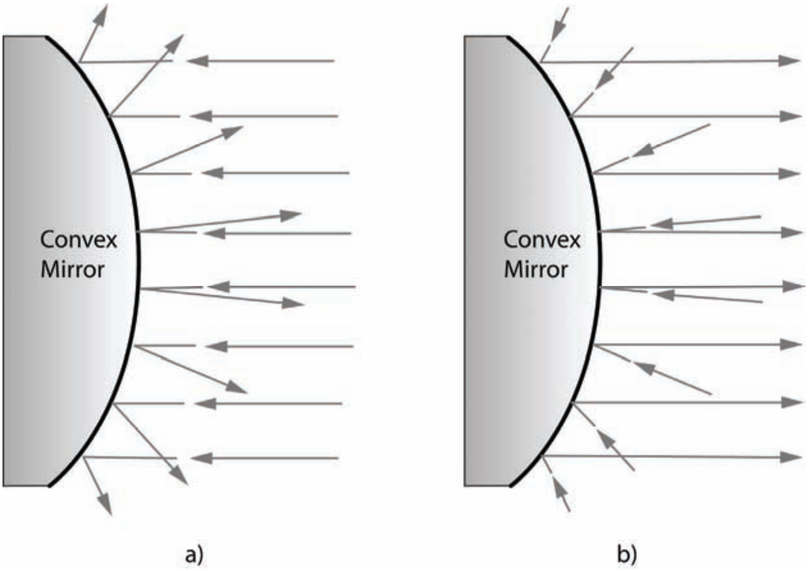

Fig. 2.8 (a) Incoming parallel light rays reflect from a convex mirror and bounce off in many directions — they diverge. **(b)** In reverse, the light rays come from divergent places and leave in parallel.

added thrill, see if you can find the point where the object (you) passes through the focal point of the mirror. What happens to your image at this point?

If you have a polished spoon, try looking into the backside of the spoon (the convex side). If you compare the images from the bathroom mirror and the spoon, you will see that the spoon image is smaller and right-side up, but that you can see more of the room. This will always be the case for convex mirror images, because these images are made by light that seems to come from a point on the other side of the mirror. The rays from the convex mirror never cross, so the image is always upright and smaller than the object. The advantage, though, is that more of the light from the space surrounding the object comes into view. With the flip of a spoon we can see a grain of sand or the world.

2.6 The Rough Edges

Most things are not polished smooth like a mirror. We know this without even touching them. How? For starters, we can see them. If every object was polished smoothly, we'd live in a frightening and confusing world. Everything would be like clean stainless steel. The Law of Equal Angles would rule absolutely. Need

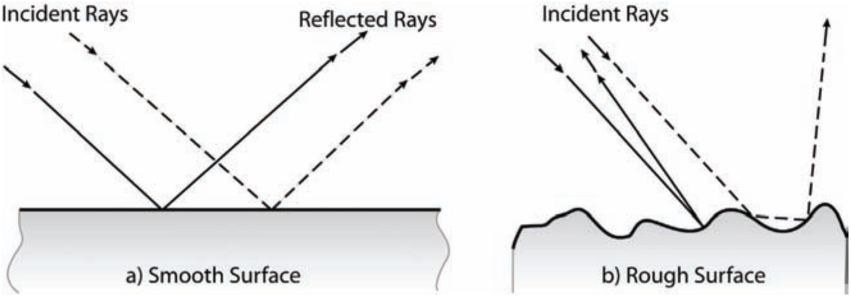

Fig. 2.9 (a) With specular reflection, incident light rays that are parallel to each other will be reflected in parallel. Often we can see images of distant objects in such a surface. **(b)** With diffuse reflection, incoming parallel beams are reflected in different directions. It's difficult to see objects reflected in a matte surface.

to grab that coffee mug? Don't look at the mug itself — look at the reflection in the mug of your hand approaching it. When your hand and the image of your hand come together, you've reached the mug. Often you wouldn't even be able to tell the difference between the thing you wanted to look at and its image. Thankfully, the world is not polished smooth, and we can see actual objects, not just their images. The property that lets us see the world is more a property of objects than it is of light, but it is important to our discussion nonetheless. When light encounters a smooth surface, such as in Fig. 2.9(a), every reflection is perfect at each point, and light rays that were parallel before they struck the surface will be parallel after they reflect. This is known as *specular* reflection. Every light ray from an object gets reflected perfectly, and we can see the image of that object in the smooth surface.

Conversely, *diffuse* reflection occurs when light encounters a surface that is uneven. This is the case in Fig. 2.9(b). Light rays encounter the rough surface and are reflected in many directions. Notice that at each point the reflection still obeys the Law of Equal Angles. However, each reflecting surface is not parallel to the next. Since every light ray from the object is not reflected in parallel, the object's light that reaches our eyes is not coherent, so we cannot see an image of it. The light is diffused and we only see the reflecting object itself, not images of other objects in its surface.

Photo labs will ask if you want your photographic prints glossy or matte. You'll notice that the glossy prints are smooth and reflect surrounding light quite well, while matte prints are rough and keep light reflection to a minimum.

One of the earliest forms of photography, the daguerreotype, relies heavily on the reflection of light. Let's shift our focus from the general properties of light and take a closer look at the beautiful art and science of daguerreotypes.