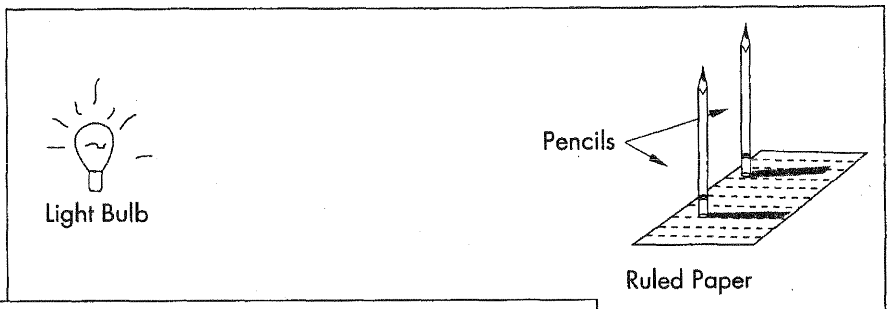
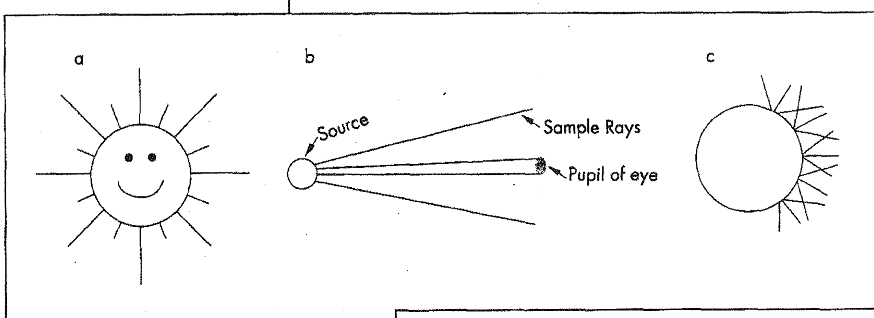
Only the Shadow Knows

When I was a youngster, I was taught that light goes in straight lines. At some point, I also became aware that light spreads out from a light source such as a light bulb. However, it still seemed to me that I was missing something important. I couldn't figure out why shadows had such blurry edges. If the light goes straight, shouldn't the edge of a shadow be sharp? And what really bothered me was, if the light spreads out—gets bigger in a sense—and we use our pupil to grab a tiny fraction of that light, why can we see the whole object?

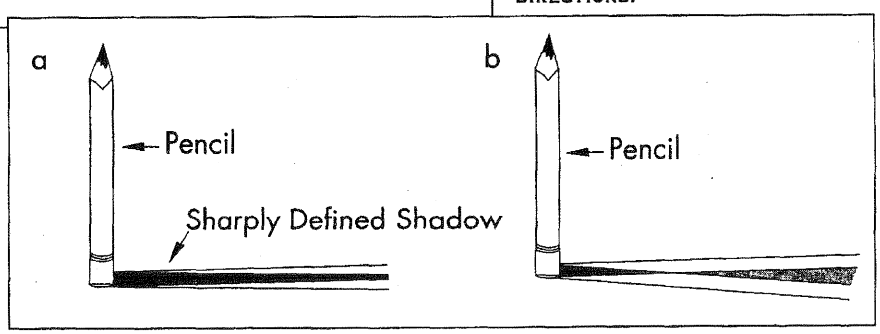
This column looks at some very simple experiments to help youngsters understand something of the propagation of light. I have tried to choose experiments in which scattering, diffraction, etc. are not dominant features and can be safely ignored; I will mention these more later.



▶ FIGURE 1. LAYOUT FOR TWO-PENCIL EXPERIMENT.



◀ FIGURE 2. THE MISCONCEPTION THAT LIGHT FROM EACH PART OF A SOURCE PROPAGATES IN ONLY ONE DIRECTION. (A) A TYPICAL CHILD'S ILLUSTRATION OF THE SUN; (B) AN ERRONEOUS VIEW OF PROPAGATION; (C) A MORE ACCURATE VIEW SHOWING THE LIGHT LEAVING EACH POINT OF THE SURFACE IN ALL DIRECTIONS.



▲ FIGURE 3. CHARACTER OF OBSERVED PENCIL SHADOWS FROM A VIEWING PERSPECTIVE TO THE SIDE OF AND ABOVE THE PAPER. (A) SHADOW OF THE PENCIL WHEN SIX FEET FROM THE BULB; (B) SHADOW OF THE PENCIL WHEN SIX INCHES FROM THE BULB.

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Shadows and Direction

I started by asking a few youngsters in the 10-15 year age range the following questions: "If you held two pencils vertically, do you think their shadows would go out straight and parallel, or go out like this (demonstrating divergence with my hands), or what? Would the answer always be the same, or would it depend on anything?"

One 10-year old said she would expect the shadows to meet. Then she changed her mind, and decided they would be parallel, but on a slant compared with the two pencils. An 11-year old said that if the sun was out, there would be two long parallel lines, and if the sun was high, there would be no shadows. If the experiment were done indoors using a lamp, she thought the shadows would still be parallel. Others weren't certain what would happen. A 15-year old said the shadows would diverge indoors, but they would be parallel if you were outside because the sun was so far away.

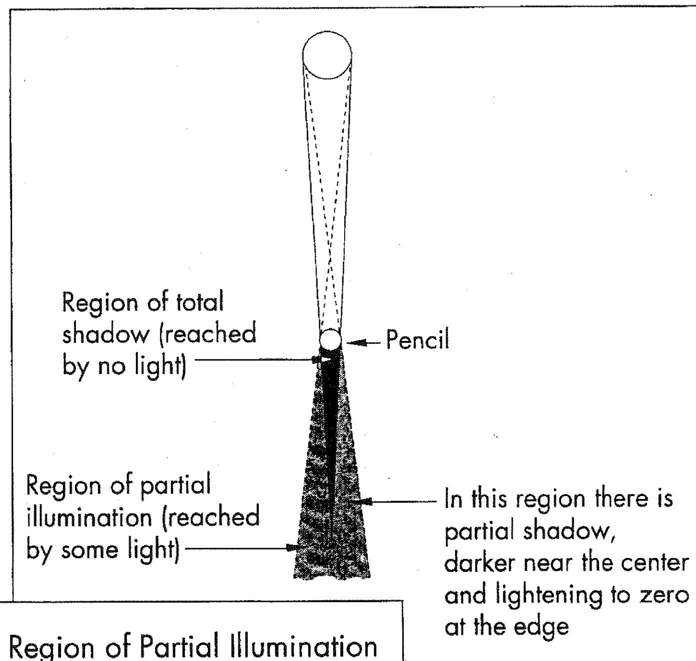
Of the kids I queried, only the older one was able to figure out what seems so obvious to adults: although light can travel in straight lines (within the limits of the caveats above), the direction of the shadows depends partly on the relative placement of the object and the source. To illustrate this, you can take the lamp shade off a lamp in an otherwise darkened room, then take a notebook with lined paper and hold it roughly six feet from the lamp. Hold a pencil vertically, eraser down, on one of the lines on the paper. Then align the notebook so that the shadow goes down one of the lines, as in Figure 1.

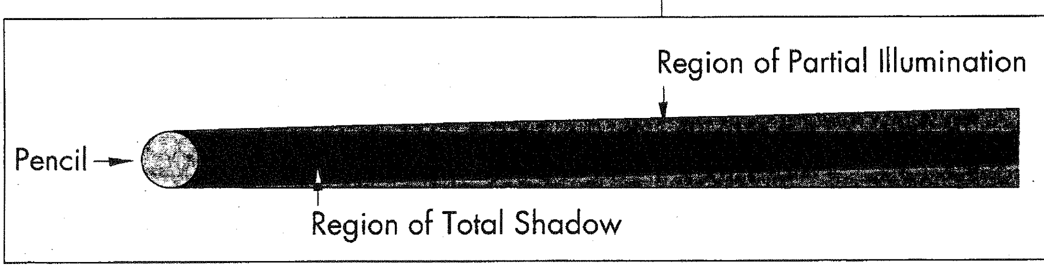
Now let the youngster hold another pencil on the notebook, also vertically, on another line a couple inches from the first pencil. The child should be able to notice that the second shadow diverges from the straight lines on the paper, as in Figure 1. Try this with the second pencil at a larger distance from the first pencil. Why do the shadows diverge? My 12-year-old was not sure, but then realized that the shadows point to the lamp. The 15-year old noted that it's like a triangle, with the lamp and the two pencils at the corners. The shadows continue along the direction of the sides of the triangle.

I next asked what they thought would happen if we went twice as far away. Both of them were able to predict that there would be less divergence, because the triangle is shaped differently. But what about sunlight? "Oh, I get it. The sun's so far away that it (the pair of shadows) doesn't diverge at all, or at least it's so small (*i.e.*, the divergence is so small) you probably can't see it."

With a young child, it's probably sufficient to stick to the idea that light can go in a straight line, but that the shadows might go in the same direction and might go in different directions, depending on how close you are to the light. A youngster might like to walk outside and look at the shadows of light poles and other objects, all going in the same direction. Inside, you might ask them what would happen if you turn on two lights, and let them see the results.

▶ **FIGURE 4. GEOMETRY OF THE SIX-INCH EXAMPLE SHOWN IN FIGURE 3B, AS VIEWED FROM ABOVE.**





▲ **FIGURE 5. GEOMETRY OF THE SIX-FOOT EXAMPLE SHOWN IN FIGURE 3A, AS VIEWED FROM ABOVE (LAMP IS OFF THE PAGE TO THE LEFT).**

WHAT ABOUT SIZE?

Now we come to the second major concept—that the light field is not only affected by where the light source is, but by the angular extent of the source. In particular, this next section will introduce the concept that with a source such as a light bulb, the light is emitted in all directions from each point on the bulb.

This concept can seem so obvious to adults trained in optics that it's hard to know how to teach it to a young person. It might help to have an example of the type of confusion that can occur. When I was in grade school, I saw lots of drawings of the sun much like that shown in Figure 2a, with light diverging normal to the surface. I assumed light diverged *only* normal to the surface, for all sources. In particular, I visualized reception of light by the pupil as shown in Figure 2b, and could not understand how we see the full object. A more accurate understanding of the light emittance, as illustrated in Figure 2c, could have helped clear up this confusion, as well as confusion about why the edges of shadows may not be sharp. (At least it could have been somewhat enlightening.)

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To help my youngsters understand the impact of the character of the source, we brought our two-pencil experiment back to six feet and I asked the kids if they noticed anything about the shape of the shadows. They noticed that the shadows were sharp near the base and fuzzy near the end, as shown in Figure 3a. They could not explain this. We tried it at 12 feet, and found the effect still there, but less pronounced. At three feet, the shadow became quite diffuse, except near the base of the pencil. But at six inches, the shadow took on a quite different shape, as shown in Figure 3b.

I ran this experiment separately with the 12 and 15-year-old. Both kids puzzled over this last shadow at six inches for awhile, then said it was because the light bulb was bigger than the pencil, and the two edges of the light bulb cast shadows in different directions. I agreed, and drew an illustration similar to Figure 4, to show them how the whole shape comes about. Here you can make the point that each part of the bulb is sending light in all directions.

So how does this explain the shadow observed at a six-foot range? You can have the youngster run a horizontal pencil up and down the vertical pencil, and see that the shadow near the base is the shadow of the base, and the shadow near the end is the shadow of the top. Now visualize stretching the lamp-to-pencil distance in Figure 4 from six *inches* to six *feet*. At a six-foot range, the two-inch size of the bulb is relatively quite small, and the rays corresponding to those in the illustration become nearly parallel. The black portion of the shadow shown in Figure 4 elongates, and the grey part becomes quite narrow, as shown in Figure 5. The result is that the shadow appears quite sharp near the base of the pencil.

F. Dow Smith suggests another appealing view of this shadowing. Imagine you are an ant crawling around on the paper and looking back toward the light source. If you can see the entire source of light, you are at a place on the paper where there is no shadow at all. If you cannot see the source because it is blocked by the pencil from your viewpoint, you are in a region of total shadow. But if you can see part of the source, you are in the partial shadow along the edges.

We discussed the idea that the light comes from all parts of the light bulb, and it goes in all directions from each part of the bulb. We discussed the classic illustration that you can see the bulb from all parts of the room, and therefore it is sending light in all directions. Furthermore, you can see the full bulb, not just some little part of it, and that shows that all the parts you can see are emitting light in all directions.

If the kids you're working with are still interested—and it's daylight—you can mention that, although the sun is quite far away, it still has a finite angular size (about 1/2 degree), and you can thus see the same effects outside. If you hold a pole vertically on the ground, the part near the base of the pole will have a pretty sharp shadow, and that further from the base will not. Shadows of telephone poles look pretty sharp, but if you look at the edges of shadows, you will see the same effect. The shadows of overhead wires, in particular, look quite fuzzy.

One final word about diffraction and quantum effects. Even though these effects are probably beyond the scope of this demonstration with kids, it's still important not to mislead children into thinking that this way of looking at the light is rigorous. I suggest indicating that there are more complicated effects such as diffraction and scattering, but that in many situations, it is useful to treat light as going in straight lines. In this way, I think we can fairly avoid the more complicated concepts, and try to help youngsters understand some of the very simple, but not so obvious, concepts of classical optics and rectilinear propagation.