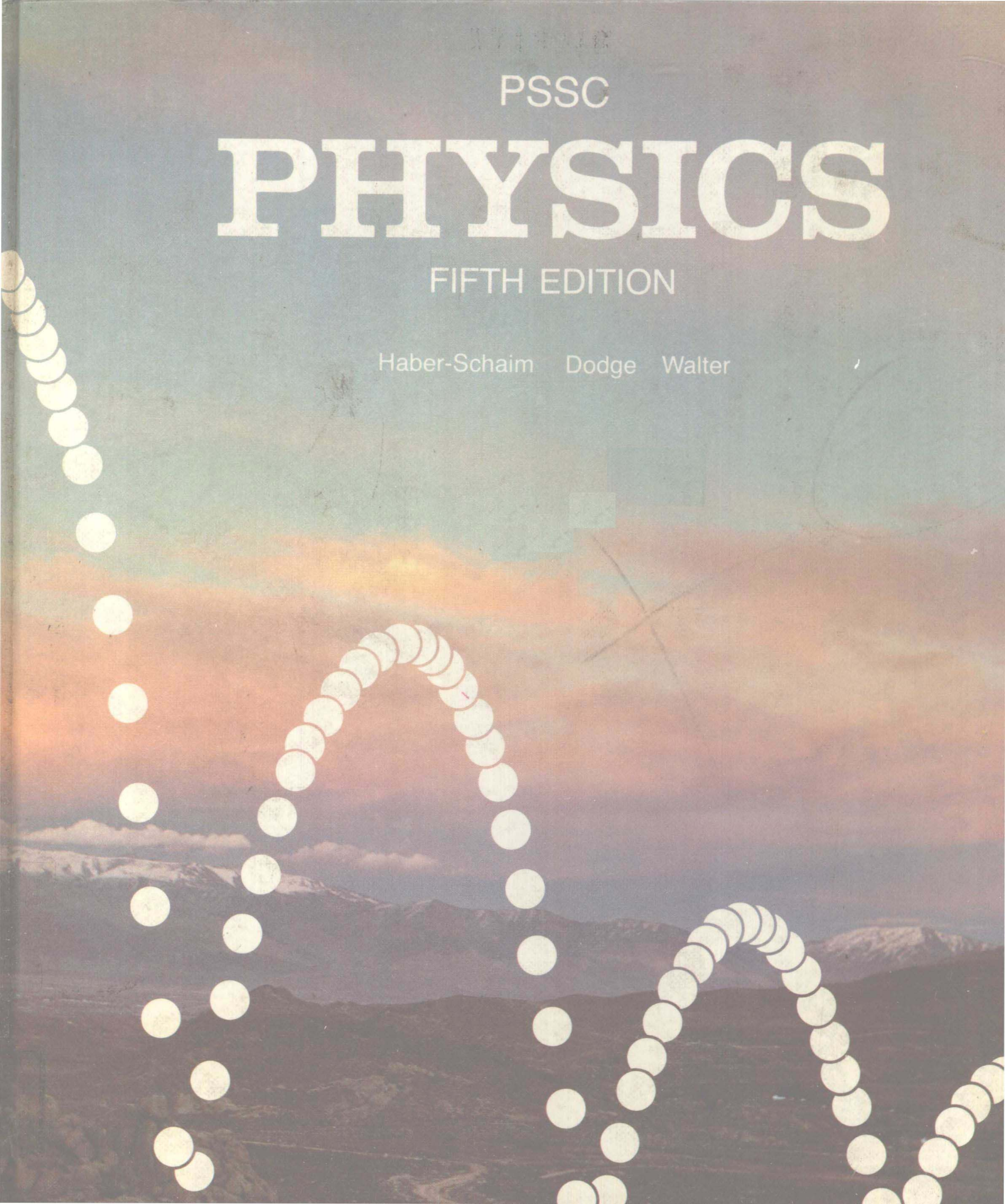
PSSC

PHYSICS

FIFTH EDITION

Haber-Schaim Dodge Walter



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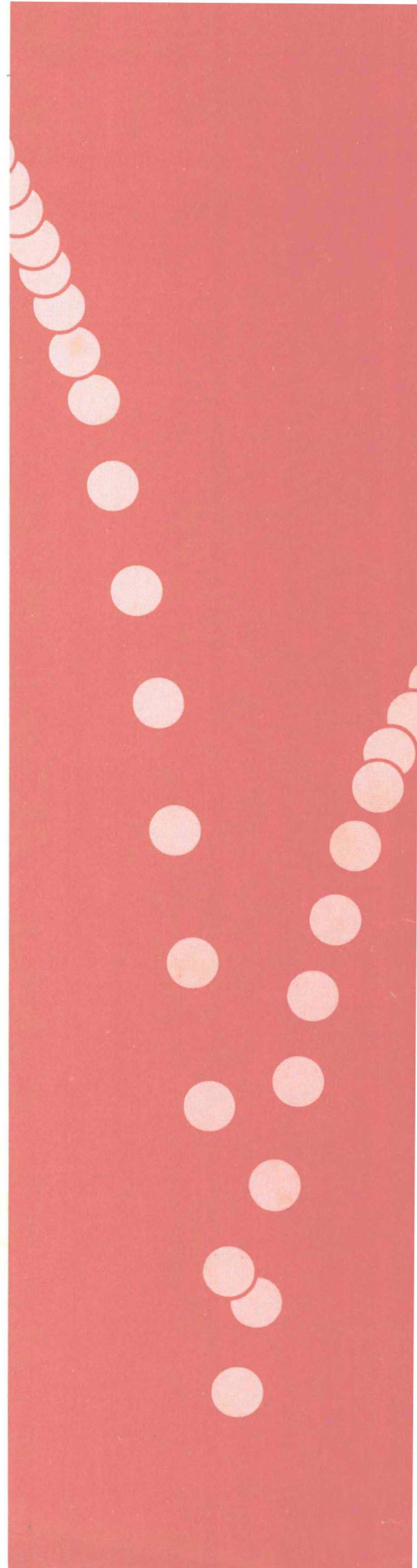

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Preface to the Fifth Edition

PSSC Physics has been serving students in the United States and abroad for twenty years. The basic laws of physics have not changed during that period, but the frontiers of research, as well as new needs of technology and society, have to be reflected in secondary school physics. It would be counterproductive to try to include all the latest topics from quarks to black holes, thereby overloading the course and reducing it from a vehicle for studying nature to an aid to memorizing vocabulary. On the contrary, we decided to further streamline the course and thereby provide room for some subtle changes in emphasis, which will enable the students to better relate the fundamentals of physics to the world around them.

The most prominent example of such a change is greater emphasis on the particle nature of light and the energetics of light relative to the wave motion of light. The increased interest in the utilization of solar energy requires understanding of photoelectric processes (including photochemical processes), which can be understood only with the quantum model of light. In the previous editions, we introduce a qualitative particle model of light before studying particle dynamics. After discarding this model in favor of the wave model we came to the photon model only toward the end of the book.

In this edition Newtonian Mechanics, including the mechanics of charged particles, *precedes* optics. This sequencing enables us to include radiant energy in the overall picture of energy changes and to study the interaction of light with matter in a quantitative way, leading directly to a modern particle model of light. The wave model still retains its function in addressing the propagation of light; the final synthesis of the two models and its central role in modern physics becomes more explicit.

The last decade has provided new insights into how students learn physics and how teachers can better monitor that learning in order to facilitate it. We took notice of this progress in several ways, among them is the addition of many new single-step questions and their placement between Sections so that they serve both as immediate reinforcement and connecting tissue.

In this edition we added a number of excursions to the structured development of physics. They take the form of short photo essays which highlight a natural phenomenon or a technical application related to the chapter in which they appear.

Acknowledgements

Many ideas for this edition originated at a two-day meeting with the following PSSC teachers: Thomas Dillon, Robert Gardner, Richard Heckathorn, Don Iverson, and Dr. Maria B. Penny. We wish to thank all of them for sharing their thoughts and experience with us.

We are greatly indebted to Professor Philip Morrison, who was a member of the original group, and to Professor Michael Mendillo, for writing several photo essays, and to Professor Alan Portis for helpful suggestions. Thanks are due to Edward A. Shore for photographing new equipment.

We wish also to express our appreciation to the editorial and art departments of D. C. Heath and Company for their cooperation.

The fact that this course is in its fifth edition constitutes, we believe, a vote of confidence in the original team that put the course together. The story of that effort is found in Appendix 1.

Uri Haber-Schaim
John H. Dodge
James A. Walter
June 1980

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Appendix

A freight train is rolling down the track at 65 kilometers per hour. Out of the fog a kilometer behind, a fast express appears, going at 120 kilometers per hour on the same track. The express engineer slams on his brakes. With the brakes set he needs 3 kilometers to stop. Will there be a crash? What we are called upon to do here is to predict where the two trains will be at subsequent times, and to find in particular whether they are ever at the same place at the same time. In a more general sense, we are asking about the connections between speeds, positions, and times.

The general subject of such relationships is called kinematics. In studying kinematics we do not concern ourselves with questions such as "Why does the express train need 3 kilometers to stop?" To answer such a question we would need to study in detail how the brakes slow down the train. Such questions as these will be considered in later chapters. Here we just consider the description of motion. We shall start with the discussion of motion along a straight-line path. Then in the third chapter we shall extend the discussion to describe more general motions.

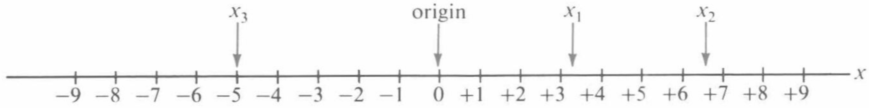
In both of these chapters we shall draw on our ability to measure time and position, for all motion is the changing of position as time goes on. Usually, we shall not think consciously of the time and position measurements, but without them we would in fact be talking words without meaning.

1–1 Position and Displacement Along a Straight Line

The first step in the study of motion is to describe the position of a moving object. Consider a car on an east-west stretch of straight highway. To answer the question "Where is the car?" we have to specify its position relative to some particular point. Any well-known landmark can serve as our reference point, or origin for measuring position. We then state how far the car is from the landmark and in which direction, east or west, and the description of position is complete. Thus, for example, we say that the car is 5 km west of the center of town, or it is 3 km east of the Sandy River Bridge. It is not enough to say only, "five km from the center of town." You would not know whether this means 5 km east or 5 km west.

Similarly, if you wish to describe the position of a point on a straight line that you have drawn, you must specify some origin and state a distance and direction from that origin. But this time the direction cannot be given as east or west, for the line may not run that way. You might try "right and left," but how would someone standing on the other side of the line interpret these directions? To get a description of direction along the line about which we can all agree, we shall call the line on one side of the origin positive, on the other side negative; we can then specify position on the line by a positive or negative number which gives both the distance (in some convenient units) and the direction of that point from the origin. We shall refer to such a number, with its sign and units, as

Figure 1–1 The x coordinate line.



the coordinate of the point. If we call the line the x coordinate line, we shall label these coordinates as x_1, x_2, x_3, etc. (Fig. 1–1).

We shall often want to refer to the change of position in our study of motion and we shall give it a special name, the *displacement*. If an object moves from position x_1 to position x_2, the displacement is given by the difference $x_2 - x_1$, that is, the later position coordinate minus the earlier one. Displacement can be either positive or negative (positive when x_2 is greater than x_1, negative when x_2 is less than x_1). Whether the displacement is positive or negative depends only on the direction of motion; it does not depend on where on the x coordinate line the displacement takes place. The two displacements in Fig. 1–2 (a) are positive and equal to each other. The displacements in Fig. 1–2 (b) are negative and also equal to each other.

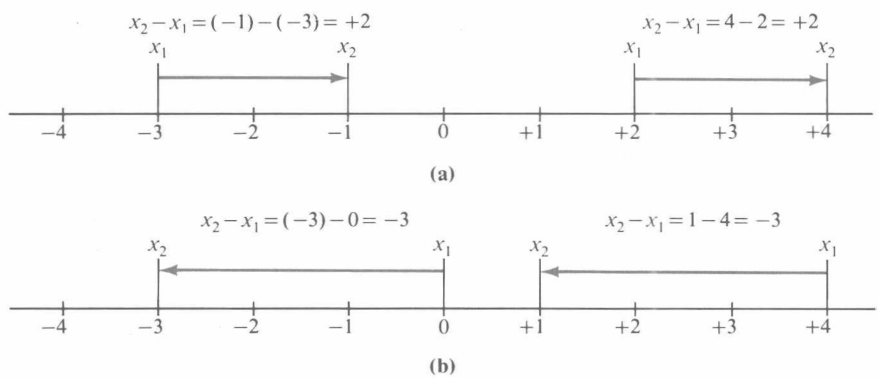


Figure 1–2 Two equal displacements, (a) positive and (b) negative.

Displacements are also independent of the point chosen for the origin of the coordinate line. Figure 1–3 shows the position coordinates of the same points as those in Fig. 1–2 but on a coordinate line whose origin is at a different place. The position coordinates are different, but the displacements, being differences, are the same.

Differences, or changes, occur so often in science and mathematics that a special notation is used to express them. The Greek letter delta, written as Δ (Greek capital D), is usually chosen to stand for "difference" or "interval" or "change of" or "increase of." Thus Δa means "change in a" or "increase in a" and is read as "delta a." It makes no sense to separate the Δ from the a. The whole symbol Δa has a special meaning: the change in a or an interval of a. It does not mean Δ multiplied by a.

Specifically, in the case of a change in position, the displacement is written as

$$\Delta x = x_2 - x_1$$

where x_2 is the later position.

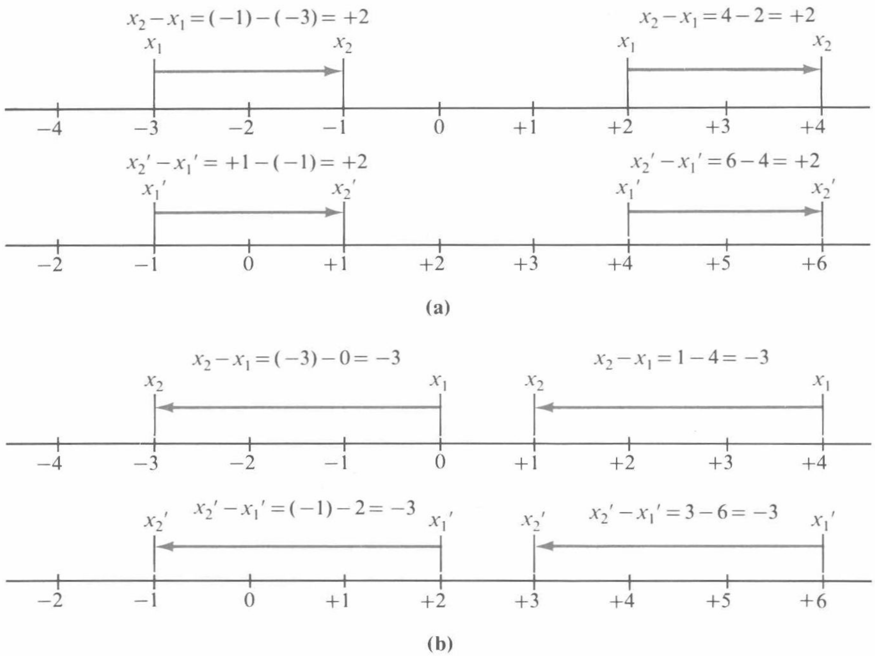


Figure 1–3 In (a) the same displacements as in Fig. 1–2(a) are shown on top; underneath they are referred to a coordinate axis with a different origin. In (b) the displacements of Fig. 1–2(b) are referred to a different origin.

To describe the motion of an object along a coordinate line, it is often convenient to make a graph of position against time. In such graphs, we usually plot the time along the horizontal axis and the position along the vertical axis. Figure 1–4 is an example of such a graph. There are many qualitative features about the motion which you can learn immediately from the graph.

The object was at position $x = 3.0$ cm at the time chosen as zero time. It stayed there till $t = 3.0$ s. At that instant it started moving away from the origin. Its farthest position was $x = 6.5$ cm and it arrived there at $t = 10.2$ s. It then reversed its direction, crossed the origin, and stopped again at $x = -2.0$ cm, etc.

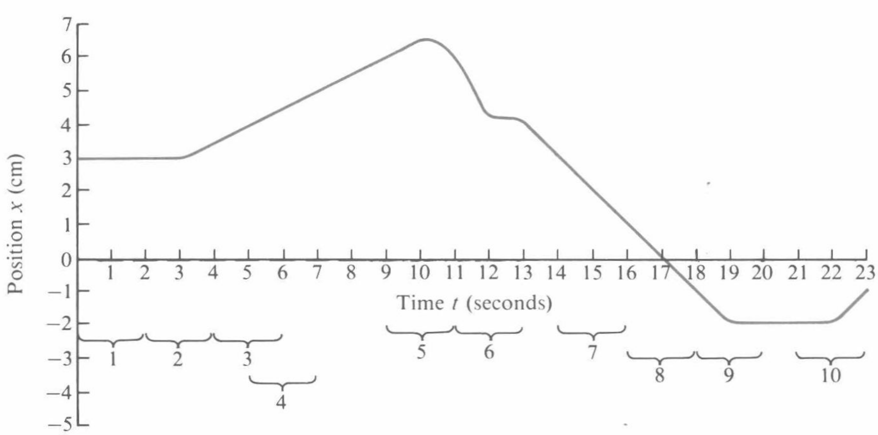


Figure 1–4 A position-time graph.

	x_1(m)	x_2(m)
(1)	5	8
(2)	7	−2
(3)	−5	−2
(4)	15	12
(5)	0	2
(6)	−5	−8
(7)	−5	0

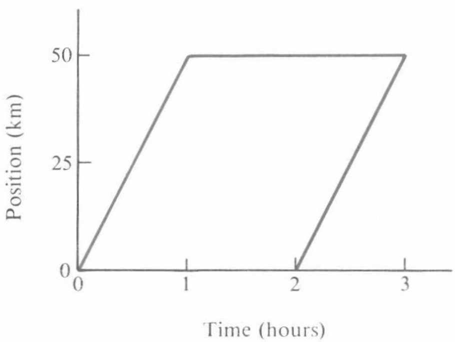


Figure A

1. Express the change in the following quantities, using the Δ notation:
   (a) The temperature T_1 of a room at 9 AM was 19°C, and an hour later the temperature T_2 was 25°C.
   (b) The reading d_1 of the odometer at the beginning of a trip was 2380 km, and the reading d_2 at the end of the trip was 4060 km.
   (c) Before dieting, a person's mass w_1 was 80 kg, and after dieting the person's mass w_2 was 70 kg.
2. In the table at the left, which displacements are equal?
3. Does the graph of a car trip in Fig. A represent a real situation? Explain.

1–2 Steady Motion: Constant Velocity

Moving fast and moving slowly are very familiar terms to everyone, but you may not have noticed that there are two different (although related) ways of expressing this distinction quantitatively. In sports we say that a runner a is faster than runner b, if a covered the same distance as b in less time. When it comes to highways, we say that on the expressway you can drive faster because you are allowed to cover more km in one hour than on a side road.

We can use the graph showing position as a function of time (Fig. 1–4) to find when the object was moving fast or slow. We shall do so by the second method, that is, by comparing displacements made in equal time intervals. Since a time interval is the difference between two time coordinates t_1 and t_2, it is appropriate to designate the difference $t_2 - t_1$ by Δt.

As an example let us compare the displacements of the object whose motion is described in Fig. 1–4 for time intervals $\Delta t = 2$ s, beginning at various times (Table 1).

Table 1 tells us that the object moved fastest during intervals 6, 7, and

Table 1

NUMBER OF INTERVAL	t_1 (s)	x_1 (cm)	t_2 (s)	x_2 (cm)	Δt (s)	Δx (cm)
1	0	3.0	2.0	3.0	2.0	0
2	2.0	3.0	4.0	3.5	2.0	0.5
3	4.0	3.5	6.0	4.5	2.0	1.0
4	5.0	4.0	7.0	5.0	2.0	1.0
5	9.0	6.0	11.0	6.0	2.0	0
6	11.0	6.0	13.0	4.0	2.0	−2.0
7	14.0	3.0	16.0	1.0	2.0	−2.0
8	16.0	1.0	18	−1.0	2.0	−2.0
9	18.0	−1.0	20.0	−2.0	2.0	−1.0
10	21.0	−2.0	23.0	−1.0	2.0	1.0

8, and that it was moving to the left. (In these intervals Δx is largest in magnitude, and negative.)

In intervals 1 and 5 the displacement was zero. Does this mean that the object was at rest during those time intervals? The table alone is not enough to settle the question. Going back to the graph in Fig. 1–4, you see that at any instant during interval 1—that is, between $t = 0$ and $t = 2.0$ s—the object was at rest at $x = 3.0$ cm. However, during interval 5—between $t = 9.0$ s and $t = 11.0$ s—the object was first moving to the right (upward on the x scale) and then to the left (downward on the x scale). It just happened that at the end of the time interval it was at the same position as at the beginning.

Now let us examine the motion during intervals 6, 7, and 8; in all three the displacement was −2.0 cm. Was the motion the same in these intervals? To answer this question, we shall redraw Fig. 1–4 on a larger scale and divide each time interval into two equal parts, and find the corresponding displacements (Fig. 1–5). The results are shown in Table 2.

You see from the table that the subdivision of interval 6 shows that there were unequal displacements, whereas the subdivision of intervals 7 and 8 showed equal displacements to within the accuracy of the reading of the graph. Further subdivisions of intervals 7 and 8 show that for any equal time intervals these smaller displacements are also equal. A motion for which this is the case is called *steady motion*. On a position-versus-time graph, portions corresponding to steady motion must be

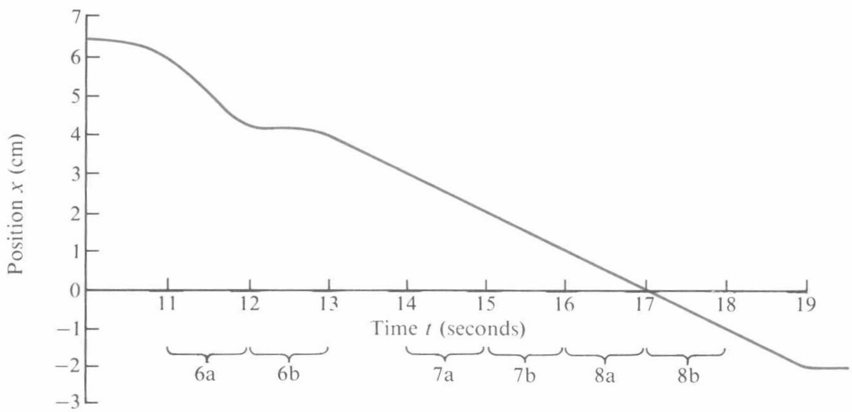


Figure 1–5 A part of Fig. 1–4 redrawn on a magnified scale.

Table 2

NUMBER OF INTERVAL	t_1 (s)	x_1 (cm)	t_2 (s)	x_2 (cm)	Δt (s)	Δx (cm)
6a	11.0	6.0	12.0	4.2	1.0	−1.8
6b	12.0	4.2	13.0	4.0	1.0	−0.2
7a	14.0	3.0	15.0	2.0	1.0	−1.0
7b	15.0	2.0	16.0	1.0	1.0	−1.0
8a	16.0	1.0	17.0	0	1.0	−1.0
8b	17.0	0	18.0	−1.0	1.0	−1.0

straight-line segments, since only for a straight line do equal changes along one axis correspond to equal changes along the other.

We can look at the steady motion in intervals 7 and 8 in another way. In each second the displacement is 1.0 cm; in 2.0 s it is twice as much or 2.0 cm; in 3.0 s it is three times as much or 3.0 cm, and so on, as long as the motion is steady. We can generalize this result as follows: if for any equal time intervals the displacements are equal, then the displacement is proportional to the time interval:

$$\Delta x = v\Delta t$$

where v, the proportionality constant, is the *velocity.* Since Δx has the dimension of length and Δt the dimension of time, v has the dimension of length divided by time, or length per unit time. Its units depend on the units in which the displacement and time are expressed. For example, if Δx is expressed in cm and Δt in seconds, then v is given in cm/s. This is seen best by writing

$$v = \frac{\Delta x}{\Delta t}.$$

For the straight section of the graph in Fig. 1–4 which we have just discussed, $v = \dfrac{-2.0\text{ cm}}{2.0\text{ s}} = -1.0\text{ cm/s}$. The sign of the velocity is always the same as the sign of the displacement Δx, because Δt is always positive. The magnitude of the ratio $\dfrac{\Delta x}{\Delta t}$ is a measure of the steepness of the straight part of the x vs t graph; it is called the *slope* of the line.

When the ratio of two changes is involved, as it is in determining a velocity, it is understood that the change in the numerator "takes place during" the interval of the denominator. Thus $v = \dfrac{\Delta x}{\Delta t}$ (which is read "v equals delta x over delta t") means "to find the velocity, take the change in position Δx and divide it by that time interval Δt during which it took place." In general, when we write $\Delta a/\Delta b$, we mean that we shall use the change in a that corresponds to a given change in b.

4. Express the following velocities in kilometer/hour. Give examples of objects that move with such velocities.
(a) 1 m/s (b) 10 m/s (c) 25 m/s (d) 250 m/s (e) 8000 m/s

5. Identify the parts of the graph in Fig. 1–4, page 3, where the motion is steady, and determine the velocity of the object in those regions.

6. Find the slopes of the graphs in Fig. B. State the units in each case.

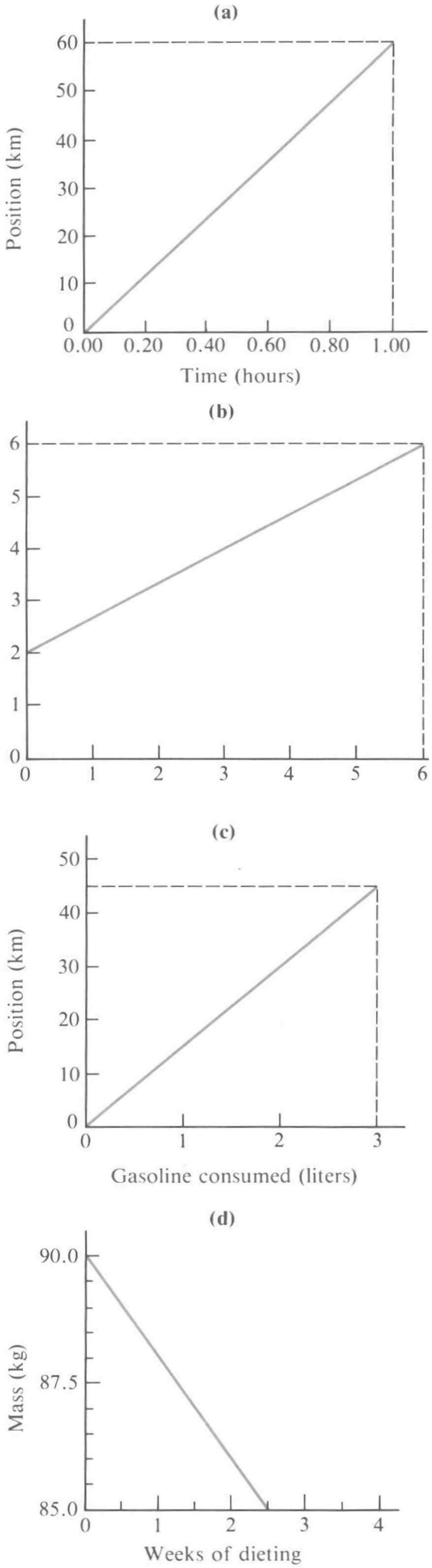
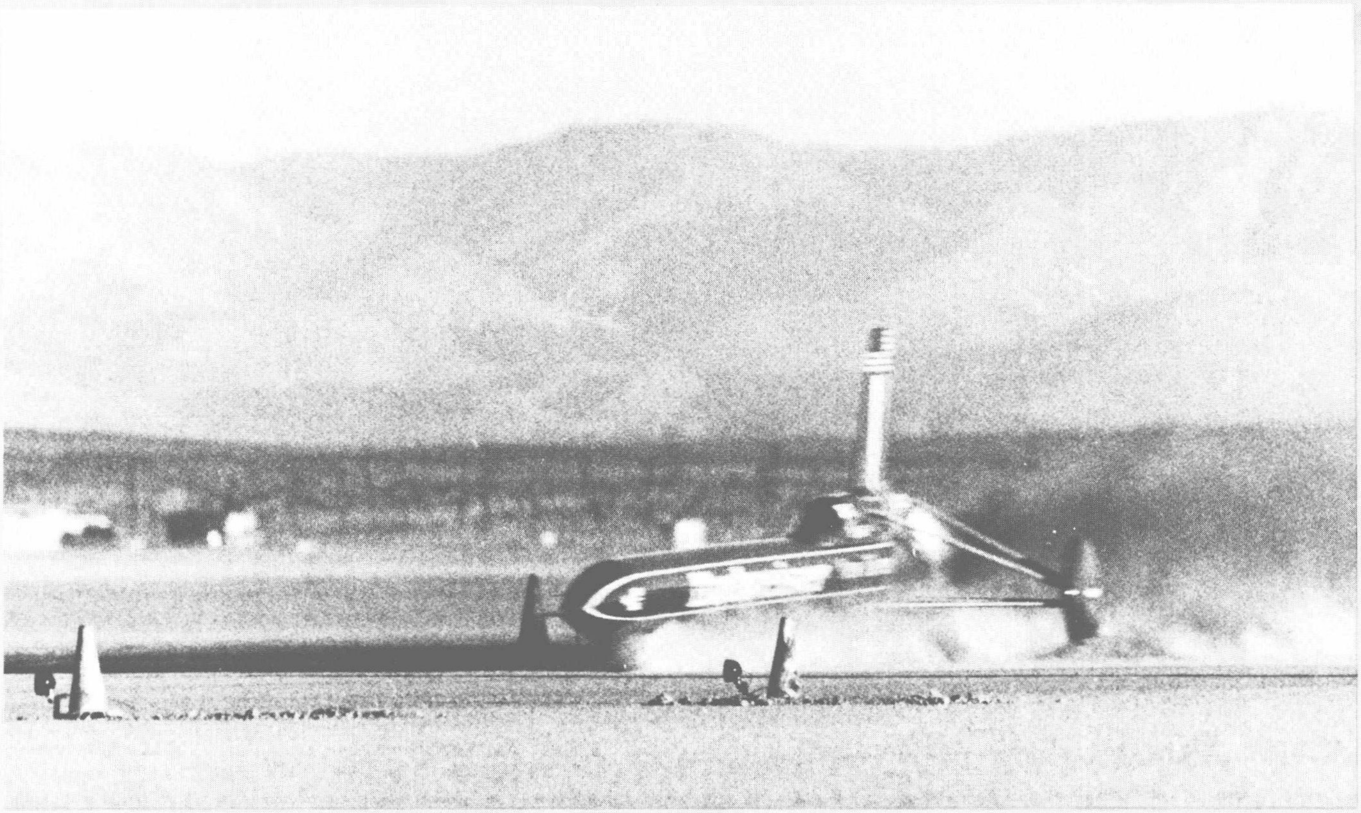


Figure B



Breaking the Sound Barrier

On December 15, 1979, this rocket-powered car sped over the dry sands of Rogers Dry Lake in California, at a speed of 330 m/s. The temperature in the early morning desert air was $-7°$ C. At that temperature sound travels through the air at a speed of 327 m/s. Thus the rocket car exceeded the speed of sound by 3 m/s. It moved at a supersonic speed.

The speed was not measured by two observers with synchronized stop-watches positioned along the path. Rather, the speed was measured indirectly by observing the motion of the car's image on a radar screen. To be reliable, such indirect methods of measurement are first tested against direct methods.

But what is so great about moving at a speed greater than that of sound? Airplanes have been flying at supersonic speeds for over 20 years. Moreover, while you are reading this essay you are moving at a speed of 3×10^4 m/s in orbit around the sun, and you do not even notice it.

It is not the speed itself but the rapid change in speed which is impressive. It took the car only 20s to reach 330 m/s. This amounts to an average acceleration of close to 17 m/s^2. (Actually, the initial acceleration was over three times larger.)

You may wonder why the car was so long (12 m) and narrow (0.5 m). Why was a Sidewinder missile engine, with 4.8×10^4 horsepower, used? Why was the engine not connected to the wheels as is the case in other racing cars?

At top speed the wheels were turning 150 times per second. Could this be the reason why they were made of forged aluminum and not rubber?

You will be able to figure out the answers to these questions after studying the next few chapters, in which we go beyond the description of motion and take up the question of how objects are made to move.

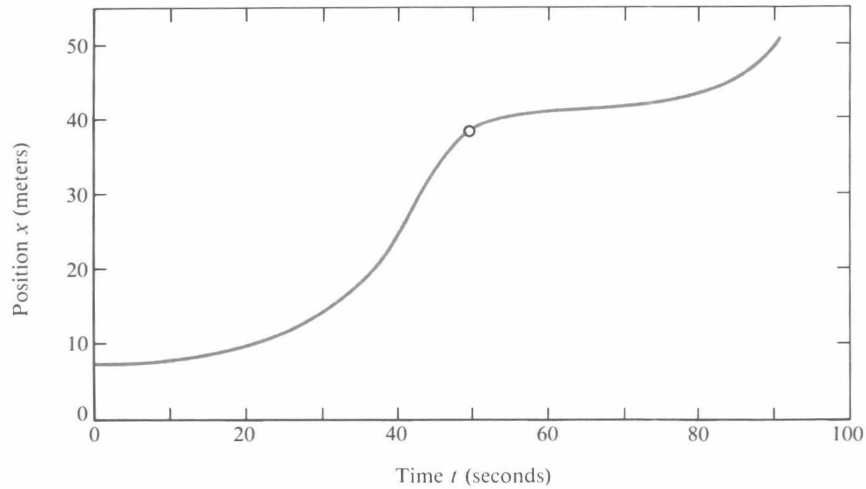


Figure 1–6 Position-time graph for an object with continually changing velocity.

1–3 Instantaneous Velocity

We have seen that for steady motion the change in position, i.e., the displacement, is proportional to the change in time. But most motions are not steady, and their position-versus-time graphs will not have straight segments. Is there a measure for how fast an object moves when its motion is not steady?

Consider the position-versus-time graph shown in Fig. 1–6. How fast is the object moving at $t = 50$ s? The motion around that time is not steady, as you see from the fact that the line is curved. Now let us look with a magnifying glass at only the part of the graph between $t = 45$ s and $t = 55$ s (Fig. 1–7). The magnified part of the graph looks straighter than the whole graph, because it is only a small portion of it. A still greater magnification shows us the interval which covers only 0.5 s before and after the 50-s mark (Fig. 1–8). In this small interval the line is almost straight, and we can find the velocity by measuring the slope of the "straight" line. We choose two points 1 and 2 in Fig. 1–8 near 50 s; then, reading from this graph, we find

$$t_1 = 49.86 \text{ s}, \qquad x_1 = 38.42 \text{ m}.$$

$$t_2 = 50.16 \text{ s}, \qquad x_2 = 38.58 \text{ m}.$$

Consequently, the slope is given by

$$\frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1} = \frac{+0.16 \text{ m}}{0.30 \text{ s}} \approx +0.53 \text{ m/s},$$

and the velocity at the point 50 s from the start is very close to +0.53 m/s. Thus we can say that the velocity of the object at $t = 50$ s is very nearly 0.53 m/s in the positive direction.

The magnified part of a graph looks straighter than the whole graph because in the magnified picture we look at only a small portion of the unmagnified graph. When we magnify sufficiently, we look at only a small interval of x and t. In effect, therefore, we find the slope of a small portion of the curve by taking the ratio

$$\frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1}$$

for a pair of points 1 and 2 which are very close together. The points we use must be close enough together so that the graph is essentially a straight line in between.

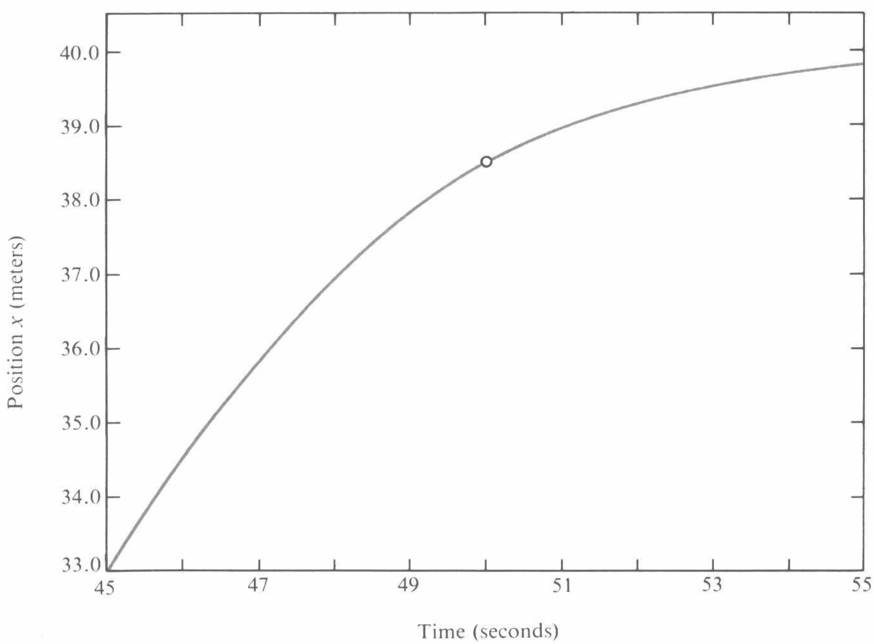


Figure 1–7 In this figure, part of the graph is enlarged.

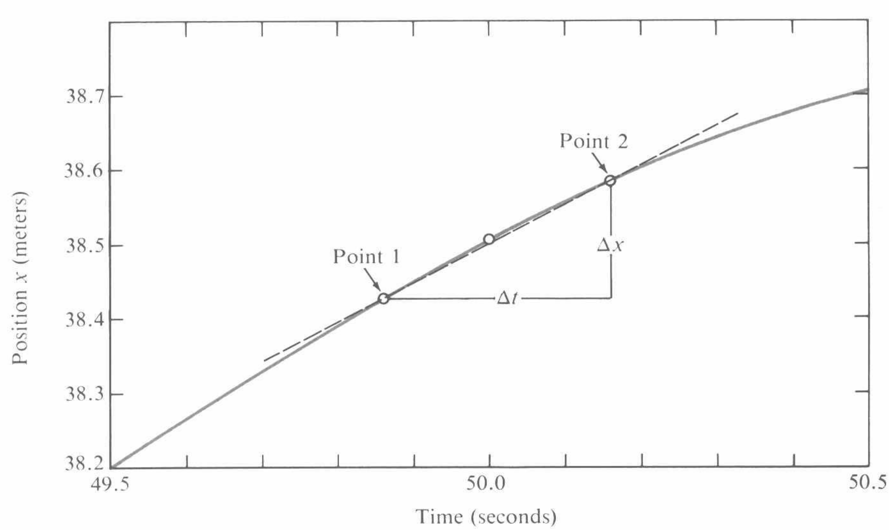


Figure 1–8 At a magnification of 100, a very small portion of the graph appears to be almost straight.