

Stop Faking It!

Finally Understanding Science

So You Can Teach It

LIGHT

NSTApress®

NATIONAL SCIENCE TEACHERS ASSOCIATION

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Claire Reinberg, Director
Andrew Cocke, Associate Editor
Judy Cusick, Associate Editor
Carol Duval, Associate Editor
Betty Smith, Associate Editor

ART AND DESIGN Linda Olliver, Director
Brain Diskin, Illustrator

NSTA WEB Tim Weber, Webmaster

PERIODICALS PUBLISHING Shelley Carey, Director

PRINTING AND PRODUCTION Catherine Lorrain-Hale, Director
Nguyet Tran, Assistant Production Manager
Jack Parker, Desktop Publishing Specialist

PUBLICATIONS OPERATIONS Erin Miller, Manager

sciLINKS Tyson Brown, Manager

NATIONAL SCIENCE TEACHERS ASSOCIATION
Gerald F. Wheeler, Executive Director
David Beacom, Publisher

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Preface

Back when I was in college, there was a course titled Physics for Poets. At a school where I taught physics, the same kind of course was referred to by the students as Football Physics. The theory behind having courses like these was that poets and/or football players, or basically anyone who wasn't a science geek, needed some kind of watered-down course because most of the people taking the course were—and this was generally true—SCARED TO DEATH OF SCIENCE.

In many years of working in education, I have found that the vast majority of elementary school teachers, parents who home school their kids, and parents who just want to help their kids with science homework fall into this category. Lots of “education experts” tell teachers they can solve this problem by just asking the right questions and having the kids investigate science ideas on their own. These experts say you don't need to understand the science concepts. In other words, they're telling you to fake it! Well, faking it doesn't work when it comes to teaching *anything*, so why should it work with science? Like it or not, you have to understand a subject before you can help kids with it. Ever tried teaching someone a foreign language without knowing the language?

The whole point of the *Stop Faking It!* series of books is to help you understand basic science concepts and to put to rest the myth that you can't understand science because it's too hard. If you haven't tried other ways of learning science concepts, such as looking through a college textbook, or subscribing to *Scientific American*, or reading the incorrect and oversimplified science in an elementary school text, please feel free to do so and then pick up this book. If you find those other methods more enjoyable, then you really are a science geek and you ought to give this book to one of us normal folks. Just a joke, okay?

Just because this book series is intended for the nonscience geek doesn't mean it's watered-down material. Everything in here is accurate, and I'll use math when it's necessary. I will stick to the basics, though. My intent is to provide a clear picture of underlying concepts, without all the detail on units, calculations, and intimidating formulas. You can find that stuff just about any-

Preface

where. Also, I'll try to keep it lighthearted. Part of the problem with those textbooks (from elementary school through college) is that most of the authors and the teachers who use them take themselves way too seriously. I can't tell you the number of times I've written a science curriculum only to have colleagues tell me it's "too flip" or "You know, Bill, I just don't think people will get this joke." Actually, I don't really care if you get the jokes either, as long as you manage to learn some science here.

Speaking of learning the science, I have one request as you go through this book. There are two sections titled *Things to do before you read the science stuff* and *The science stuff*. The request is that you actually DO all the "things to do" when I ask you to do them. Trust me, it'll make the science easier to understand, and it's not like I'll be asking you to go out and rent a superconducting particle accelerator. Things around the house should do the trick for most of the activities. This book also includes a few goodies (filters and a diffraction grating) for the activities that require special equipment.

By the way, the book isn't organized this way (activities followed by explanations followed by applications) just because it seemed a fun thing to do. This method for presenting science concepts is based on a considerable amount of research on how people learn best and is known as the *Learning Cycle*. There are actually a number of versions of the Learning Cycle but the main idea behind them all is that we understand concepts best when we can anchor them to our previous experiences. One way to accomplish this is to provide the learner with a set of experiences and then explain relevant concepts in a way that ties the concepts to those experiences. Following that explanation with applications of the concepts helps to solidify the learner's understanding. The Learning Cycle is not the only way to teach and learn science, but it is effective in addition to being consistent with recommendations from *The National Science Education Standards* (National Research Council 1996) on how to use inquiry to teach science. (Check out Chapter 3 of the *Standards* for more on this.) In helping your children or students to understand science, or anything else for that matter, you would do well to use this same technique.

As you go through this book, you'll notice that just about everything is measured in *Système Internationale* (SI) units, such as meters, kilometers, and kilograms. You might be more familiar with the term *metric units*, which is basically the same thing. There's a good reason for this—this is a science book and scientists the world over use SI units for consistency. Of course, in everyday life in the United States, people use what are commonly known as English units (pounds, feet, inches, miles, and the like).

The book you have in your hands, *Light*, covers three different scientific models of what light is. Each model is useful for explaining different kinds of observations. With those three models, you'll be able to understand how and

why light bends, how optical instruments form images, what causes rainbows, how to draw 3-D images, and why the sky is blue. There's also an entire chapter on how the eye works. I do not address a number of light topics that you might find in a physical science textbook, choosing instead to provide just enough of the basics so you will be able to figure out those other concepts when you encounter them. You might also notice that this book is not laid out the way these topics might be addressed in a traditional high school or college textbook. That's because this isn't a textbook. You can learn a great deal of science from this book, but it's not a traditional approach.

One more thing to keep in mind: You actually CAN understand science. It's not that hard when you take it slowly and don't try to jam too many abstract ideas down your throat. Jamming things down your throat, by the way, seemed to be the philosophy behind just about every science course I ever took. Here's hoping this series doesn't continue that tradition.

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This book was reviewed by Pamela Gordon (Randall Middle School, Florida); Olaf Jorgenson (Director of Science, Social Sciences, and World Languages, Mesa Public Schools, Arizona); and Daryl Taylor (Williamstown High School, New Jersey).

About the Author

Bill Robertson is a science education writer, teaches online math and physics and trains new faculty for the University of Phoenix, and reviews and edits science materials. His numerous publications cover issues ranging from conceptual understanding in physics to how to bring constructivism into the classroom. Bill has developed K–12 science curricula, teacher materials, and award-winning science kits for Biological Sciences Curriculum Study, the United States Space Foundation, the Wild Goose Company, and River Deep. Bill has a master's degree in physics and a Ph.D. in science education.



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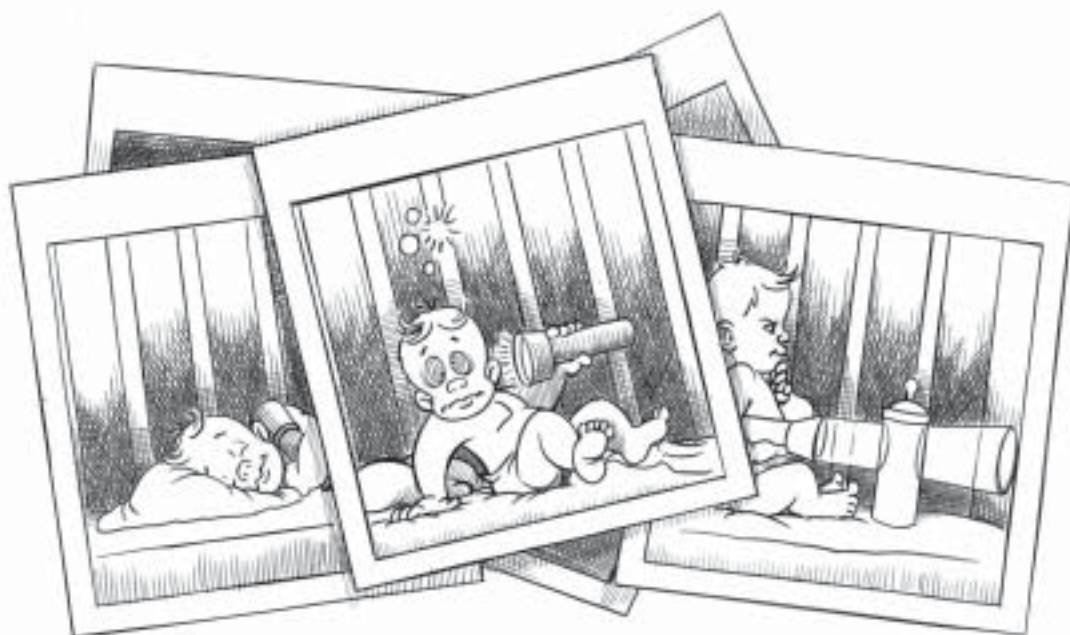
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Light—The Early Years

I'm going to start this book with a rather simplistic view of what light is. There are better explanations than the one I'll use in this chapter, and I'll get to those later. We'll start with the simple explanation, though, because it's the easiest to understand and it does explain quite a few things. Also, historically, it's the one that came first; hence, the title of this chapter. Before I get to the explanation, though, you have a few —

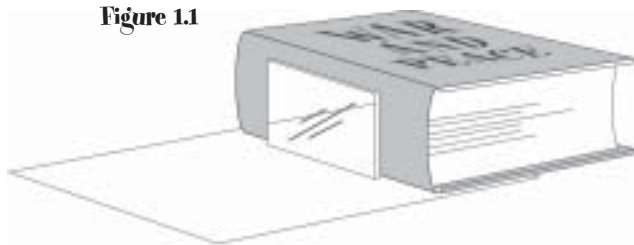
Things to do before you read the science stuff

Find yourself a flashlight, a piece of white paper, scissors, cellophane tape, a pen or pencil, an index card, and a mirror with at last one flat edge (a rectangular hand mirror works best). The mirror shouldn't have a frame, so that you can set



1 Chapter

Figure 1.1



of the flashlight so the open end of the slit just meets the edge of the flashlight. Check out Figure 1.3.

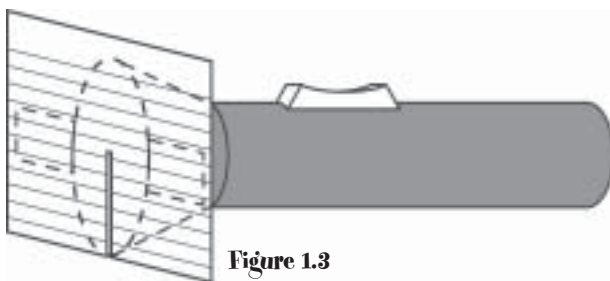


Figure 1.3

Turn on the flashlight and set it on a sheet of white paper that's on a flat surface. Adjust the angle of the flashlight until you get a narrow beam of light that is visible all along the paper (Figure 1.4). The beam will probably spread out a bit, but as long as it's not a lot, you'll be okay.

Prop the mirror up against a large, heavy book or other similar object so it's standing vertically on its edge on the sheet of paper. Shine your flashlight beam toward the mirror so you can see both the incoming and the reflected beam on the sheet of paper, as in Figure 1.5.

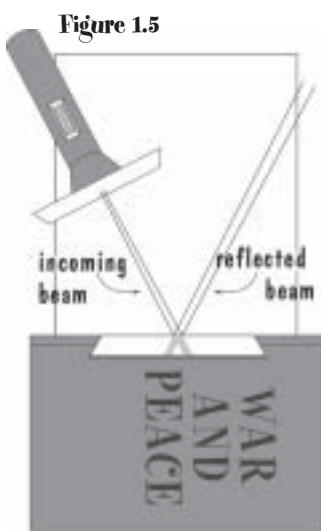


Figure 1.5

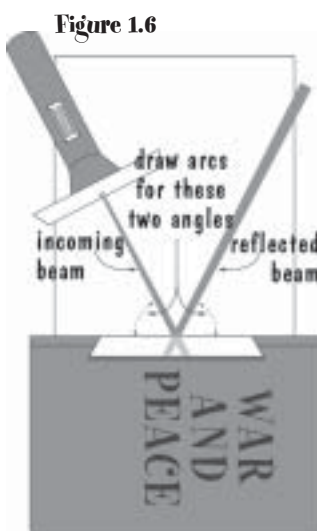


Figure 1.6

a flat edge directly onto a sheet of paper, as shown in Figure 1.1.

Cut a narrow slit (no more than a few millimeters in width) in the index card, as shown in Figure 1.2.

Now tape the cut index card

over the front of the flashlight so the open end of the slit just meets the edge of the flashlight. Check out Figure 1.3.

Turn on the flashlight and set it on a sheet of white paper that's on a flat surface. Adjust the angle of the flashlight until you get a narrow beam of light that is visible all along the paper (Figure 1.4). The beam will probably spread out a bit, but as long as it's not a lot, you'll be okay.

Prop the mirror up against a large, heavy book or other similar object so it's standing vertically on its edge on the sheet of paper. Shine your flashlight beam toward the mirror so you can see both the incoming and the reflected beam on the sheet of paper, as in Figure 1.5.

Now carefully draw an arc that shows the angle the incoming beam makes with the mirror, and another arc that shows the angle the reflected beam makes with the mirror (Figure 1.6).

Figure 1.2



Figure 1.4



Repeat this for the beam hitting the mirror at a different angle (Figure 1.7). Then repeat again for a third angle. Once you're done drawing these angles, compare each incoming beam angle with each corresponding reflected beam angle. If you have a protractor (something that measures angles), great. Otherwise, just eyeball it to see whether one is consistently larger or smaller than the other, or whether they're about the same.

The science stuff

Time for that simplistic explanation of light, which is basically that light can be thought of as traveling in *rays*, which move in straight lines until they hit something like a mirror. So, for example, the light emitted from a lightbulb travels outward in a bunch of straight-line rays, as shown in Figure 1.8. To figure out what happens to the light, all you have to do is follow the individual rays that leave the bulb.

What makes this a simplistic explanation of light is the fact that light does not always travel in straight lines.¹ From this point on, I'll refer to this explanation as the *ray model*.²

Let's use the ray model of light to describe what happens when light reflects off a mirror. We can represent the incoming and reflected beams of light each as a single ray of light. Actually, the beams

Figure 1.7

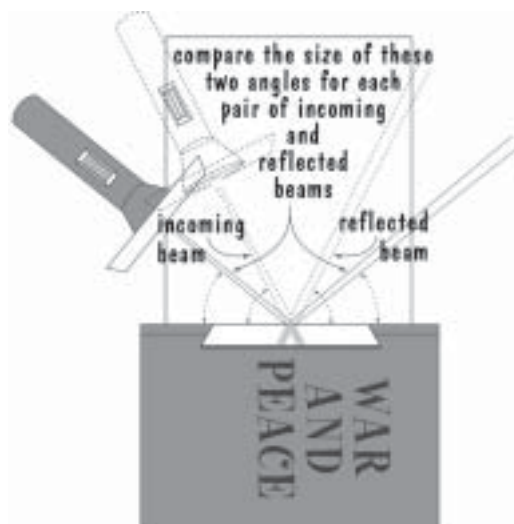


Figure 1.8

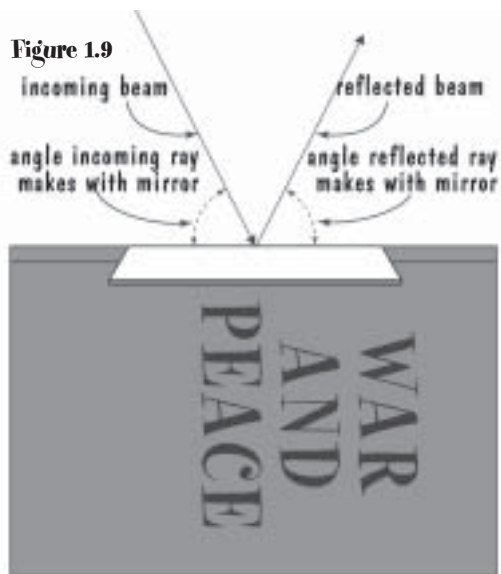


¹ Many elementary school textbooks state, incorrectly, that light always travels in straight lines. We'll see later that this just isn't true. By the time you finish this book, maybe you'll do like I do and cringe every time you read that mistake in a textbook.

² The term *ray model* refers to the fact that representing light as rays is a scientific model. More on what a scientific model is later in this chapter.

1 Chapter

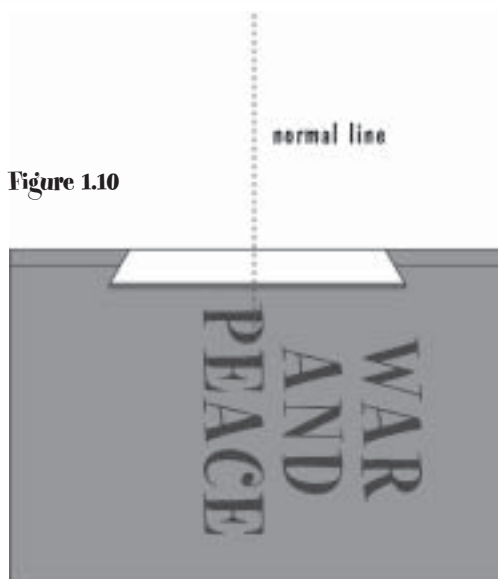
Figure 1.9



consist of a large number of rays of light, but we're just focusing on one ray per beam. Then the mirror situation looks like Figure 1.9.

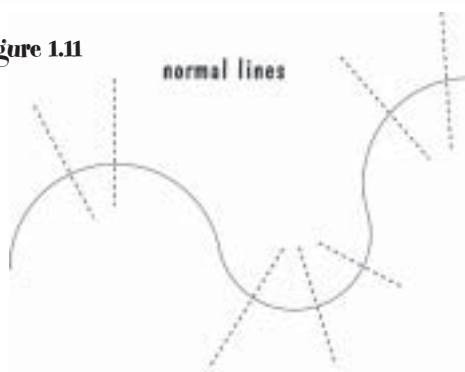
If you drew and measured carefully, you undoubtedly discovered that the angle the incoming beam (or ray) makes with the mirror is equal to the angle the reflected beam (or ray) makes with the mirror. Actually, you probably *didn't* get exactly the same angle measures because a) your light beam spread out a bit, making it difficult to get an exact angle, and b) you didn't draw and measure all that carefully because you're not getting a grade on this project, thank you very much. If you didn't get exactly equal angles, trust me—with a very narrow beam of light and careful measurement, you'll get exactly equal angles every time.

Figure 1.10



So now you know how reflected light behaves, except for the fact that I had you measure the wrong angles! Well, not exactly the *wrong* angles, but not the angles scientists use when describing reflection of light. In order to use the scientifically correct angles, I have to define something known as the *normal* to a surface. A line that is *normal* to a surface is one that is perpendicular to that surface. Figure 1.10 shows the normal line for our mirror.

Figure 1.11



For a curved surface, the normal to the surface is in a different direction at each part of the surface, as shown in Figure 1.11.

At any rate, the angles we should measure if we're good little scientists are the angles the incoming and reflected beams make with the line that is normal to the reflecting surface. When we use those angles, they're called the *angle of incidence* and the *angle of reflection*, respectively.

Turns out these two angles are also equal to each other for any reflected beam of light (Figure 1.12). Don't believe me? Measure them.

With the properly defined angles, we can now write down what's known as the **law of reflection**, which is that:

Angle of incidence = angle of reflection

Okay, big deal. If you've ever looked at a book about light, you've seen the law of reflection written down somewhere, so why did we just spend a whole lot of time getting to it? There are a couple of reasons. First, it's important that you actually experience something before I formalize it. If you did what I asked, then you saw firsthand that the angle of incidence is equal to the angle of reflection. That experience beats the heck out of believing something just because it's written down in a book. Second, I took the time to explain that picturing light as a bunch of rays that travel in a straight line is just one model of what light is. The ray model is useful for explaining reflection of light but not so useful for explaining other things that light does. One of the keys to understanding science is understanding what a scientific model is and understanding the limitations of whatever model you're using. In that vein, keep the following in mind.

People who develop science concepts *make them up*. These ideas are *not* handed down from deities on high and they are not facts. What makes concepts and models hang around is that they help explain and predict observations. If they cease to do that, they gradually go to the scientific model graveyard. That said, it's not as if you can come up with any old explanation and call it a valid scientific theory. There are conventions for evaluating theories to determine how good they are. The theories, or models, that are in this book have been around awhile, so you can be pretty sure they won't be out of vogue tomorrow.

Before moving on, let's recap. I introduced a ray model of light and used it to explain how reflected light behaves. I introduced *normal lines* and the fact that scientists measure the angles that light rays make with the normal line, rather than the angles the light makes with the reflecting surface.

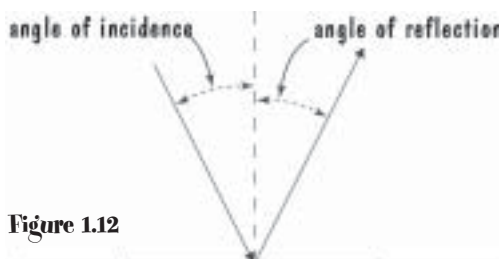


Figure 1.12



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1 Chapter

More things to do before you read more science stuff

In this section, you're going to see what happens when light travels from one substance to another. In the explanation section that follows, I'll use a ray model of light to explain what's going on.

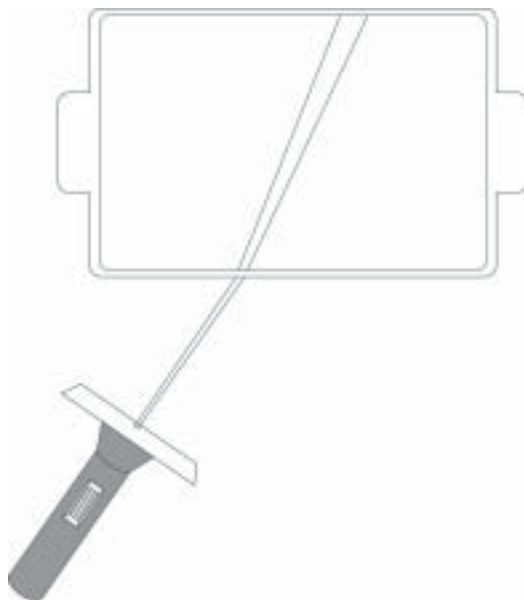


Figure 1.13

If you happen to have a solid, rectangular block of glass, Lucite, or other thick, transparent material, get it. If you don't have anything like that, and I expect that's the case, find a rectangular clear glass or Pyrex baking pan and fill it with water. I'll assume from here on that you're using the pan of water, but everything applies to the other props. Also, grab the flashlight and index card thingie you put together in the first part of this chapter.

Place the pan of water on a flat surface and dim the lights in the room or turn them off altogether. Shine your narrow beam of light towards the pan of water so you can see the beam on the flat surface before it hits the side of the pan (Figure 1.13).

You should be able to see what happens to the light beam after it crosses into the water. If not, move the flashlight around a bit until you can. [Hint: The direction the beam is moving should change once it hits the water.]

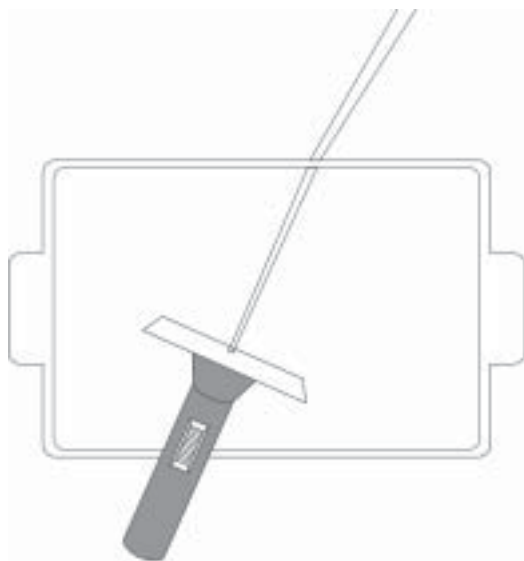


Figure 1.14

If the light gods are smiling upon you, you will be able to trace the path of the light beam all the way through the water, and then when it emerges from the other side of the pan. More likely, though, the light beam sort of dies out after it's in the water. If that's the case, shine your flashlight from above the pan so you can see what the light beam does when traveling from the water back into air (Figure 1.14). [Hint: The beam should change direction again as it travels from the water to the air.]

More science stuff

If you were able to follow the light beam as it went from air to water and then back out into the air, you should have seen something like Figure 1.15.

This means that light rays bend, or change direction, when they travel from air to water and from water to air. Of course, this doesn't just happen with air and water. Whenever light travels from one substance to another, it bends. This bending is known as **refraction**. And just so we have the correct terminology, scientists talk about light traveling from one **medium**³ to another, rather than from one substance to another. Water and air are different mediums, sugar water and plain water are different mediums, cold water and hot water are different mediums, and Miss Cleo and John Edward are different mediums.

It's natural to ask *why* light refracts in traveling from one medium to another. In fact, that "why" question is what causes scientists to develop scientific models. Later on, I'll introduce a scientific model of light that provides a pretty good explanation of refraction. Our current ray model, however, doesn't do much to help us understand the reason for refraction.⁴

The ray model does help *describe* what's going on with refraction, though. For that description, we can use our old friend the *normal* to a surface. Figure 1.16 shows a top view of the boundary between air and water, with the normal to that boundary drawn in.

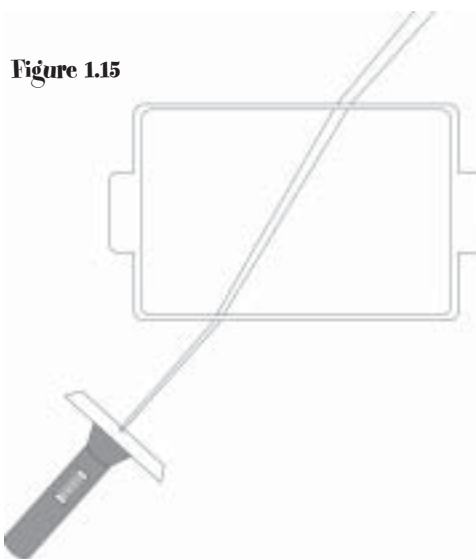


Figure 1.15

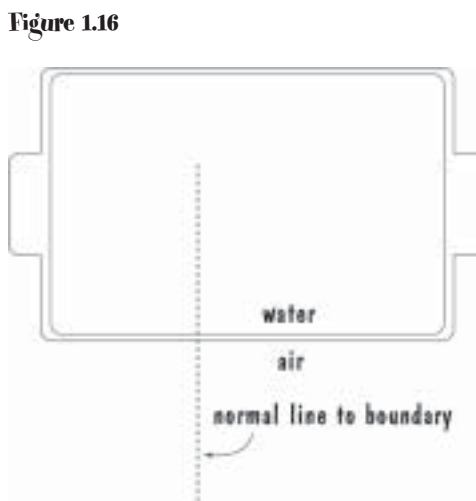


Figure 1.16

³ See the second or third definition of this word in your local dictionary.

⁴ Actually, there's something known as Fermat's principle that, when coupled with a ray model, provides an explanation of refraction. Because it's kind of a strange principle, I'll address it in the Applications section rather than get totally off track here.

1 Chapter

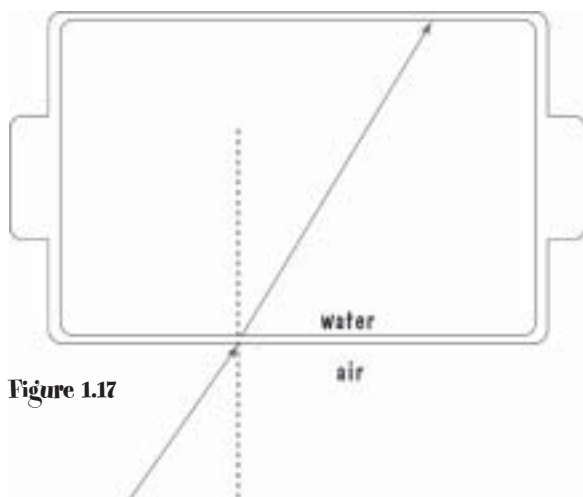


Figure 1.17

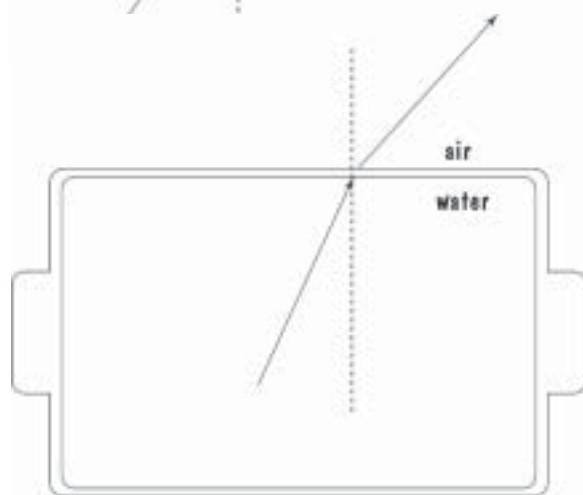


Figure 1.18

When a light ray travels from air to water, it refracts as shown in Figure 1.17. When a light ray travels from water to air, it refracts as shown in Figure 1.18.

Now, water is more *dense* than air,⁵ so we might be tempted to generalize our result and say the following:

When light travels from a less dense medium to a more dense medium, it refracts *towards* the normal. When light travels from a more dense medium to a less dense medium, it refracts *away from* the normal.

And by golly, that turns out to be true in all cases. In fact, there's a mathematical relationship that describes exactly how much and in what direction light bends when it goes from one medium to another. If I could be sure everyone had a nice, uniform block of Lucite, I could have you sort of "discover" that relationship for yourself, just as I had you "discover" the law of reflection. But since most of you are dealing with a crude baking pan filled with water,

I'm just going to give you the relationship. Before I do that, though, I have to define something known as the **index of refraction**. It's represented by the letter n , and each medium has its own value of n . Basically, the denser the medium, the higher the index of refraction of that medium.⁶ The index of refraction of a vacuum (meaning *empty space* rather than something Mr. Oreck

⁵ The more dense a medium is, the more "stuff" it has in a given volume. This usually means that its molecules are more closely packed together than in a less dense medium.

⁶ The exact definition of the index of refraction of a medium is the speed of light in that medium divided by the speed of light in a vacuum (empty space). We'll discuss in Chapter 2 why the speed of light should have something to do with the value of n .

would like you to buy) is 1.0, the index of refraction of water is 1.33, and the index of refraction of glass is about 1.5.

Okay, so now it's time to write that relationship. You won't immediately recognize everything, so don't freak out, all right?

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Note for the math phobic

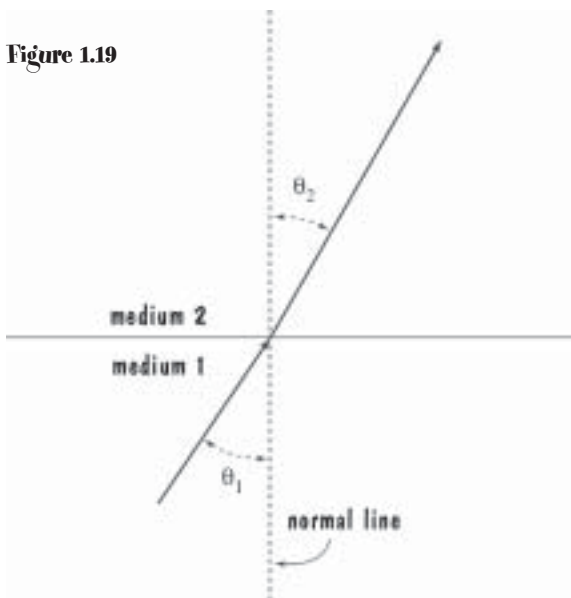
Just so you don't get totally intimidated by the symbols in an equation, here's a brief explanation. An equals sign means that whatever is on the left side of the sign is numerically the same as what's on the right hand side. If two things are in parentheses and next to each other, as in (speed)(time), that means you multiply the two together. If there's a slash between those parentheses, as in (distance)/(time), you divide the first by the second. If there are just letters and no parentheses, two letters next to each other, as in vt , should be multiplied and two letters with a slash in between, as in d/t , means divide the first by the second.

Figure 1.19 will be a big help in understanding this relationship.

We have light going from medium 1 to medium 2, which can be, for example, light going from air into glass. The index of refraction of medium 1 is n_1 and the index of refraction of medium 2 is n_2 . θ is the Greek letter "theta." θ_1 is the angle between the incident light ray and the normal line, and θ_2 is the angle between the refracted light ray and the normal line.

Now $\sin \theta$ means you take the sine of the angle θ . What's a sine? Well, think back to high school math and things called sines and cosines. If you want to look up the actual definition of sines and cosines, feel free to do that. Suffice it to say they have to do with how a particular angle relates to the triangle it might be part of. You don't really need the formal definitions, though, because we aren't going to be calculating any numbers with our relationship. Oh, and by the way, $n_1 \sin \theta_1 = n_2 \sin \theta_2$ is known as **Snell's law**.

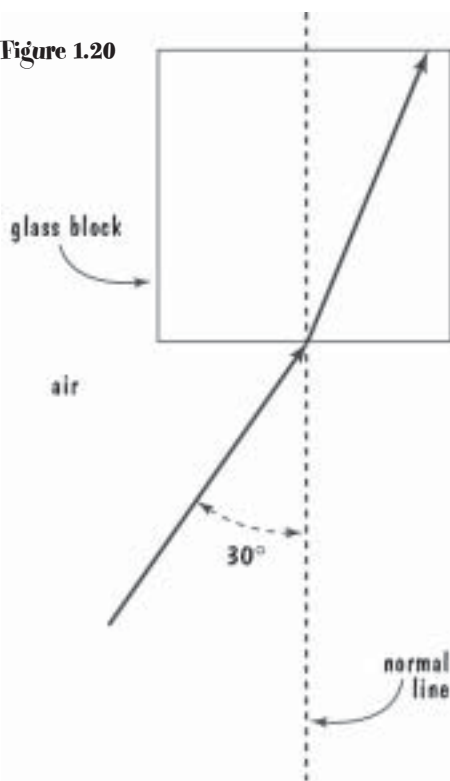
Figure 1.19



1 Chapter

Snell's law works for all different mediums and it has built into it the whole business of refracting toward or away from the normal. I'll do one example to convince you of that. Suppose you shine a light beam from air into a solid block of glass and you do it at a 30-degree angle to the normal (Check out Figure 1.20). We already know what's going to happen—the light will bend towards the normal because it's going from a less dense to a more dense medium.

Figure 1.20



Snell's law will tell us exactly how much the light refracts towards the normal. The index of refraction of air is almost equal to 1, so we'll just let it be 1, and the index of refraction of glass is about 1.5. Snell's law gives us:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

or, in this particular case:

$$n_{\text{air}} \sin \theta_{\text{air}} = n_{\text{glass}} \sin \theta_{\text{glass}}$$

Putting in the values for the n 's and θ 's, we get:

$$(1.0)(\sin 30^\circ) = (1.5)(\sin \theta_{\text{glass}})$$

It helps here if you remember that sets of parentheses next to each other mean multiplication. I'm not going to bother you with the algebra we have to do to solve for θ_{glass} (you're welcome)⁷, so you can just trust me that the result is:

$$\theta_{\text{glass}} = 17.5^\circ$$

This angle is smaller than 30° , meaning the light beam refracts towards the normal. Okay, neat. We can describe exactly what light will do when going from one medium to the next,

but keep in mind that it is just a description. Snell's law doesn't do anything to explain *why* light refracts.

Time for another recap. I used a ray model of light to describe exactly how light behaves when traveling from one medium to another. That exact description is Snell's Law, which is a bit more complicated than the law of reflection I introduced earlier.

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⁷ For those of you who really want to see the steps, here's how it goes. First divide both sides of the equation by 1.5. After doing the math on the left side, you get $0.33 = \sin \theta_{\text{glass}}$. This means that $\sin \theta_{\text{glass}}$ is equal to 0.33. The angle whose sine is 0.33 is 17.5° , which you can figure out on your calculator or look up in a table of sines.

Even more things to do before you read even more science stuff

Set up your light beam and pan of water as in Figure 1.14, so the light travels from the water out into the air. The beam should refract away from the normal, yes? Now gradually increase the angle between the incoming beam and the normal, as in Figure 1.21.

Keep doing this until the refracted beam is almost parallel with the edge of the pan. Keep increasing the angle beyond this point, and you will get to where the entire light beam is reflected back into the water as in Figure 1.22.

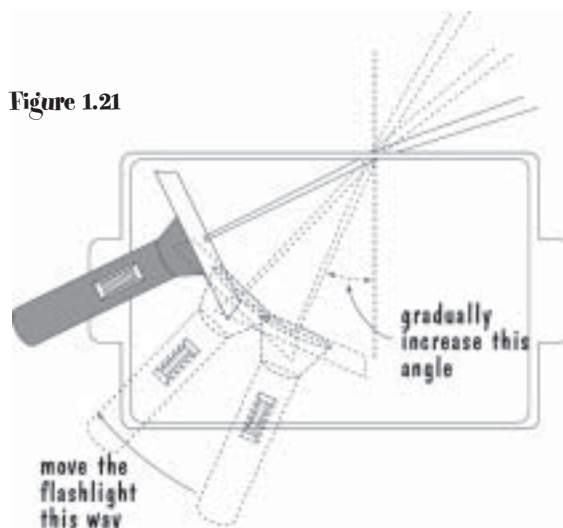


Figure 1.21

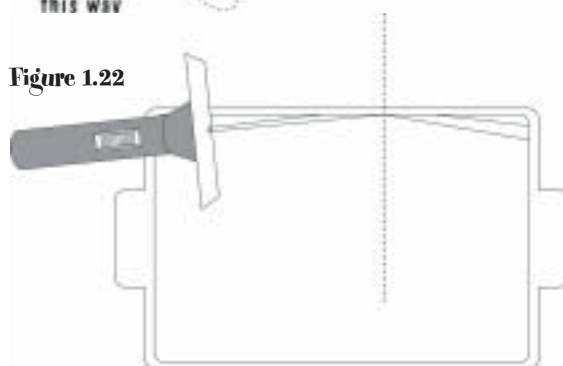


Figure 1.22

Even more science stuff

What you just observed is known as **total internal reflection**. If you were really observant in earlier sections, you might have noticed that even when the light beam travels on into the second medium, some of the beam is always reflected. The greater the angle between the incident beam and the normal, the more light is reflected rather than refracted. (You might want to go back to your setup and verify this. Then again, maybe not!) Beginning at a certain angle, known as the **critical angle**, *all* of the light is reflected.

And this is how fiber optics works. When you send light into the end of a tube made of Lucite or glass or other dense, transparent substance, the light keeps traveling along the tube, undergoing total internal reflection each time it hits the side (Figure 1.23).

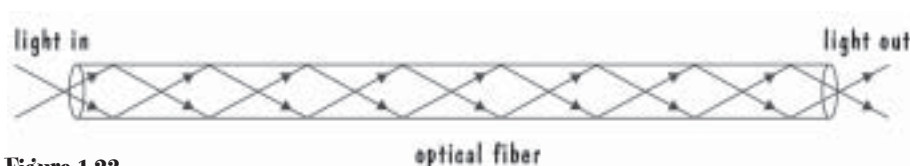
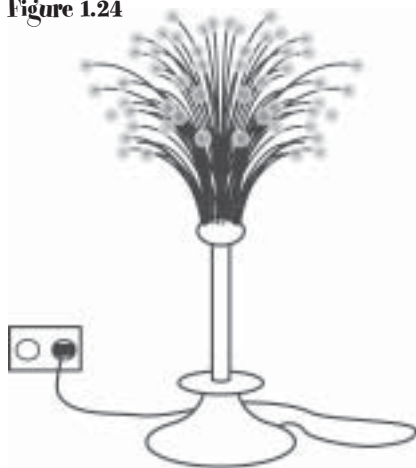


Figure 1.23

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So now you know how those cool lights you get at gift shops work. You know, the ones that have dozens of thin, glass-like strands that fan out in a circle from the center, but only light up at the tips, as in Figure 1.24. All the light starts at the base of the lamp, and undergoes total internal reflection all the way out to the tips. If one of the strands bends in the middle, the middle lights up because you've created a spot where the light hits the side at something less than the critical angle, and it escapes.

Figure 1.24



We also use fiber optic cables to send information from one place to another. We just have to turn the entering light on and off really fast. The rate at which the light turns off and on can carry information. It's sort of like sending Morse code by turning a flashlight on and off. Of course, the on and off of a fiber optic cable is about a gazillion times faster than turning a flashlight on and off.

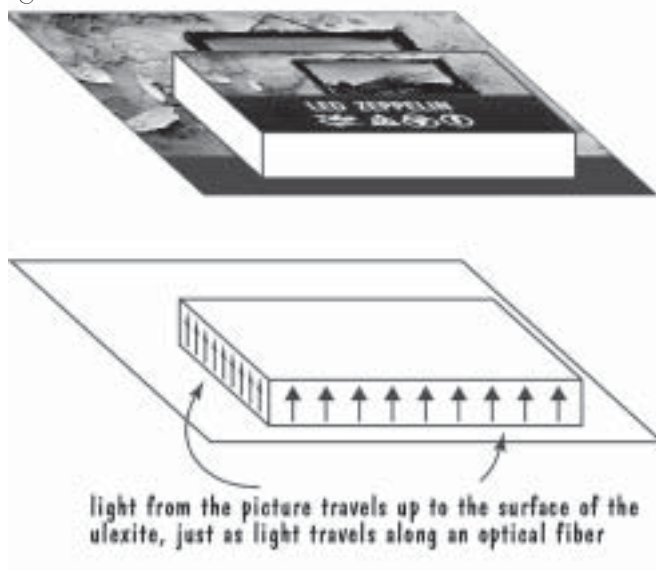
If you're in the mood for a field trip, head to your local rock shop and ask to see a piece of *ulexite*. Place the ulexite over some newsprint for a neat effect. It turns out ulexite is made of tiny strands that act just like optical fibers, so you can read the print at the top surface of the ulexite, demonstrated in Figure 1.25.

And even more things to do before you read even more science stuff

Now that you know something about reflection and refraction, it's time to get to something a bit more interesting. In this section, we'll focus on the images we see as a result of various reflections and refractions.

Find yourself any old mirror—the bathroom mirror will work. Hold up an ob-

Figure 1.25



ject and look at its reflection in the mirror. How far does the reflected object appear to be from you?

Take a stab at using a diagram of light rays to explain why the object appears where it is and how far away it is.

Look at your reflection in the back of a metal spoon. See if you can explain why your face looks the way it does. Is this an improvement in your facial features?

Get a glass of water and stick your finger inside. Look at your finger from the side and notice how the image of your finger changes as you move your finger around the glass. See if you can explain what's going on.

And even more science stuff

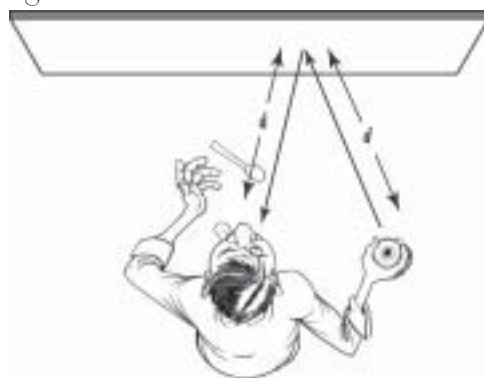
To figure out why you see what you see when looking at various reflected and refracted images of an object, it helps to imagine that the object is emitting light rays that travel outward in all directions.⁸ By tracing the paths of just a few of these rays, we can figure out what's going on. Let's start with the simple one—looking at the reflection of an object in a mirror (Figure 1.26). I'm going to draw a light ray that goes from the object, reflects off the mirror, and goes to your eye.

Now forget the fact that you know this light is reflected off a mirror. If you didn't know you were looking at reflected light, where would you say this light ray originated? In other words, where does the actual object appear to be? Well, the light ray has traveled a total distance of $2d$ (see Figure 1.27), so we think the object is a distance $2d$ away from us.⁹ Being ignorant and not knowing this is a reflection, we also assume the light rays that leave the object travel in straight lines and don't bounce off things, so we think the ob-

Figure 1.26



Figure 1.27



⁸ Unless the object creates its own light, the light it emits is actually reflected light.

⁹ We use all sorts of cues to judge distance, such as the size of the image and the difference between what the left eye and right eye see.

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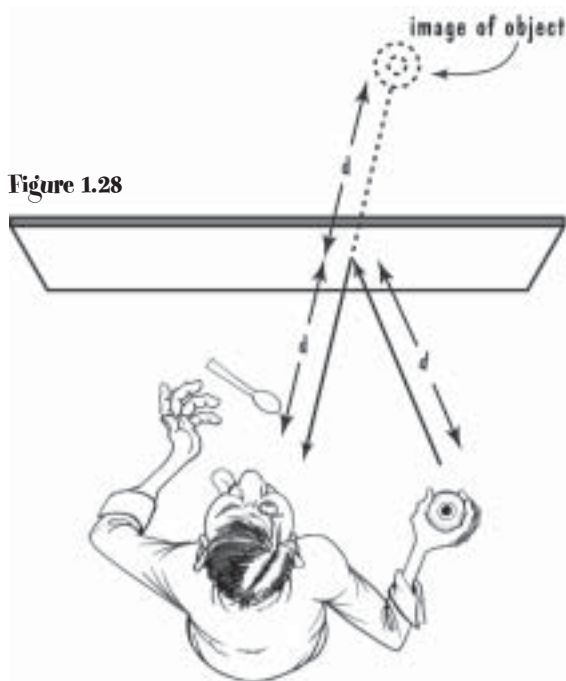


Figure 1.28

ject is a straight-line distance of $2d$ away from us. In other words, we see the image of the object *behind* the mirror (Figure 1.28).

This is true of all images you see in a flat mirror. They're behind the mirror, and they're just as far behind the mirror as the actual object is in front of the mirror.

All right, what about curved mirrors, and in particular, the back of a spoon? Let's trace the light rays you see when looking at your own reflection in the spoon. Figure 1.29 shows a top view of your head and a flat mirror, and a top view of your head and a curved mirror (the spoon).

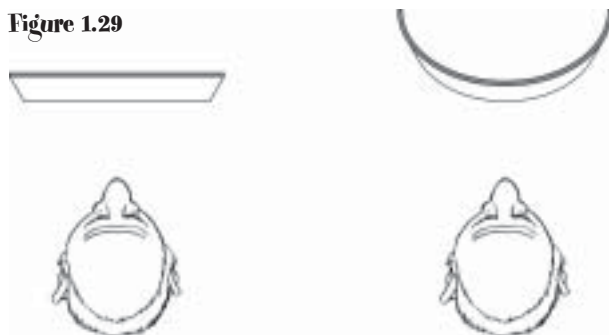


Figure 1.29

For convenience, let's assume you're a cyclops with only one eye in the middle of your head (apologies to all the cyclopes out there). I'm going to draw light rays that leave your ears, reflect off the mirror (flat or curved), and travel to your eye. Those rays are shown in Figure 1.30.

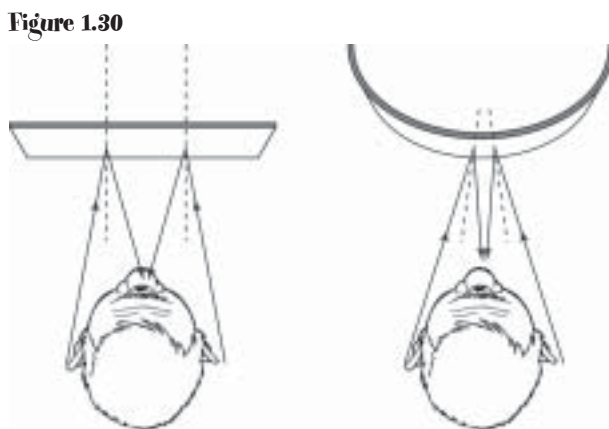


Figure 1.30

Notice that, for each reflection, the angle of incidence equals the angle of reflection, and those angles are the ones made with the normal line at each reflection point. Also notice that the direction of the normal line changes quite a bit across the surface of the curved mirror. If you're really careful in drawing those lines, you get the result in Figure 1.30. To see what your reflection looks like, just figure out where whose rays that hit your eye *appear*

to come from, assuming they travel in a straight line instead of reflecting. I've done that in Figure 1.31.

As you can see, your reflection in a flat mirror is the same size as your actual head. In the curved mirror, though, your head appears to be shrunken in width. The more sharply curved the mirror is, the more shrunken your head appears to be. See Figure 1.32.

Take a close look at the spoon, and you'll see that it is curved more sharply from side to side than it is along its length. See Figure 1.33.

Therefore, the image of your head shrinks more along one direction than along the other, making your head look long and skinny, or short and wide, depending on how you hold the spoon.

Okay, on to how your finger looks in a glass of water. When you have it on the far side of the glass, away from your eyes, it looks pretty darned fat. To see why, what say we draw, umm—light rays! Instead of being reflected, the light rays you see have been *refracted* as they travel from your finger, through the water, and out into the air to your

Figure 1.31

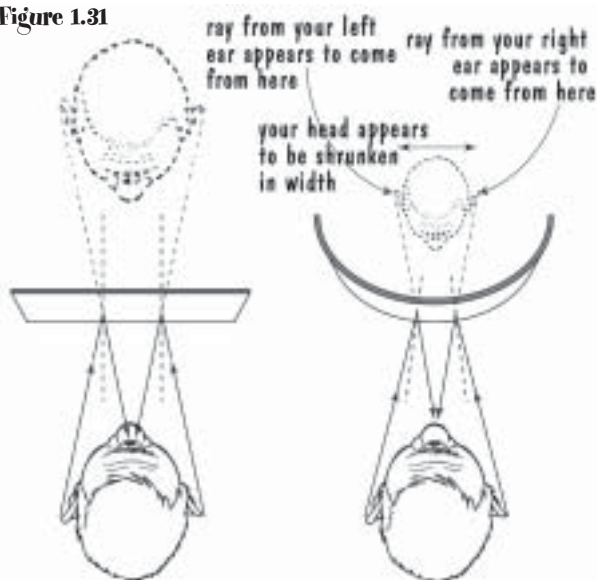


Figure 1.32

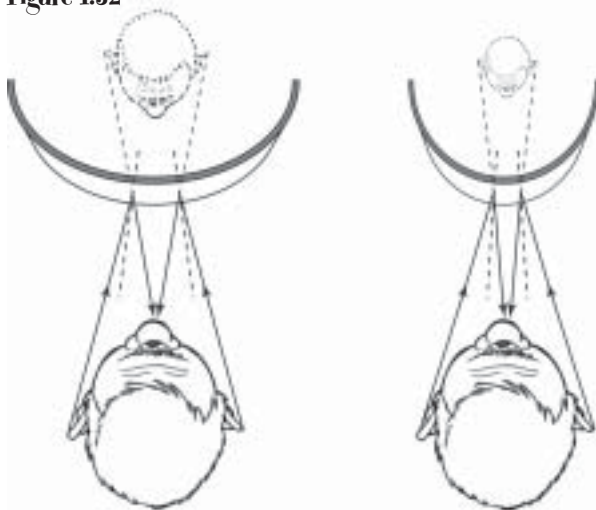
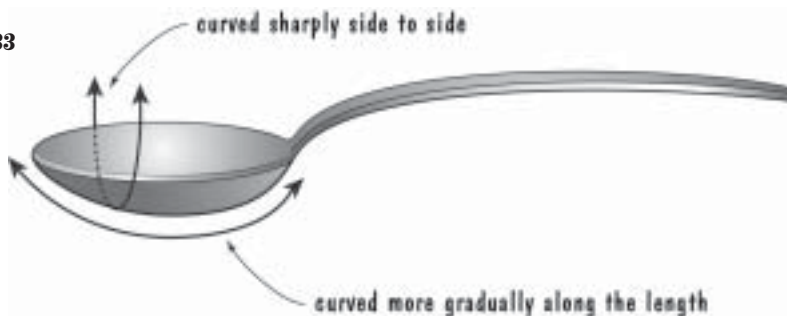


Figure 1.33



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eyes.¹⁰ Again, I'll assume you are a cyclops and I'll just draw the rays that go from the edges of your finger. In going from a more dense medium (water) to a less dense medium (air), the rays will bend *away from the normal*, and since the side of the glass is curved, the normal will be in a different direction at different parts of the glass. The diagram of light rays is in Figure 1.34. Note that the figure shows only two selected light rays—those that leave the sides of your finger and eventually, after refracting, reach your eye. When those rays leave your finger, they are not initially headed for your eye. After they refract, however, they go towards your eye. Any light rays that start out headed for your eye won't reach it, because they'll refract when they get to the glass-air interface.

As with reflection, your uninformed eye doesn't know the light has been refracted. Your eye assumes the light rays hitting it traveled in a straight line. To figure out the image your eye sees, we trace the rays that hit it back along the direction they came from, as in Figure 1.35.

Your eye sees the image of your finger that's dotted in Figure 1.35. In other words, your finger looks much larger to you than it really is.¹¹ When your finger is on the side of the glass closest to you, the effect isn't nearly as pronounced. Figure 1.36 shows why.

Figure 1.34

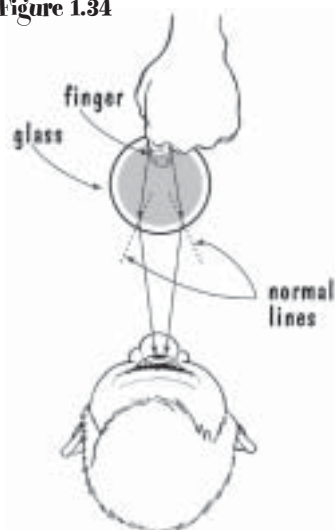


Figure 1.35

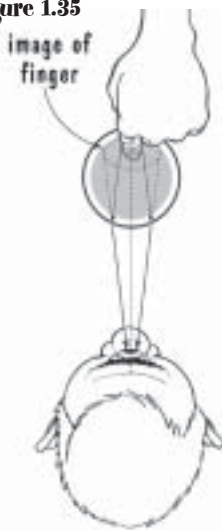
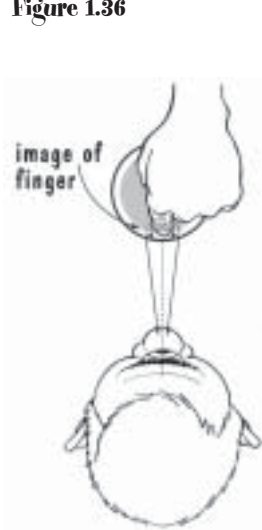


Figure 1.36



¹⁰ You might notice that I'm ignoring the glass that holds the water. To be completely accurate, I should include the refraction that happens when going from water to glass and then from glass to air. All that would do is make our diagrams more complicated, and who needs that? The basic idea is still the same.

¹¹ A little foreshadowing here. Can you think of a use for something that makes objects look bigger than they actually are? Sure you can.

Chapter Summary

- One model for light is that it is composed of rays that travel out in all directions from a light source.
- When light rays go from one medium to another, the light rays could be a) totally reflected back into the original medium, b) partially reflected and partially transmitted into the second medium, or c) totally transmitted into the second medium.
- Reflected light obeys the law of reflection, which states that the angle of incidence is equal to the angle of reflection. Those angles are the angles between the incident and reflected rays and the *normal* to the reflecting surface.
- When light travels from one medium to another, it often bends, or *refracts*. Snell's law describes the exact relationship between the incident and refracted rays.
- The *index of refraction* of a substance is a measure of how dense the substance is and also a measure of how much light refracts when it travels from one medium to another.
- When light travels from a more dense to a less dense medium, there is a chance that the incoming light gets *totally internally reflected*, meaning it reflects back into the more dense medium. This phenomenon is the basis for fiber optics.
- To figure out where a reflected or refracted image is formed, you first draw light rays that come from the original object. Then you trace these rays back along the line of the rays that come straight to the viewer. Where the rays *appear* to come from is where the image is.

Applications

1. When you walk by a store or restaurant window, you not only can see the inside of the store or restaurant, you can see a reflection of yourself. Why is that? Well, remember that, unless you're dealing with total internal reflection, when light travels from one medium to another, some of the light refracts and travels on into the second medium, and some of the light reflects. So, the light coming off you hits the window. Some travels on through, so the people inside can see you and talk about you. Some is also reflected, so you can check out just how much the wind has messed with your hair. Of course, the same thing happens in reverse, so you can see the people inside and they can see a reflection of themselves (see Figure 1.37, next page).

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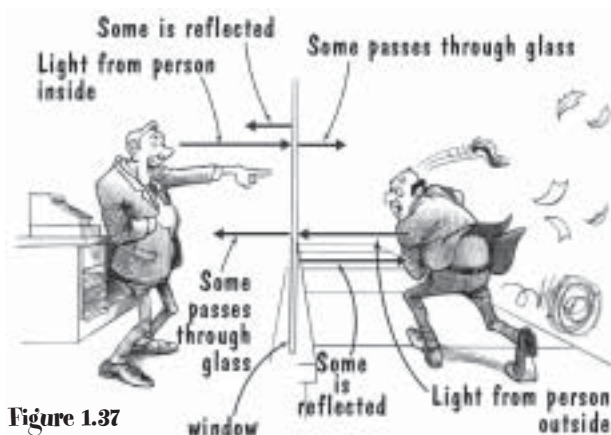


Figure 1.37

shouldn't the person in front of the mirror be able to see light coming from the person behind the mirror? Yes, that would be true *if* there were any lights on in the room behind the mirror. But the people doing the observing keep that room dark, so nothing in it, including the person be-

Two-way mirrors work the same way. These mirrors are silvered, but not so much that some of the light from you doesn't travel on through so someone behind the mirror can see you. And that's the main point of two-way mirrors; someone uses them to spy on someone else, as shown in Figure 1.38.

But wait a minute. If the mirror isn't completely silvered,

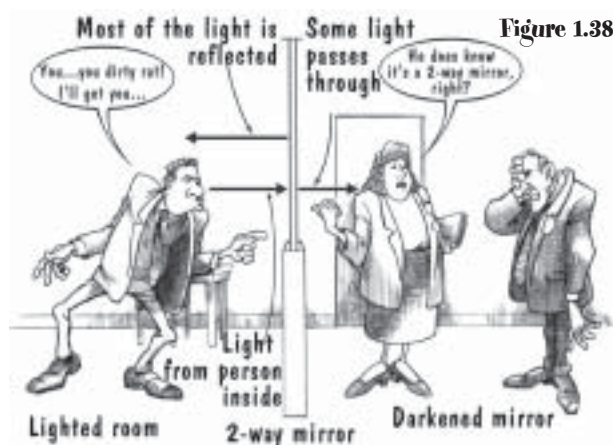


Figure 1.38

hind the mirror spying on you, emits any significant light for you to see.

Because it's related, I now have to tell you how they make ghosts in the Haunted House at Disneyland. As you ride along in your chair, you see an empty room in front of you. You also see ghosts moving around. Those ghosts are just images that are reflected from a transparent screen in front of you. The real objects (the ones that lead to the ghost images) are actually below you. Check out Figure 1.39.

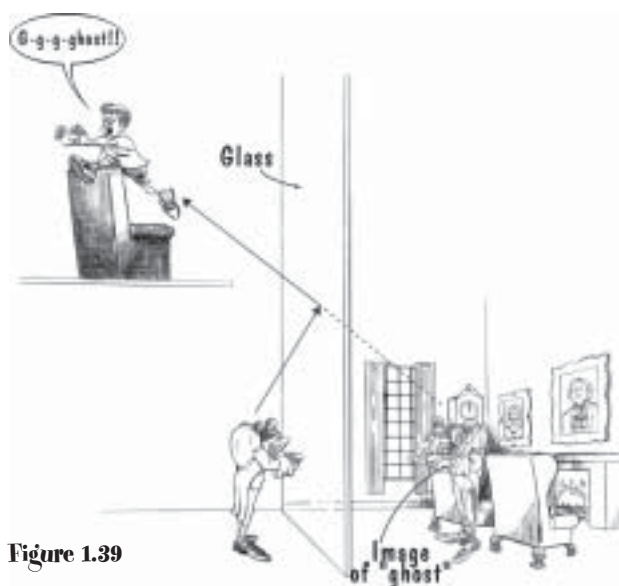


Figure 1.39

2. I remember as a kid riding in the car on a long stretch of road in the Arizona desert, seeing what looked like water on the road up ahead. Of course this had to be a mirage, because as everyone knows, it rains only two thousandths of an inch a year in Arizona. Okay, not true. Anyway, what causes these mirages? Well, on very hot summer days, you often get a temperature inversion, in which the air near the road is much hotter than the air above it, and the change from hotter to cooler air is gradual. The hotter air is less dense than the cooler air.¹² The result is that light from the sky refracts as it travels from the more dense air to the less dense air, and gives you the situation shown in Figure 1.40.

When you trace the light rays reaching your eyes back along the direction from which they came, you see that there's an image of the sky smack dab in the middle of the road up ahead (Figure 1.41). Sure looks like water! Of course, the refracting

light ray shown isn't the only one emitted by that patch of sky. That patch of sky also emits light rays that travel straight to you, so you still see the sky where it's supposed to be.

Figure 1.40



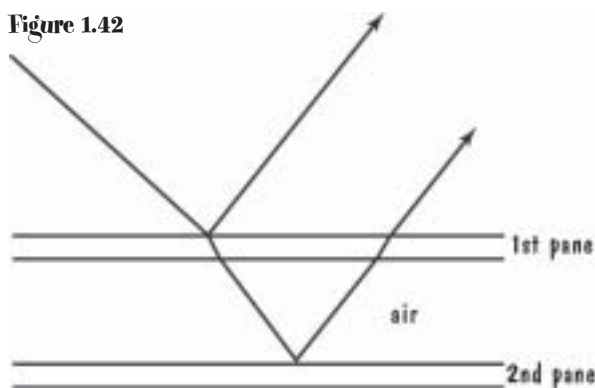
Figure 1.41



¹² See the *Stop Faking It!* book *Energy* for an explanation of this.

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Figure 1.42



3. In our house we have a security system with little red and green lights. I still get a little freaked out when I see the reflection of these lights in a window, because there are two sets of lights in the reflection, giving more of an impression of a tiny alien spaceship than a set of security lights. The reason I see two sets of lights is that the windows are double-pane windows. Figure 1.42 shows what happens to the red and green lights.

When the light from a security light hits the inside pane, some is reflected and some refracts on through. The refracted light emerges from the other side of the window pane, passes through the air space between the panes, and reflects off the second pane. Some of the light travels back through the second pane, and the result is that you end up with two images of each light. Either that or it's a tiny alien spaceship.

4. Here's sort of a homework problem. First, look in a regular, flat mirror. Right and left are reversed, right? Use the diagram in Figure 1.43 to figure out why.

Now see if you can set up two flat mirrors so they're at right angles. Look at yourself in this setup. Now right and left are no longer reversed. Use the ray diagram in Figure 1.44 to figure out why.

Figure 1.43

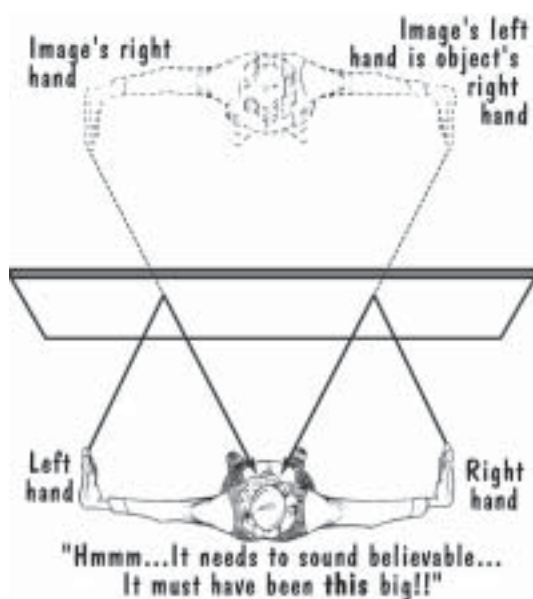
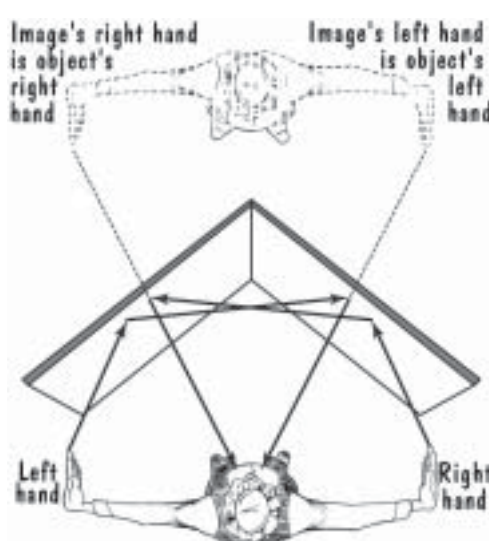


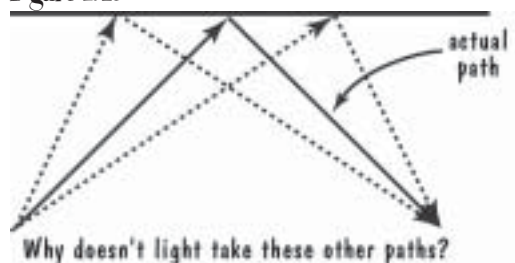
Figure 1.44



5. I promised in one of the footnotes that I'd explain Fermat's principle. It's kind of esoteric, so if you want to skip this, no big deal. It won't affect your understanding of the rest of the book.

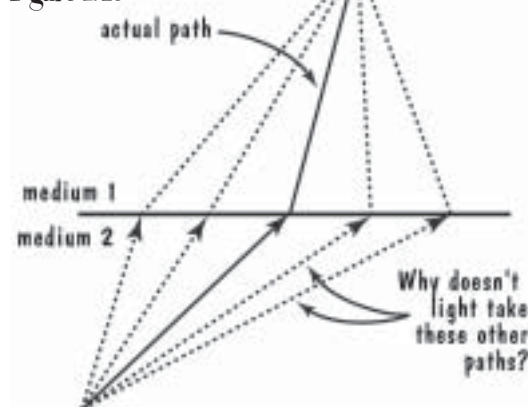
Anyway, here are a few questions. How does light “know” that it has to obey the law of reflection? Instead of the angle of incidence being equal to the angle of reflection, why can't you have something like Figure 1.45?

Figure 1.45



Also, how does light “know” that it has to obey Snell's law? Shown in Figure 1.46 is the path light takes when it obeys Snell's law (let's suppose I calculated it and drew it exactly). But why can't the light travel in the other paths shown?

Figure 1.46



Well, a French nobleman and mathematician named Pierre de Fermat came up with—surprise—Fermat's principle. The principle states that when light goes from one place to another, it travels a path that takes equal or less time than any nearby paths.¹³ It turns out that the paths that obey the law of reflection and Snell's law also obey Fermat's principle.

Fine, but how does the light know to take the least amount of time? Here's where it gets a little strange. The path of least time actually is the *most probable* path for the light to take. The nearby paths are so much less likely to occur, that we never see light take them. Now here's where it gets even weirder.

If you go beyond Fermat's time to the 1900s, you can explain what happens by saying that light actually *does* take those nearby paths, but the effect of taking them cancels out. It's still based on probability, but it's as if the light tests out all the nearby paths and figures out that the least-time path is the proper result. Of course, light doesn't have a mind of its own—I don't think.

¹³ Note that the path of least time isn't necessarily the shortest path. That's because light travels at different speeds in different mediums (see Chapter 2), meaning it might be quicker to have most of the path traveled in the faster medium, even if the overall path in both mediums is longer.



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