EXECUTE: As in Example 37.4, but with $l_0 = 56.4\text{ m}$,

$$l = l_0\sqrt{1 - \frac{u^2}{c^2}} = (56.4\text{ m})\sqrt{1 - (0.990)^2} = 7.96\text{ m}$$

EVALUATE: This answer does *not* say that the crew measures their spaceship to be both 400 m long and 7.96 m long. As measured on earth, the tail of the spacecraft is at the position of O_1 at the same instant that the nose of the spacecraft is at the position of O_2. Hence the length of the spaceship measured on earth equals the 56.4-m distance between O_1 and O_2. But in the spaceship frame O_1 and O_2 are only 7.96 m apart, and the nose (which is 400 m in front of the tail) passes O_2 before the tail passes O_1.

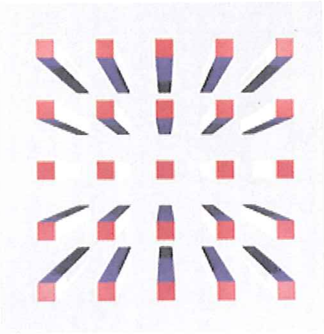
How an Object Moving Near *c* Would Appear

Let's think a little about the visual appearance of a moving three-dimensional body. If we could see the positions of all points of the body simultaneously, it would appear to shrink only in the direction of motion. But we *don't* see all the points simultaneously; light from points farther from us takes longer to reach us than does light from points near to us, so we see the farther points at the positions they had at earlier times.

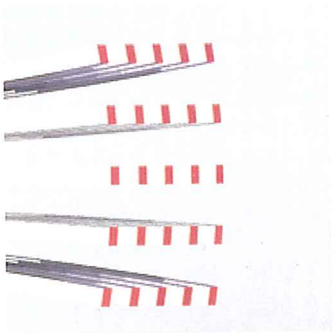
Suppose we have a rectangular rod with its faces parallel to the coordinate planes. When we look end-on at the center of the closest face of such a rod at rest, we see only that face. (See the center rod in computer-generated Fig. 37.14a.) But when that rod is moving past us toward the right at an appreciable fraction of the speed of light, we may also see its left side because of the earlier-time effect just described. That is, we can see some points that we couldn't see when the rod was at rest because the rod moves out of the way of the light rays from those points to us. Conversely, some light that can get to us when the rod is at rest is blocked by the moving rod. Because of all this, the rods in Figs. 37.14b and 37.14c appear rotated and distorted.

37.14 Computer simulation of the appearance of an array of 25 rods with square cross section. The center rod is viewed end-on. The simulation ignores color changes in the array caused by the Doppler effect (see Section 37.6).

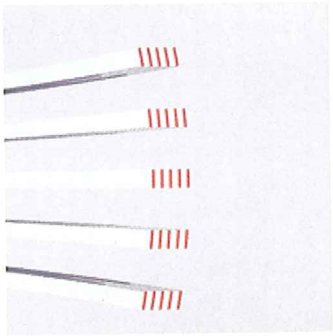
(a) Array at rest



(b) Array moving to the right at 0.2*c*



(c) Array moving to the right at 0.9*c*



Test Your Understanding of Section 37.4 A miniature spaceship is flying past you, moving horizontally at a substantial fraction of the speed of light. At a certain instant, you observe that the nose and tail of the spaceship align exactly with the two ends of a meter stick that you hold in your hands. Rank the following distances in order from longest to shortest: (i) the proper length of the meter stick; (ii) the proper length of the spaceship; (iii) the length of the spaceship measured in your frame of reference; (iv) the length of the meter stick measured in the spaceship's frame of reference.

37.5 The Lorentz Transformations

In Section 37.1 we discussed the Galilean coordinate transformation equations, Eqs. (37.1). They relate the coordinates (x, y, z) of a point in frame of reference S to the coordinates (x', y', z') of the point in a second frame S'. The second frame moves with constant speed u relative to S in the positive direction along the common x-x'-axis. This transformation also assumes that the time scale is the same in the two frames of reference, as expressed by the additional relationship $t = t'$. This Galilean transformation, as we have seen, is valid only in the limit when u approaches zero. We are now ready to derive more general transformations that are consistent with the principle of relativity. The more general relationships are called the **Lorentz transformations.**

The Lorentz Coordinate Transformation

Our first question is this: When an event occurs at point (x, y, z) at time t, as observed in a frame of reference S, what are the coordinates (x', y', z') and time t' of the event as observed in a second frame S' moving relative to S with constant speed u in the $+x$-direction?

To derive the coordinate transformation, we refer to Fig. 37.15 (next page), which is the same as Fig. 37.3. As before, we assume that the origins coincide at the initial time $t = 0 = t'$. Then in S the distance from O to O' at time t is

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4.7), the events cannot be causally related because there is no way for them to ''communicate'' in time for a causal connection. As we already remarked, the Lorentz transformations demonstrate that such events may be measured to occur in any temporal sequence, depending upon the direction and speed of the inertial observer's motion.

Special relativity predicts disagreements among inertial observers about where and when things occur, but there can never be a disagreement about whether or not a causal relation is possible.[12]

4.9 How Objects Appear When Moving By at Very High Speeds

We have noted that as objects move by an observer at very high speeds, their measured lengths are contracted in the direction of travel (it turns out that no such length contractions take place in directions other than that of the motion of the object). How would such ''contracted'' objects appear if it were possible to look at them or to photograph them?

It is interesting that this question received no thorough analysis until 1959.[13] Nor is the question an easy one to answer, for a number of things happen at once to introduce several kinds of ''distortions'' in what one actually *sees*. Here we will indicate the general issues to be considered in arriving at an answer, and then we will provide some specific examples.

First some general remarks. In our discussion of special relativity, we have used the verb ''to measure'' in describing determinations of lengths and times made by various ''observers.'' At the same time we have avoided the verbs ''to see'' and ''to observe'' in this connection unless the measurements did involve the actual receipt of a light signal. The verb ''to measure'' refers to what one determines as length and time values using an array of observers and clocks along the track synchronized to a common system of time. These *measurements* do not refer to what one would actually see

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[12] In appendix C we discuss possible consequences of the existence of *tachyons*, hypothetical particles that move faster than light. Such particles could permit causally related events to occur in either order. This fact has been used as an argument against the existence of tachyons.

[13] See French, *Special Relativity*, pp. 149–152; the footnote on page 150 of French's book gives references to original work. Our discussion in this section owes much to French's book, to Rindler, *Essential Relativity*, pp. 57–60, and to the paper by G. D. Scott and M. R. Viner, ''The Geometrical Appearance of Large Objects Moving at Relativistic Speeds,'' *American Journal of Physics* 33 (1965): 534–536, and references 1–7 therein. All of these treatments are intended for advanced students of physics.

with the eye or photograph with a camera.[14] We mentioned this fact early in our discussion of relativity theory, although we did so only in passing, and we have avoided discussion of what one would really see in high-speed motion to reduce confusion in our discussion of relativity itself. Let us begin our discussion of what one actually sees in relativity experiments by analyzing a familiar situation, as we have done several times before.

We return to our place at the side of the railroad track along which Gertrude moves at some uniform speed v. Consider two events in figure 4.8: event 1 is Gertrude's passage by your position along the tracks; event 2 is Gertrude's passage by the position of the railroad crossing sign at the side

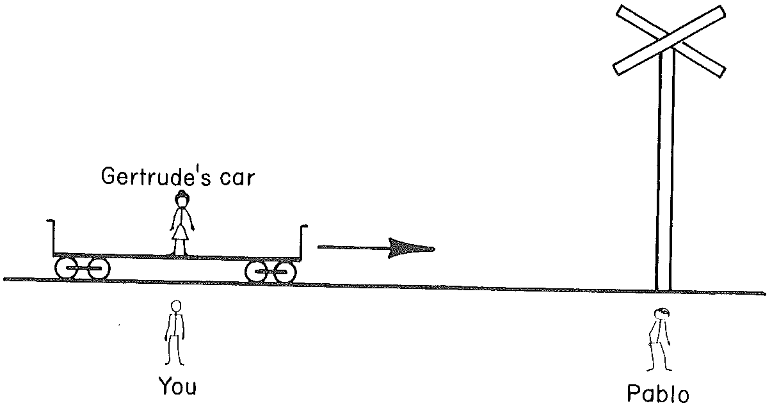

FIGURE 4.8

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[14] For example, in the discussion of Gertrude's moving light clock in section 3.7 we use an array of "observers stationed at rest along the side of the track" to "report to you the time required for the pulse of light in Gertrude's clock to make a round trip." Later on (section 3.8) we discuss the determination of Gertrude's length with respect to that of the tunnel by you and Gertrude. In interpreting figures 3.19 to 3.23 we have replaced an array of observers with mirrors that permit you and Gertrude to receive light signals from the crucial events. Because both sets of mirror apparatus are constructed so that the distance from the mirrors to your and Gertrude's eyes is the same, the simultaneity (or the lack of simultaneity) of the two events can be determined by "seeing" if the flashes of light from the two events reach your eye simultaneously. This apparatus was used in section 3.8 because although it yields conclusions fully equivalent to the results of making a measurement with an array of observers, it is far easier to visualize and to interpret. On the other hand, the times at which you and Gertrude *see* the flashes are not the common times at which the corresponding events occur. The apparatus permits a direct determination of simultaneity but not of common time—for that you need an array of observers.

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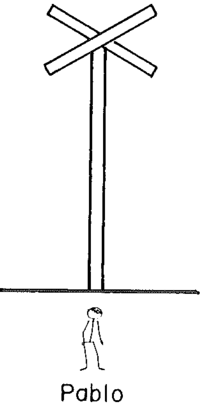

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of the tracks. Recall again what we mean by the times of these events. By Einstein's definition, the time of an event is the time given by a clock synchronized (according to his stated procedure) to the common system of time for all who share your state of rest with respect to the tracks, and located at the same point in space at which the event occurs. In figure 4.8, the time of event 2 (Gertrude's passing the crossing sign) cannot be observed directly by you because you are not at the same location as event 2; instead you must rely on Pablo, your helper, who is at the same position as event 2, and who determines the time of the event there with a synchronized clock. You learn of the time of event 2 by a report of some kind that you receive from Pablo; that is, your information must be second-hand—this is a matter of necessity.

We can represent these same two events on a Minkowski or spacetime diagram, as shown in figure 4.9. You, the sign, and Pablo stay fixed by the side of the tracks; the corresponding world lines are, accordingly, vertical, meaning that for all time values you have the same position. We also show the world line for the front of Gertrude's car as it moves along the track at the speed v (the solid line). Notice that Gertrude's position coincides with yours at the event we have called 1; similarly, the front of her car passes the crossing sign at the event labeled 2 in the diagram.

From this diagram we can tell the times of events 1 and 2 on the common time system. These we read as 2 and 3.4 time units, respectively. Again, these are the times for the events on the common time system as recorded and then reported by you and Pablo by the tracks.

Let us now ask what you *see*. First you see event 1, and because you happen to be right at the position of this event, the time of this event is the same as the time that you read on your clock when you actually see the event. But not so for event 2. Look at the spacetime diagram again. Event 2 occurs some distance from you. Therefore it takes light some amount of time to travel the distance from the sign to your location, and so you will see event 2 at a time on your clock later than that reported by Pablo as the time of the event. We can use the spacetime diagram to determine just when you will see event 2. At event 2, draw a dashed line representing the motion of the flash of light showing that the front of Gertrude's train has just passed the sign. Here and in what follows the world line for any flash of light is a dashed line inclined at 45 degrees to the time or distance scales.[15] The flash

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[15] As discussed in detail in appendix A.2, throughout this book we have arbitrarily chosen the units of time and distance measurements in our Minkowski diagrams so that world lines of light are inclined 45 degrees to the time and distance scales.

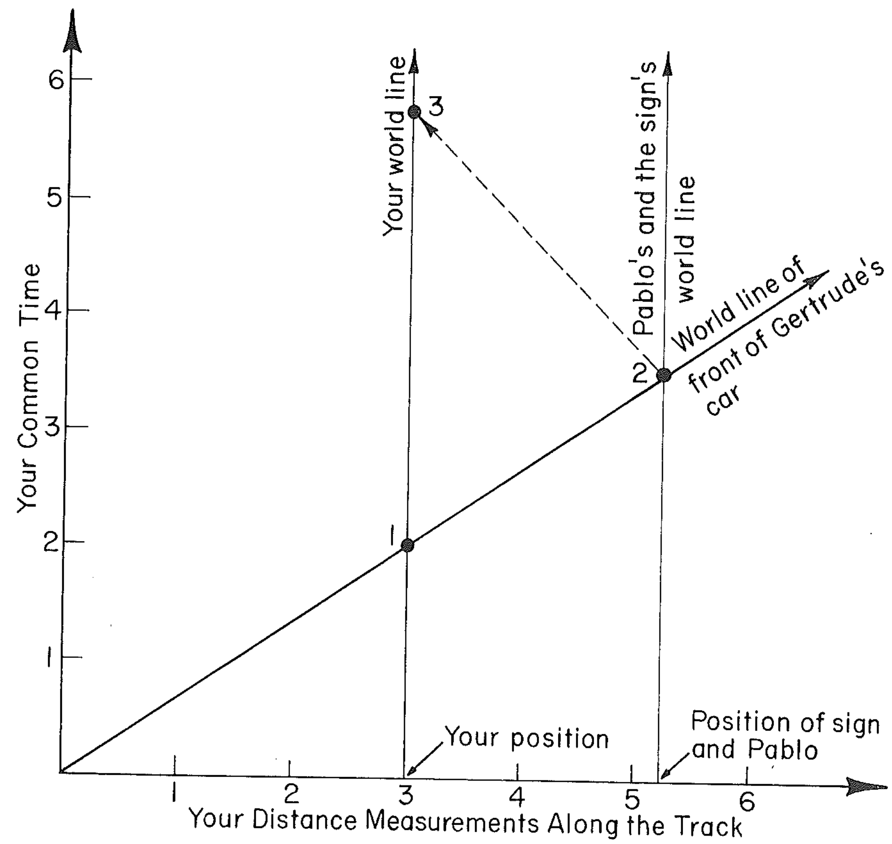
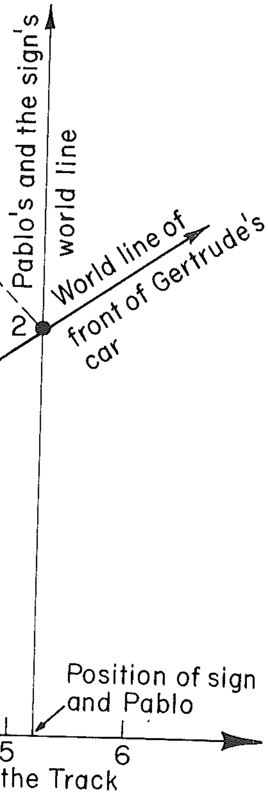


FIGURE 4.9

of light marking event 2 is seen to cross your position by the side of the tracks at event 3. Event 3 marks your first sight of event 2.

We have been rather long-winded about all of this because it is so important to understanding what observers *see* of natural phenomena, as opposed to what they will *measure*. Relativity theory (through the Lorentz transformations) refers to measurements with clocks and rulers of common times and positions of events. By considering how light leaves these events and travels to our eyes (or to the lens of our camera) we can also use relativity theory to deduce what you and any other observer will actually see. This is just what we have done in the Minkowski diagram in figure 4.9; we have added the appropriate light-ray path to determine when and where you will see event 2. This act of viewing event 2 we call event 3. By following



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a similar procedure (using Minkowski diagrams or the Lorentz transformation equations) for various sorts of events one can reach general conclusions concerning the ''distortions'' that are *seen* in objects moving by at high speed.

In general there are three effects at work that serve to ''distort'' what one actually sees of a moving object. Let us consider each of these in turn, and to make the discussion specific we will again use Gertrude moving by you in her car at a substantial fraction of the speed of light (to make the effects more noticeable). Figure 4.10 is the sort of bird's-eye diagram of Gertrude and the track that we used earlier in discussing your measurement of Gertrude's length (figures 3.19 to 3.23). We will suppose that you are standing

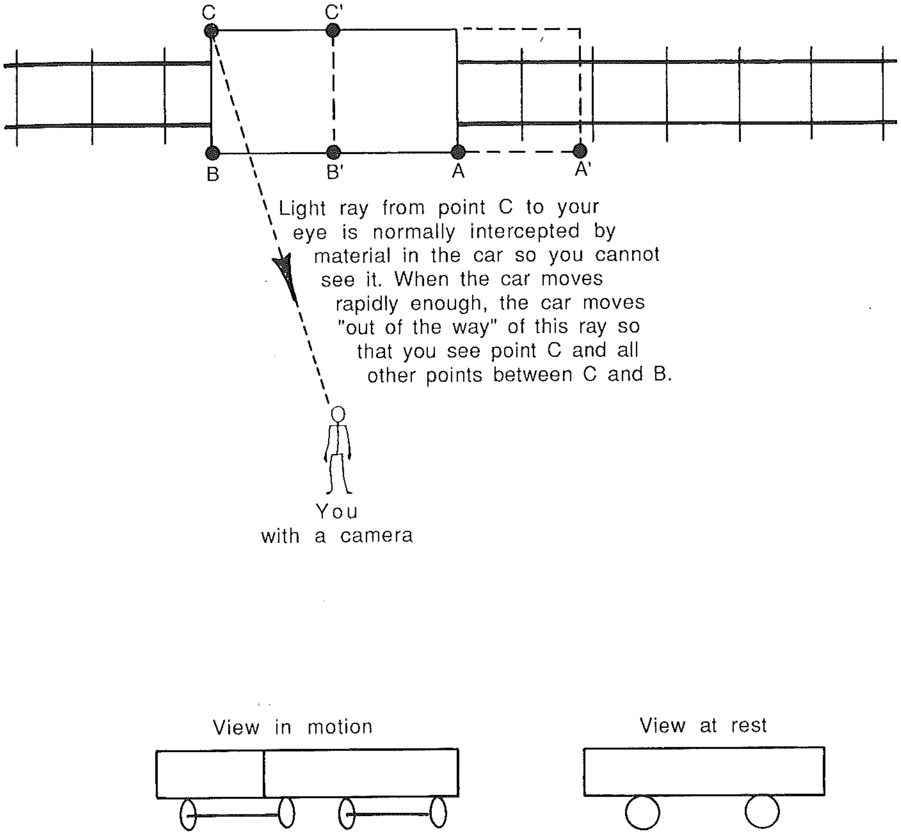

FIGURE 4.10

beside the track with a camera having an extremely fast shutter so that you are able to ''stop'' the image on the film without appreciable blurring. When the center of Gertrude's train appears in your viewfinder to be directly opposite your position along the trackside, we suppose that you trip the shutter and take a picture. The discussion to follow will refer to the photograph that results from this procedure.

Effect #1: The Lorentz Contraction

First remember from our discussion in section 3.8 that your measurements will determine the length of Gertrude's car to be less than she knows it to be; in fact, you will also *see* Gertrude's length contracted relative to what she claims her length to be. Imagine the tunnel shown in figure 3.19 to be located over the track with its center directly opposite your camera lens; your camera now replaces the mirror apparatus of section 3.8 that permitted you to view both ends of the tunnel without moving your head. As in section 3.8, your picture shows both ends of Gertrude's car simultaneously fitting into the ends of the tunnel. In other words, your picture shows that the length of Gertrude's car just fits into the tunnel. The side of her car therefore appears shorter to your camera when the car is in motion past you than it would be if the car were photographed at rest beside the tunnel.[16] But that is not all.

Effect #2: An Apparent Rotation

Look carefully at the top portion of figure 4.10 to see what the light rays are doing as they leave the car and head toward your camera. Consider in particular light rays from point C at the rear corner of the car. We have drawn one ray (as a dashed line) emitted in your direction; but the side of the car (with corners A and B) stands between you and the path of this ray, so you normally cannot see light from point C or from any other point along the rear edge of the car between points B and C. The car itself blocks your view of these points.

But now let Gertrude begin moving past you at a very high speed. It takes light from point C a certain amount of time to travel across the width of the

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[16] Some of the original work done on the appearance of objects moving past an observer at high speed seemed to suggest—incorrectly—that the Lorentz contraction would not be observable. By 1961, however, it was realized that the contraction would be visible. Readers should be cautious in consulting pre-1961 literature in this regard.

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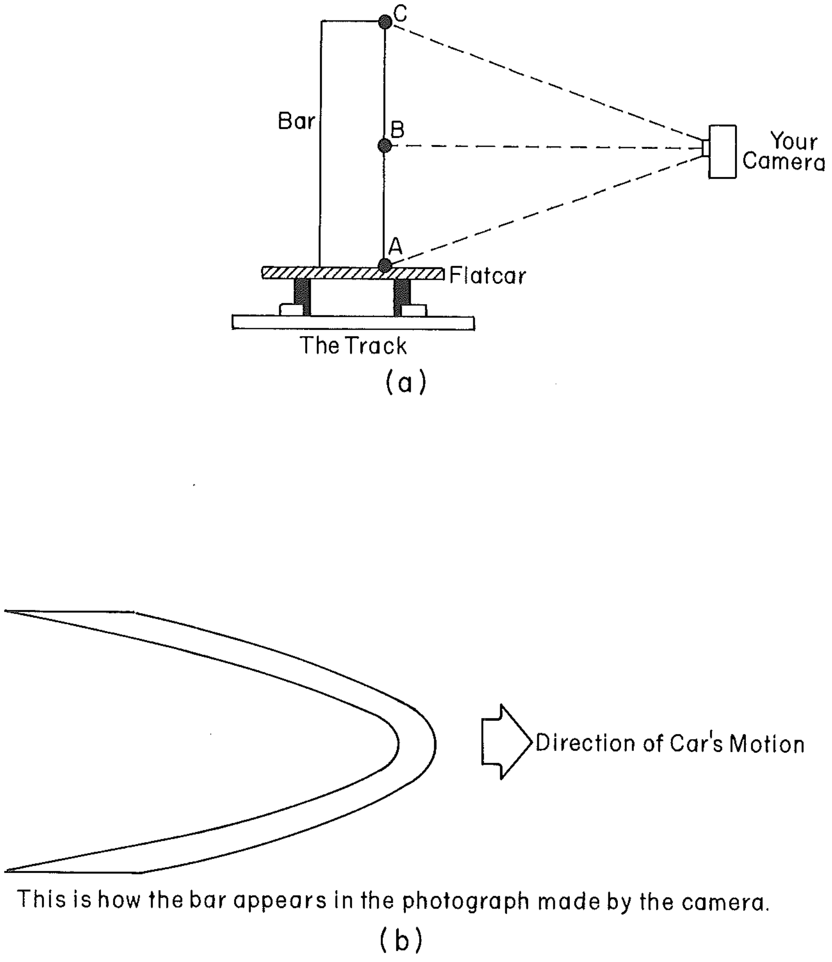
car. When the car was at rest, the matter of the car interrupted the light from point C and prevented you from seeing it, but now the rear edge of the car moves out of the way rapidly enough for the ray to clear the back of the car and move to your eye. By the time the light ray from point C has moved across the width of the car, the end of the car that used to block that ray when the car was at rest has moved on (for example, point B has moved on to point B′), well out of the way of the ray's path. In other words, you can see the far corner of Gertrude's car marked by point C. Similarly, you are able to see light from all of the other points along the rear edge of her car from B to C. The net result is that while you see the side of her car contracted, you are also able to see a foreshortened view of the rear edge of the car. This is sketched in the lower portion of figure 4.10. In effect, you no longer see Gertrude's car ''side-on'' when she moves past you. The car effectively appears somewhat rotated and now presents a kind of ''cubist'' image of itself. In fact, it turns out that if you view the car from a great enough distance, the side and the rear edge appear foreshortened in exactly the way that you would observe if the car were simply rotated a bit. The faster the car moves along the track, the greater the amount of the observed ''rotation.''

Effect #3: The Travel Time for Light

Suppose that the object moving past you now is a long, rigid bar standing vertically on Gertrude's flatcar. In the following discussion remember that the length contraction is still operating, so that the bar appears skinnier than it would at rest with respect to you; in addition ''rotation-type'' effects discussed above are present. Figure 4.11a is a view of your camera and the bar looking *along the track* from the ground level. We have located three points on the bar and have drawn dashed lines to indicate the path that light will take in moving from the bar to your camera. Light from point B at the middle of the bar will reach your camera soonest since it has the least distance to cover. Light from A and C will require more time.

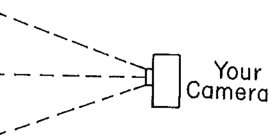
You take your snapshot when you see point B pass your position along the track. Of course the light that you see (and that strikes your camera lens) actually left point B on the bar some instants before. By the same token the light simultaneously striking your lens from points A and C had to have left the bar before the light from point B, since these points are more distant from the lens than point B. This means that the light you photograph from points A and C left the bar when it was even farther away from you on the



This is how the bar appears in the photograph made by the camera.

FIGURE 4.11

track than when the light from point B left the bar. So you see the center of the bar (point B) directly across from you while points to either side of B (such as A and C) appear to have some distance to travel before being opposite you. The amount of the "distance to travel" increases as you view points farther along the bar from point B. Thus the bar will appear bowed, with the center (point B) sticking out in a forward direction along the tracks and points to either side of B appearing farther behind along the track (it can be shown that the shape of the "bow" is that of a hyperbola). A pho-



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tograph of the bar taken with the camera would look like the sketch shown in figure 4.11b.

So even though there is no length contraction perpendicular to the direction of motion of the bar, because of the travel time for light the vertical bar appears bent or "swept back" due to its motion.

The same effect applies to the appearance of Gertrude's car. Let's take another bird's-eye view of the car as it passes directly in front of you (figure 4.12a). Pablo has painted some evenly spaced spots on the side of the car facing you and your camera to make the "distortion" easier to see. Five markers lettered A′, A, B, C, and C′ have been fixed to the trackside to aid our discussion.

To understand the appearance of the photograph you make of Gertrude's car, it is necessary to describe carefully the sequence of events leading to the opening of the camera's shutter. The shutter will open momentarily when light reaches the lens from the coincidence of the center of the car with marker B (the marker on the track directly opposite the camera lens). This defines the time at which the shutter opens, and it is important to bear in mind that only light striking the lens in the moment that the shutter is open will be recorded on the photograph. Of course the light from the cen-

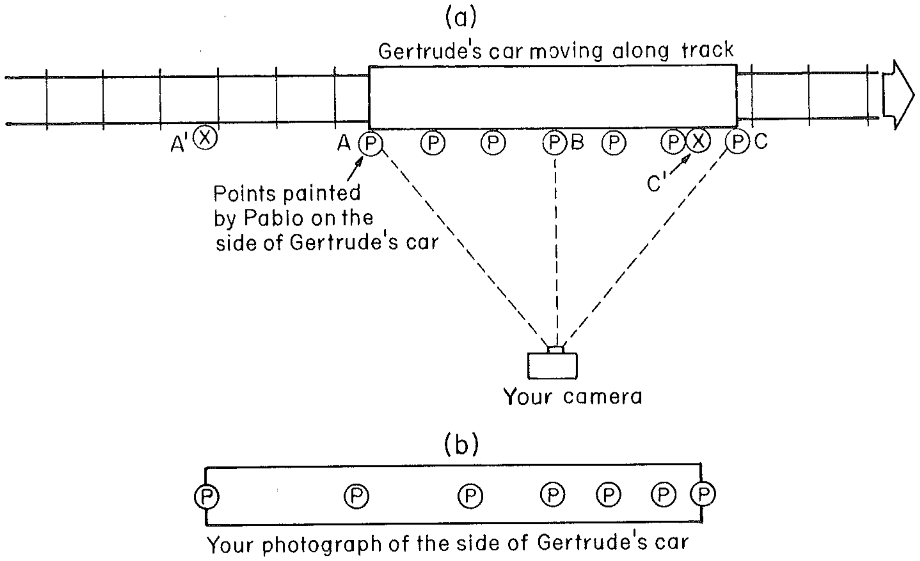

FIGURE 4.12

ter of the car at point B requires some amount of time to reach the lens; when the car's center is at marker B on the track, the front and rear of the car are at markers C and A, respectively, and light from these two markers has to travel farther to reach the lens than does the light from marker B. Therefore, light from the front and rear of the car at markers C and A will arrive at the lens later than the light from the center of the car at B and after the shutter has closed. So although the photograph will show the car's center at marker B, and although when the center of the car is at B the rear and front of the car are at A and C, the car's two ends will not be photographed at markers C and A. The light from these two points simply does not reach the lens in time to pass the open shutter.

Of course the image of the car will have a front and rear, but they will not appear along the track at markers A and C where we expect them. To reach the lens at the same time as light from the car's center at marker B, light would have to leave the front of the car before the front passed marker C—at a marker such as C′. Light from the rear of the car, to reach the lens with the light from the car's center at marker B (so as to pass the open shutter), must be emitted at a marker such as A′. So the light emitted when the rear and front of the car are at markers A′ and C′ define the rear and front of the photographed image.[17]

Figure 4.12b shows the resulting snapshot of Gertrude's car. The center of the car is at the center of the picture (at marker B, not shown in the photograph). The pattern of Pablo's spots (drawn to be evenly spaced on the side of the car) appears "compressed" in front and "stretched out" in the back.

In figure 4.13 we have combined all three of these effects to illustrate how several objects would photograph as they pass by a camera at high speed. Imagine the objects to be mounted on Gertrude's car and that you are standing with a camera beside the track as in figure 4.12a. The camera shutter is tripped when the center of each object passes directly in front of

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[17] Notice that marker A′ is located farther from marker B than is marker C′—that is, light must leave the rear of the car at an earlier time to pass the shutter than does light leaving the front of the car. The reason for this can be understood by thinking carefully about figure 4.12. We have already argued that to pass the camera shutter, light from the front of the car must leave when the front is at marker C′. When the front of the car is at C′ the rear is just slightly to the left of marker A, but notice that light from the rear at this marker has farther to travel to the lens than does light from the front at marker C′; therefore, light from the rear of the car must leave a marker even farther back along the track to reach the lens with the light from the front of the car at C′. Point A′ is such a point.

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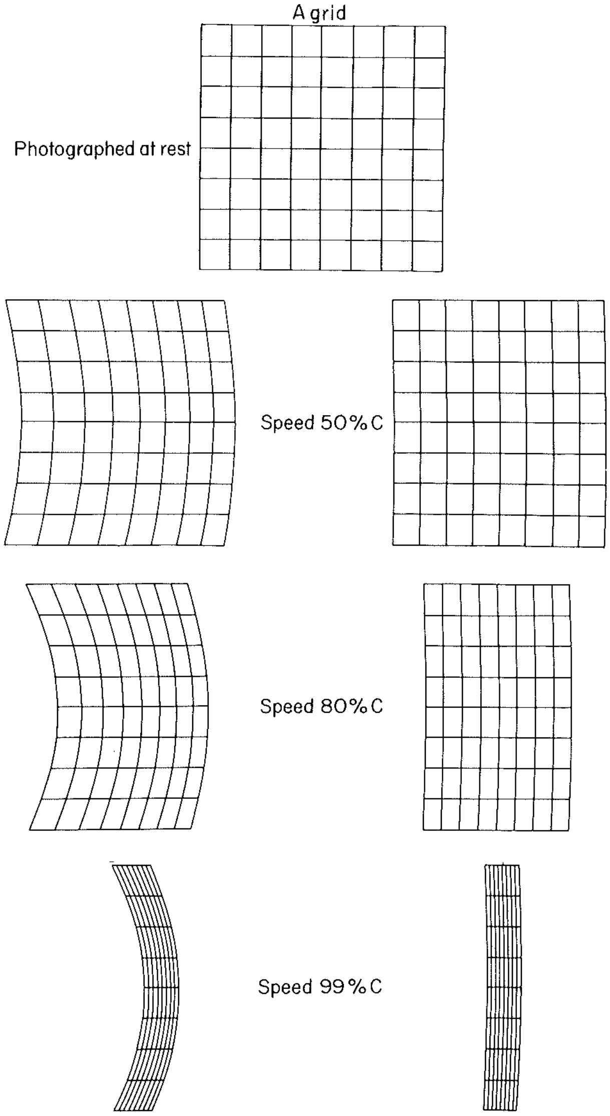
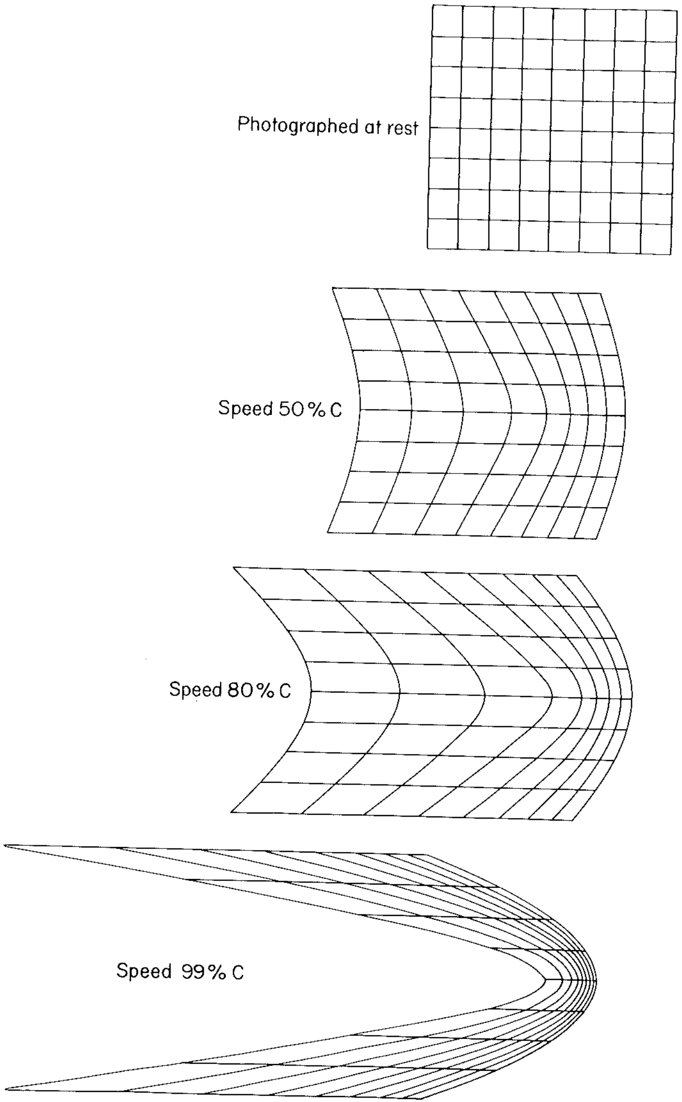


Photographed from a distance equal to the height of the grid.

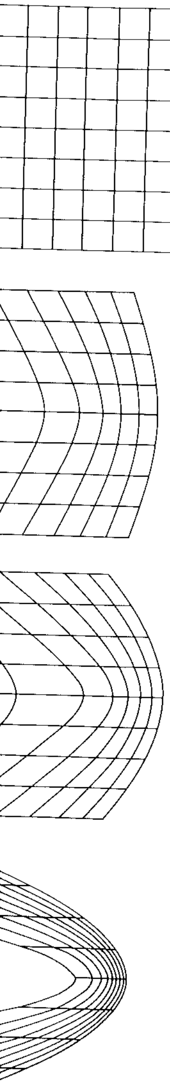
Photographed from a distance equal to ten times the height of the grid.

FIGURE 4.13a.



Photographed from a distance equal to one-tenth the height of the grid.

FIGURE 4.13b.



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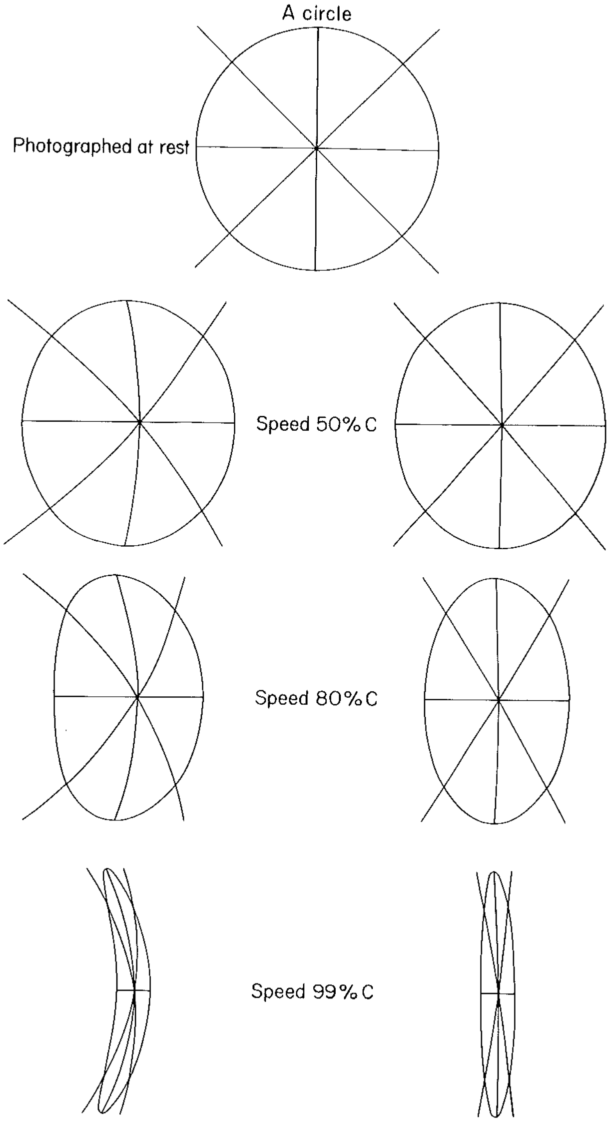
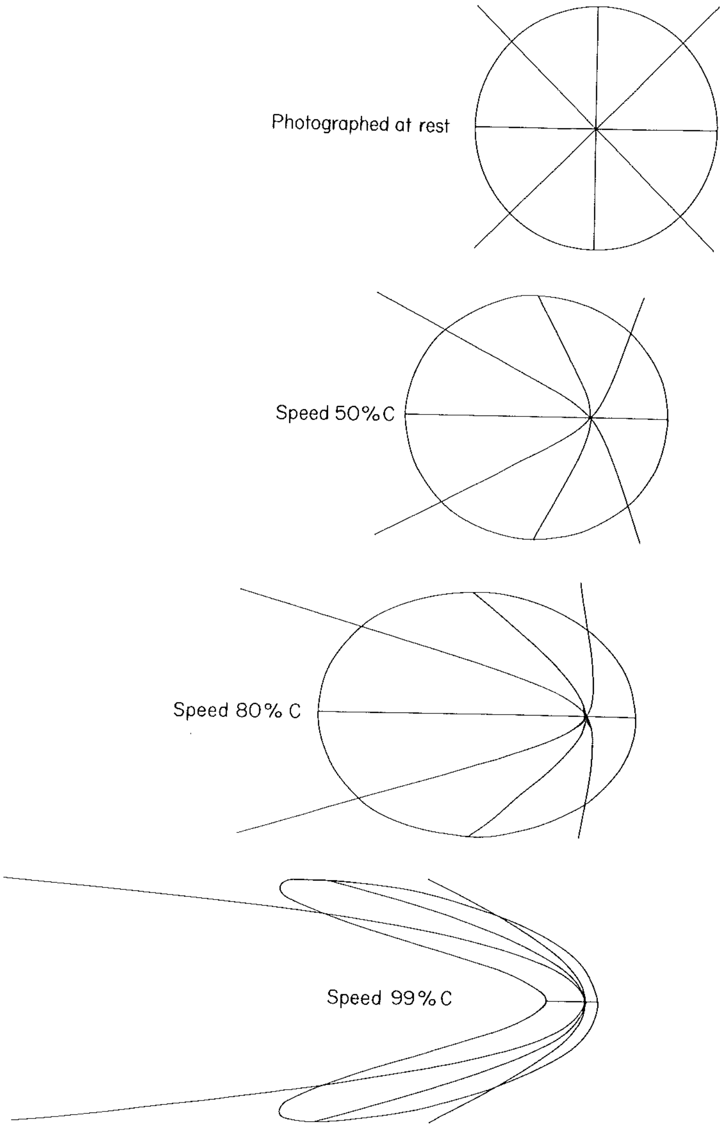


Photographed from a distance equal to the diameter of the circle.

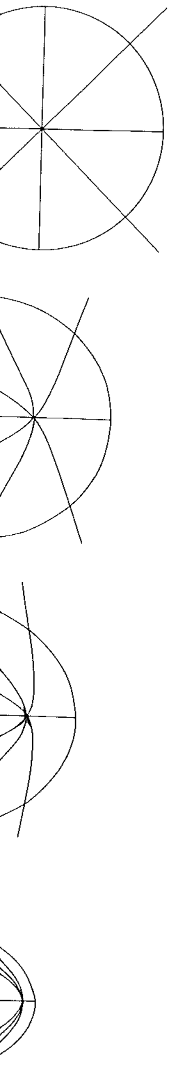
Photographed from a distance equal to ten times the diameter of the circle.

FIGURE 4.13c.



Photographed from a distance equal to one-tenth the diameter of the circle.

FIGURE 4.13d.



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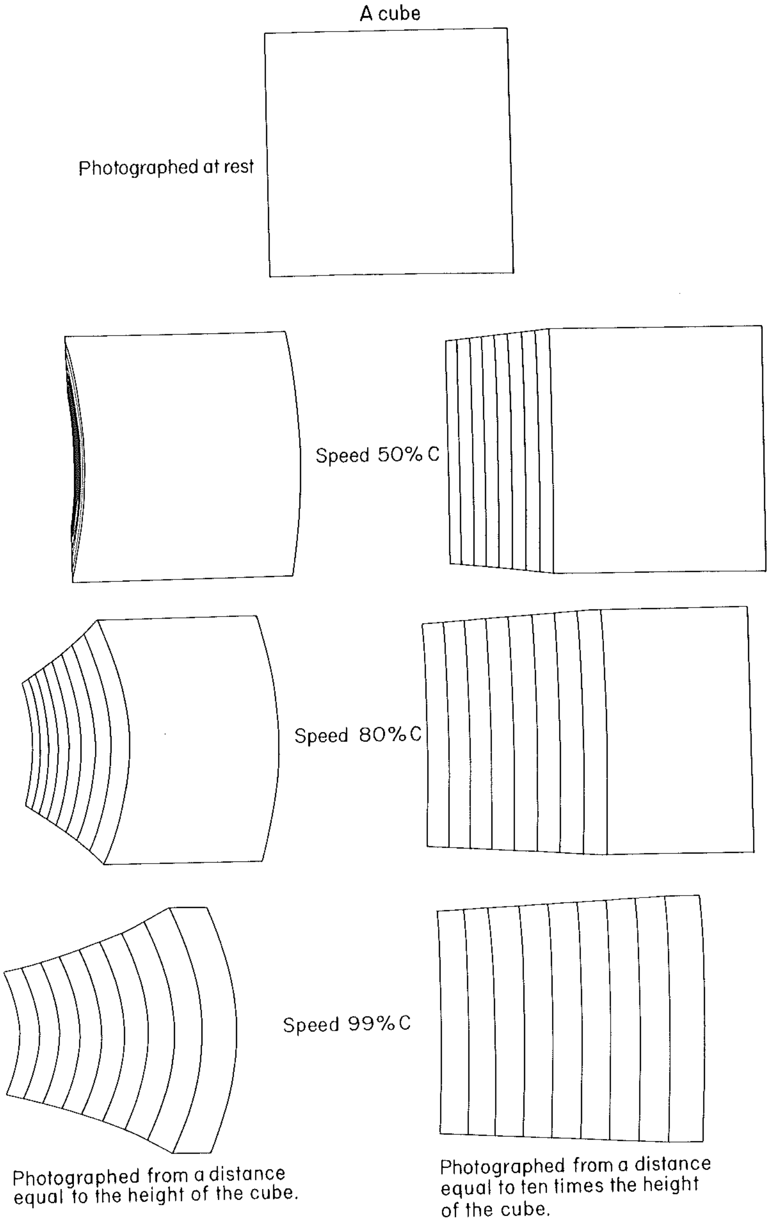
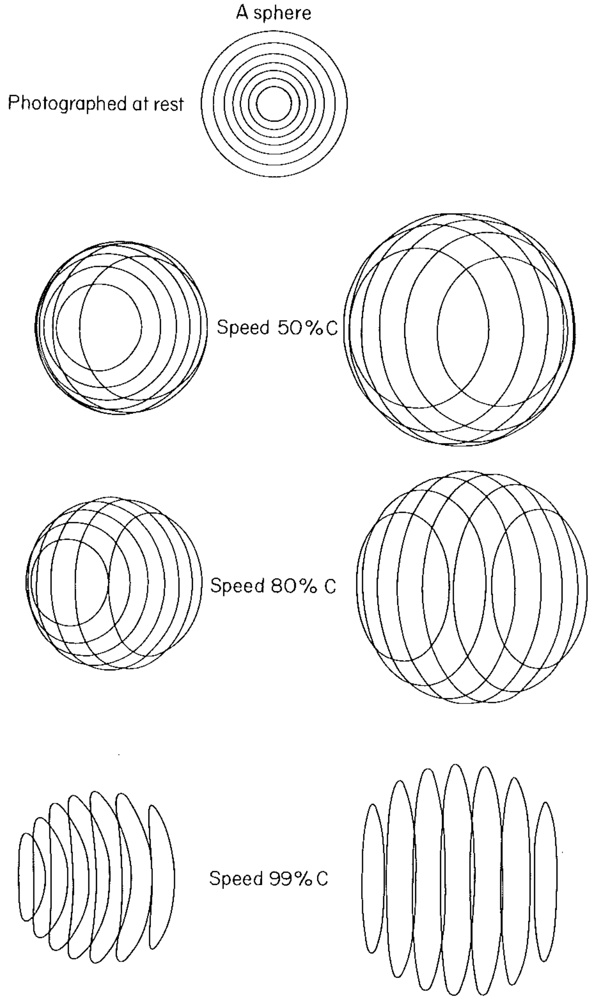


FIGURE 4.13e.



Photographed from a distance equal to the diameter of the sphere.

Photographed from a distance equal to ten times the diameter of the sphere.

FIGURE 4.13f.

the lens. Despite the high speed of Gertrude's car, we assume the camera shutter to be so fast that the image is not at all blurred. Photographs are taken of two flat objects (a grid and a wheel with spokes) and three solid objects (a cube, a sphere, and a cylinder).

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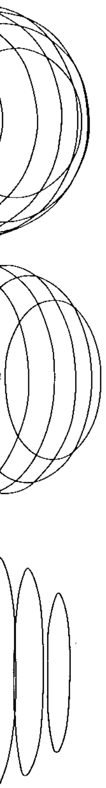

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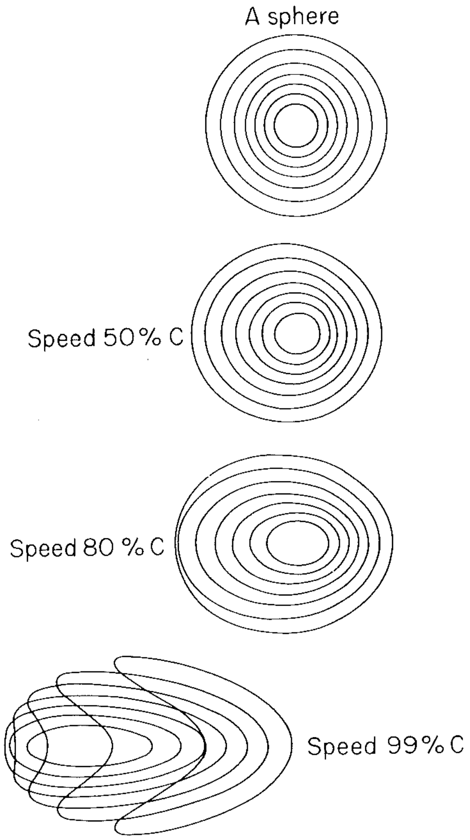
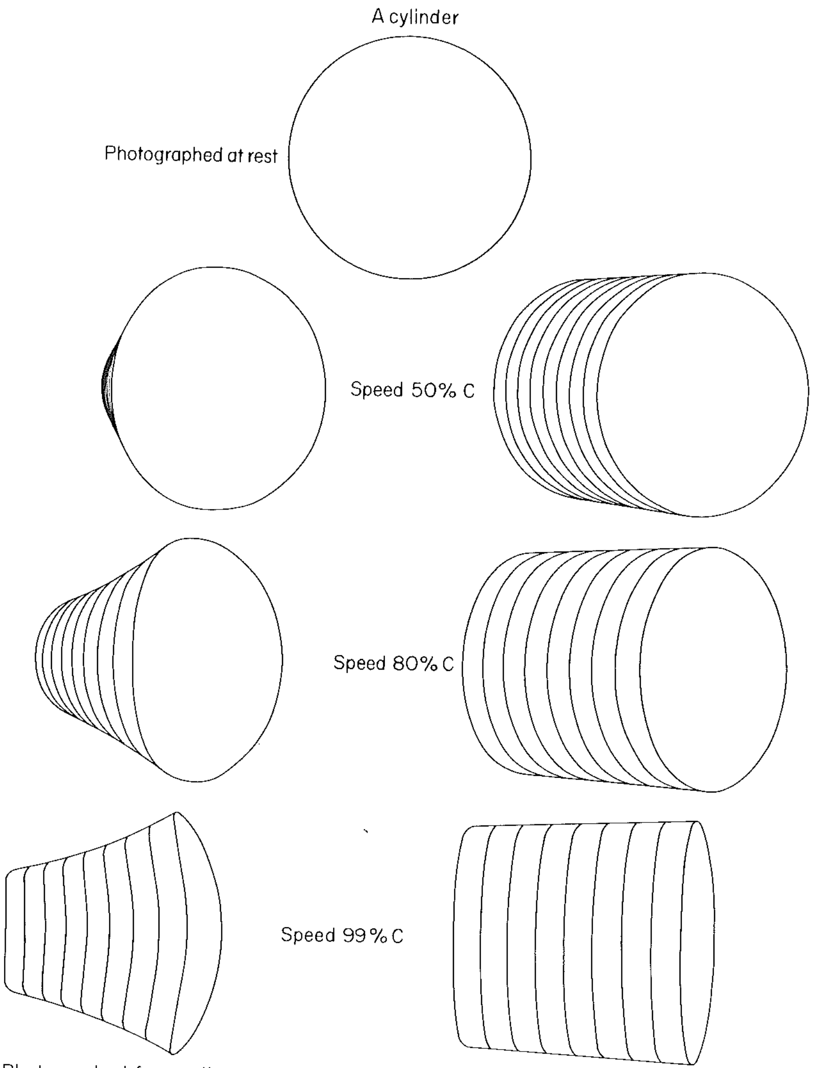


Photographed from a distance
equal to one-tenth the diameter
of the sphere.

FIGURE 4.13g.

which it passes the camera. To illustrate this effect, the objects are photographed passing the camera at each of three speeds: 99 percent, 80 percent, and 50 percent the speed of light. A photograph of each object at rest is also shown for reference.

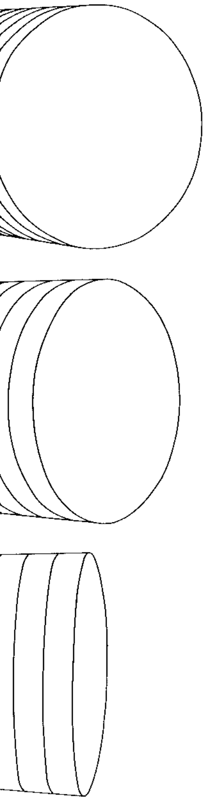
The photographed shape of the objects also depends on the distance separating the camera and the object, so we show photographs taken from several distances: extreme close-ups (the distance from the camera to the object is only one-tenth of the height of the object—a photograph that would require an extreme wide-angle lens to capture the image of the entire object), moderate close-ups (from a camera distance equal to the height of the



Photographed from a distance equal to the diameter of the cylinder.

Photographed from a distance equal to ten times the diameter of the cylinder.

FIGURE 4.13h.



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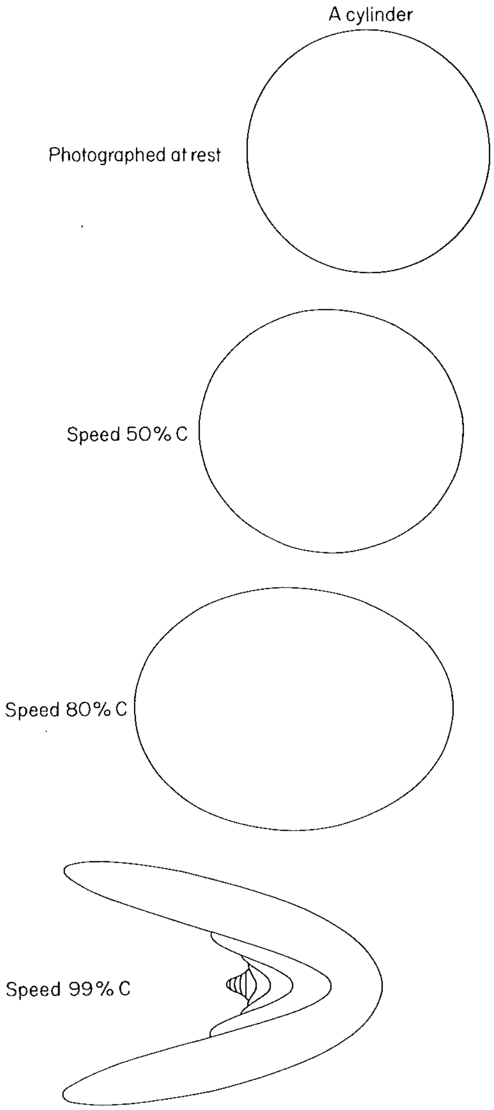

Photographed from a distance equal
to one-tenth the diameter of the cylinder.

FIGURE 4.13i.

object), and ''distant'' shots (with the camera separated from the object by ten times the object's height).

In the images of the grid and the circle, figure 4.13 clearly shows the compression and extension effect due to the travel time for light.

To clarify the ''rotation'' effects in the images of the solid objects, Pablo has painted a pattern of stripes on each. The cylinder is oriented ''end-on'' so that as it passes directly opposite the camera its circular faces are perpendicular to the line of sight. Seven stripes are painted at regularly spaced intervals around the circumference of the cylinder. When the cylinder is at rest, all the camera can see is one of the circular ends. As the cylinder moves, the relativistic ''rotation'' effect makes the pattern of stripes visible. The cube is similarly striped; it moves past the camera so that two of its faces are perpendicular to the line of sight. Seven equally spaced stripes have been painted on each of the other four faces. As with the cylinder, these stripes only become visible on the photographs when the ''rotation'' effect brings them into view. Unlike the cube and the cylinder, our sphere is transparent. If it were a transparent globe of the earth, the north and south polar points would fall exactly along the line of sight as the sphere passed directly opposite the camera; the pattern of seven stripes would then be circles of constant latitude, one of which falls on the equator. The points corresponding to the two poles are also shown in the figure.

In creating these ''photographs'' with a computer, portions of the solid objects more distant from the camera lens have been reduced in size to simulate the linear perspective a camera would impose.

Our illustrations show the expected result that ''distortions'' become more pronounced as the speed of the object passing the camera becomes larger. We also see that effect #3 discussed above (due to the travel time for light) is reduced at greater camera distances. This can be understood by looking again at figure 4.11. The farther the camera from the track, the smaller the difference in distance from the camera lens to points A, B, and C and so the smaller the ''distortion'' due to the travel time for light.

WE HAVE just illustrated some selected consequences of relativity theory. We realize that to some of our readers these consequences will be the most interesting part of this book and that they will wish that we had been more encyclopedic in our treatment. By way of excuse we can only say that we are not finished yet, for we still have to discuss the general theory of relativity wherein we will find ''distortions'' of an even more extreme and fundamental order.

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