CHAPTER

1

Representing Motion

Recommended class days: **3 (including course introduction)**

Introduction and Part I Overview

Each of the seven parts of the textbook opens with an *overview* and closes with a *summary.* Each overview is a pause, before plunging in, to look at the road map of what lies ahead. We rarely give students any rationale for the directions we take or the choices we make, and this "flying blind" approach contributes to their difficulty finding any coherence in the course. The overviews provide at least a brief look at where we're going, and why.

The Part I Overview introduces the idea of a *model.* Large numbers of students think that the purpose of physics is to be *exact,* to describe reality *exactly* as it is. They become disturbed and confused by the cavalier way physicists make what often seem to be outrageous assumptions about a situation. Part of the art of solving physics problems or analyzing phenomena is choosing the right model with the right simplifying assumptions. This is a learned skill, one that students need help to acquire. You will want to be very explicit throughout the course, but especially in the first few chapters, with *where* you are making simplifying assumptions (i.e., using a model of the situation) and *why* you are doing so.

Background Information

Chapter 1 is the first of eight chapters on dynamics. The overall goal is to find the connection between force and motion, which we will do through Newton's laws. The first four chapters are devoted to establishing and clarifying just what we *mean* by the terms *force* and *motion.* As noted in the section on physics education research, students' ideas about force and motion are quite different from Newtonian ideas. Students cannot begin to understand Newton's ideas until they have a better grasp on what force and motion *are.*

Beginning with Chapter 5 we begin to apply Newton's laws to straight-line, 2D, and rotational motion. Because of the conceptual difficulties students have with force and motion, in

Chapter 5 we begin by understanding how a single particle responds to forces. Only later in the chapter do we turn to Newton's third law and systems of interacting problems. Instructors charting their course for the first few weeks should look ahead through Chapter 8 to see how all the pieces will fit together.

Student difficulties with the concept of motion have been well studied (Trowbridge and McDermott, 1980; Trowbridge and McDermott, 1981; Rosenquist and McDermott, 1987; McDermott et al., 1987). Difficulties instructors should be aware of include the following:

- Students don't readily differentiate between position, velocity, and acceleration. They have a single, undifferentiated idea of "motion."
- Students don't easily recognize *change* of motion. They tend to see motion holistically, as a single "event," and they may find it difficult to compare the motion at two different points in a trajectory. Thus some students think that a projectile moves at constant speed along its entire path. This difficulty may stem from never having *observed* motion very carefully. This is something you can have them do with classroom demonstrations.
- Position and velocity are sometimes confused. If car B overtakes and passes car A on the freeway, both traveling in the same direction, some students will say the cars have the same *velocity* at the instant when B is alongside A.
- Velocity and acceleration are frequently confused. When asked to draw velocity and acceleration vectors, students often draw acceleration vectors that mimic the velocity vectors. At a turning point (end of a pendulum's swing, top of the motion of a ball tossed straight up, etc.), nearly all students will insist that the acceleration is zero. This is an especially difficult belief to change. A significant number of class activities involving turning points are needed for students to understand this issue.
- Acceleration is associated only with *speeding up* and *slowing down.* Very few students associate acceleration with curvilinear motion. This is not surprising, because a vector acceleration as we use it in physics is a *definition,* not a common-sense observation. Some students may know from high school physics that circular motion has a centripetal acceleration. But this is a memorized fact; almost none can tell you *why* the acceleration points to the center.
- Students identify speeding up with positive values of the acceleration and slowing down with negative acceleration. This is a difficult idea to change, and for many students it becomes a serious difficulty when they get to Newton's second law. They need much practice with coordinate systems, vectors, and vector components.

These difficulties are compounded by most students' lack of knowledge of vectors. Formal definitions, such as $\vec{a} = \Delta\vec{v}/\Delta t,$ are nearly meaningless because most students can't interpret $\Delta\vec{v}.$ Velocity and acceleration need to be introduced as *operational definitions,* and students need ample opportunities to apply the operations needed to find the displacement $\vec{d}$ and $\Delta\vec{v}.$ This is especially true if the definition for $\vec{a}$ is to make any sense. Much of Chapter 3 is focused on developing and practicing specific *procedures* for determining velocity and acceleration vectors.

A second issue addressed in this first chapter is the development of good problem-solving skills. The section on physics education research discussed the differences between student problem-solving strategies and expert problem-solving strategies. In particular, students rarely go through the steps of *describing* the problem situation through sketches, coordinate systems, and the identification of known and unknown quantities. Several studies that trained students in these aspects of problem solving showed significant increases in problem-solving ability (Van Heuvelen, 1991a; Heller et al., 1992a). Chapter 2 begins the development of a well articulated problem-solving strategy for mechanics problems, a strategy that won't be complete until Chapter 8.

Student Learning Objectives

In covering the material of this chapter, students will

- Understand and use the basic ideas of the *particle model.*
- Analyze the motion of an object by using *motion diagrams* as a tool.
- Describe motion in terms of position, displacement, and velocity.
- Express quantities using correct units and significant figures, and to be able to use scientific notation.
- Gain initial experience with displacement and velocity vectors, and the graphical addition of vectors.

The supplementary goal in this chapter is to introduce students to the features of the chapters. You may find it worthwhile to explicitly note these features and describe how you would like your students to use them:

- Each chapter begins with a preview, a visual summary of the material to come. This is another aspect of the book's strategy of giving students a "big picture" view of the material before they dig into the details. We introduced the chapter previews in response to student requests in the second edition; in the third edition, we streamlined the previews in response to further feedback from students. The heart of each preview is a "Looking Ahead" section that explains the key concepts of the chapter, along with a description of the types of problems students will solve using these concepts. This is followed by a "Looking Back" section that identifies the topic from a past chapter that will be most important for students to remember and understand, along with an exercise to help them test their recall and comprehension.
- We have also crafted a set of Prelecture Videos that give a quick, visual overview of the chapter topics. Students can watch these before class to develop a basic understanding of the key concepts and topics to be presented. Each of the prelectures also includes questions related to the material that is being presented to keep students active.
- Sections of chapters are separated by "Stop to Think" exercises. Learning is an active process, and it will be a big help to students' comprehension and retention if they do these exercises as they go along.
- Photos and paragraphs in the margin show practical applications of the material students are learning.
- Chapters finish with an Integrated Example that shows the steps of solving a more complex problem that draws on concepts and techniques from previous chapters. These Integrated Examples are "context rich," dealing with realistic problems in the wider world.
- At the end of each chapter, there is a set of questions and problems. It's worth letting your students know that the solutions to odd-numbered exercises are in the back of the book. You may wish to assign a mix of odd and even problems so that, in some cases, students can check their work as they go. We've taken pains to be sure that problems are physically reasonable, with results that students can evaluate in terms of past experience and other problems they have seen.

Pedagogical Approach

Rather than a traditional Chapter 1 that deals with minutiae such as units and measurement, *College Physics: A Strategic Approach* dives right into the consideration of motion, bringing up these practical details in context. The rationale is that students should immediately be aware that physics is about phenomena, not the memorization of facts and formulas. The approach to motion in this chapter—through the use of motion diagrams—is unconventional but straightforward. We make explicit use of the *particle model,* the first of many simplifying models introduced throughout the book. Using the particle model, concepts of coordinate systems and position, and especially *changes* in position, are developed. Changes in position naturally lead to position vectors, introduced at this point only informally as directed arrows, and then to the concept of velocity. Considerations of acceleration are delayed until Chapter 2.

In keeping with our emphasis on starting right in with motion, we don't recommend explicitly treating units, measurements, and significant figures in class. This makes for a rather dry lecture, and your first lectures set a tone for what is to come. Stick to the more interesting story of how we use models to describe nature, and have your students read about significant figures and units in the book—letting them know that they'll be responsible for this information. As you work through examples with them over the first few weeks, you can illustrate these notions in context. In this book, we typically keep two significant figures, which makes sense for the level of accuracy implied by the data in the problems we solve. You may choose to follow a different tack, but the key thing is to have students understand why they shouldn't report 10-digit results from their calculator displays.

Students generally pick up the concept of a motion diagram quickly. You should have your students work out motion diagrams from simple motions demonstrated in class. This makes the class more active, makes the point that physics is about the real world, and helps make the all-important first lectures more interesting.

Vectors are introduced graphically in the context of displacements, which leads naturally to the idea of vector addition. You'll want students to practice doing some basic vector addition (illustrated in Tactics Box 1.4) before beginning to apply this idea to motion diagrams. Be aware that some students associate a vector with the specific place it is drawn; they don't realize that you can slide a vector to another location. Don't get complicated for now—Chapter 3 will do quite a bit more with vectors—just draw a couple of vectors on the board, label them $\vec{A}$ and $\vec{B}$, and then ask students to draw the vector $\vec{A}+\vec{B}$.

In describing motion, students often make very unconventional assumptions about the initial and final conditions. If you ask them to draw a motion diagram of a cannon ball fired from a cliff, you probably *mean* for the motion to last from the point where the ball leaves the barrel until the instant of contact with the ground, and you will draw the diagram showing the motion in a vertical plane. Students will often include the launching process, the flight through the air, and various bounces or rolls until the ball stops. Some will probably draw it in a perspective diagram, and some may even draw it from a bird's-eye view. You need to explicitly address the *simplifying assumptions* we make, especially the issue of where the motion starts and ends. The larger issue here is learning to separate what's relevant from what's irrelevant—that is, really, what Chapter 1 is all about.

A concern to some instructors is that motion-diagram vectors are labeled $\vec{v}$ and $\vec{a}$, whereas what we've really defined are the average velocity $\vec{v}_{avg}$ and the average acceleration $\vec{a}_{avg}$. The motion diagram is an important tool to help students *visualize* motion, a task that many students find surprisingly difficult. But for motion diagrams to be useful, they must be simple to use. Thus motion diagrams purposefully blur the distinction between average and instantaneous quantities—a distinction that is ultimately important but that is meaningless to students at this initial stage. There's no evidence that this lack of distinction hinders students' ability to understand and use the proper definitions when they reach kinematics in Chapter 2.

It is important not to start doing complex computations in this chapter. The focus is simply on studying several representations of motion; understanding displacement, speed, and velocity; and identifying displacement and velocity vectors for different kinds of motion. Most of the "problems" in the examples and in the homework show students how to *describe* a problem statement with a pictorial representation. You should emphasize to students that they are not being asked to *solve* these problems. Students want to jump right to this last step, the plugging of numbers into equations, and having them practice on the more important early steps in the problem-solving process is good discipline at this point.

Suggested Lecture Outlines

There is no one "right" way to teach physics. The ideas for using class time in this and subsequent chapters are meant as suggestions. These ideas present an active-learning approach that has been successful for the authors and for other instructors. Adopt as much or as little of this approach as you need. The most important aspect of using class time effectively is not the specific activities as much as it is keeping the students *actively engaged* in the learning process.

DAY 1: Most instructors will spend much of Day 1 on logistical details about the course. It is important to be clear about how you will be using class time and about your expectations of students. Let them know that you're going to start right in by asking *them* to use the information in Chapter 1, and that an initial chapter reading before Day 2 is essential. To save time, and because reading is more efficient than listening, one possibility is to put all logistical course information and a day-by-day schedule on a handout for the students. Then, when reviewing your expectations, tell them that the reading quiz at the beginning of Day 2 will cover both Chapter 1 *and* the handouts!

If you do this, you can have more than half of Day 1 to present some material. This is enough time to introduce the idea of a motion diagram by asking students to imagine cutting apart the frames of a video, stacking them, and projecting them onto a screen. Ask a student to walk steadily across the front of the room, then show how this gets converted to a motion diagram. Draw stick figures; don't use the particle model on Day 1 and don't introduce position or velocity. Note that if you ask students to "hold up your movie camera and film the motion," you'll see that many pivot to "track" the student who is walking. You'll need to remind them to keep the camera *fixed* so that the object moves across the frame.

Once the basic idea is clear, have various students demonstrate speeding up, slowing down, or maybe both. To keep these initial motions as simple as possible, identify some points in the room (such as the ends of the lecture table) as being the edges of the camera's field of view. That way a student can speed up across the field of view, but students "won't see" and won't be distracted by his or her sudden deceleration before hitting the wall! You might ask a student to speed up slowly while you count frames—1, 2, 3, . . . Then you can ask students to compare the distance traveled between frames 1 and 2 to the distance between frames 5 and 6.

Have students draw each motion diagram and then compare it with their neighbor's, a first-day introduction to the idea of peer interactions, a very valuable technique for keeping students engaged and active. Then put your version on the board. Students' initial motion diagrams tend to be unbelievably messy and poorly structured, so you quickly—even when most students seem to have the right idea—want to demonstrate what a "good" diagram looks like. Putting your version on the board also gives you the opportunity to clarify subtle points and to give positive reinforcement. Many students who have it right will be very unsure about their answer.

DAY 2: Have students observe various real-world motions carefully, then draw motion diagrams using the particle model. A large strobe lamp, if available, can help clarify how objects move. You can also use videos of simple motions, stepping through frames—exactly what we ask students to imagine doing. Some good real-world trajectories include

- A ball rolled down an incline, from the moment you release it until just before it reaches the bottom. This is a good place for a digression on the "start" and the "end" of the motion.
- A cart rolled across a table with enough friction that it slows and stops.

- Balls tossed in a high parabolic trajectory so that they visibly slow but don't stop.
- A ball rolled along the table, up a ramp, and back down.

Ask students to focus on the *shape* of the trajectory and on how the speed changes, drawing the particles farther apart when the object is moving faster.

Position and displacement. Now you can introduce motion diagrams placed on a coordinate axis, with times assigned to each particle position. To make things concrete, it can be helpful to use your local east–west highway as the *x*-axis. Ask how they might report, via cell phone, their position on the highway to a friend back at school. Sometimes they might say "I'm passing the gas station," but at other times, when far from any landmark, they might report "I'm 2 miles east of the gas station." This locution brings out three key aspects of any coordinate system: You need an *origin,* from which all positions are measured; your *distance* from the origin; and on *which side* of the origin you are. You can then go on to discuss our standard *x*-axis, superimposed on the highway, with the origin at the gas station. Point out that we denote positions by the *coordinate x* (or *y* for vertical motion). When the object is to the left of the origin, *x* is negative, and when it is to the right of the origin, *x* is positive. (We also adopt the convention that positive values of *y* increase going up. We recommend against using coordinate systems where positive *y*'s are down, even for examples such as a falling ball. Students find this very confusing.)

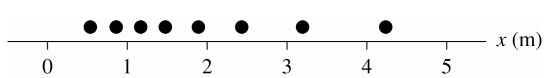
Since we're interested in the motion of objects, we need to be able to describe *changes* in an object's position. Imagine you're standing at initial position $x_\mathrm{i} = 3$ m, and you walk to final position $x_\mathrm{f} = 7$ m. Then the *change* in your position—your *displacement*—is 4 m. Notice that this is found by taking $(7\text{ m}) - (3\text{ m})$. In general, then, the displacement is $\Delta x = x_\mathrm{f} - x_\mathrm{i}$. Mention that displacements can be negative, indicating motion to the left.

At several points in each section of this guide we will present questions that you can pose to the class to check student understanding. It's best to have some method of getting feedback on students' responses so that you can gauge their progress. You can do this with a classroom response system—"clickers"—or more low-tech approaches such as flash cards or even a show of hands.

QuickCheck Clicker Question 1.4: Maria is at position $x = 23$ m. She then undergoes a displacement $\Delta x = -50$ m. What is her final position?

A. –27 m
B. –50 m
C. 23 m
D. 73 m

Time. To introduce the time "coordinate," you can draw a simple motion diagram like this one, and ask whether it represents a person moving to the left or to the right:

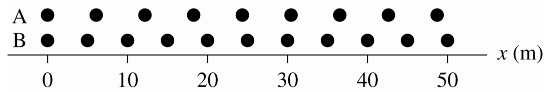


Of course, you really can't tell without more information. We need to label the *time* at each particle position. You can briefly discuss the idea of "clock readings" and the origin of time (i.e., how we assign $t = 0$). Here's an example students can work out, which also serves as a lead-in to the concept of velocity.

Example: Jane walks to the right at a constant rate, moving 3 m in 3 s. At $t = 0$ s she passes the $x = 1$ m mark. Draw her motion diagram from $t = -1$ s to $t = 4$ s.

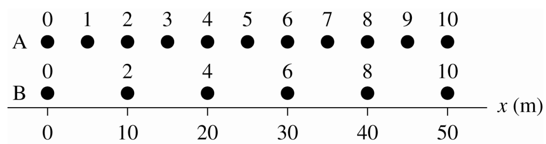
Speed and velocity. To introduce the ideas of speed and velocity it's important to connect what students intuitively know about "moving fast" and "moving slow" to our motion diagrams.

QuickCheck Clicker Question 1.2: Two runners jog along a track. The positions are shown at 1 s intervals. Which runner is moving faster?



But there's more to this idea. Try the following:

QuickCheck Clicker Question 1.3: Two runners jog along a track. The times at each position are shown. Which runner is moving faster?



A. Runner A
B. Runner B
C. Both runners are moving at the same speed.

Both runners are moving at the same speed, even though the displacement of runner A between particle positions is less than that of B. Note that although Δx_A is half of Δx_B, the *time interval* $\Delta t_A = t_f - t_i = 1\text{ s}$ for A is also half that of B, $\Delta t_B = t_f - t_i = 2\text{ s}$. We see then that we can form a single number that correctly reflects the idea that the two runners are moving at the same speed by forming the *ratio* of Δx to Δt. This is called the *velocity.* We have

$$\text{velocity} = v = \frac{\Delta x}{\Delta t}$$

You can see that this works for the two runners above:

$$v_A = \frac{\Delta x_A}{\Delta t_A} = \frac{5\text{ m}}{1\text{ s}} = 5\text{ m/s}$$
$$v_B = \frac{\Delta x_B}{\Delta t_B} = \frac{10\text{ m}}{2\text{ s}} = 5\text{ m/s}$$

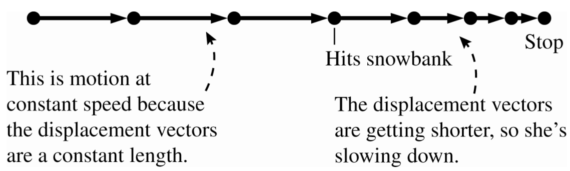
Example: At $t = 12\text{ s}$, Frank is at $x = 25\text{ m}$. 5 s later, he's at $x = 20\text{ m}$. What is Frank's velocity? This example indicates that velocities to the left are negative. The information that $t_i = 12\text{ s}$ is extraneous.

DAY 3: Vectors are introduced in this chapter in the concrete forms of displacement and velocity vectors. A more in-depth treatment of vectors is deferred until Chapter 3. At this stage we want only to establish vectors as representing quantities that have both a magnitude and a direction, and to understand the most basic properties of vector addition as applied to displacement vectors.

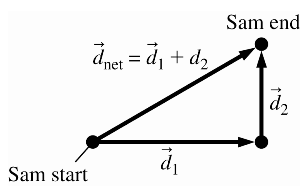
You can start the discussion by mentioning some common measurable quantities such as temperature, mass, and length. In order to report such a measurement, you need only give a *single* number (and a unit): 10°C, 23 kg, 5.0 m. Such quantities are called scalars. Other quantities, however, need both a *size* or *magnitude* and a *direction* in order to be fully specified. For instance, we've seen that in order to specify the displacement of a person as he walks from one place to another, we need to give not only how far he walks, but also the *direction* in which he walked. Your displacement in walking 2 mi to the east is not the same as when you walk 2 mi to the north. Similarly, a full specification of a car's velocity includes not only how fast it's going—its speed—but in which direction it's moving. Quantities like these are called *vectors.* Discuss our notation for vectors—a symbol with an arrow over it—and stress that it's crucial to properly use this notation for all vectors, and not to use it for other, scalar, quantities.

Displacement vectors. Introduce displacement vectors by drawing a motion diagram, and then drawing the vectors spanning successive particle positions. Point out that each vector has both a length (the magnitude of the displacement) and a direction.

Example: Alice is sliding along a smooth, icy road on her sled when she suddenly runs headfirst into a large, very soft snowbank that gradually brings her to a halt. Draw a motion diagram for Alice. Show and label all displacement vectors.
This is a good one to work through the solution with your students:

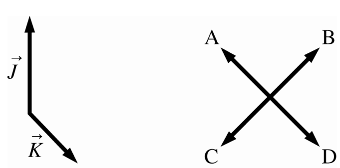


Adding displacement vectors. Sketch out a problem like this: Sam makes a trip in two legs. First, he walks 100 m to the east. Then, he walks 50 m to the north. Draw the two displacement vectors for the legs of this trip. What is his overall, or *net*, displacement? It spans from his initial to final position. So in this sense, we perform *vector addition* in this way, as shown in Tactics Box 1.4:



Example: Jenny runs 1 mi to the northeast, then 1 mi south. Graphically find her net displacement. After an example, you may wish to check student understanding.

Clicker Question: Two vectors $\vec{J}$ and $\vec{K}$ are shown below, each with its tail at the origin. Which of the labeled vectors best represents the sum of the two?



Velocity vectors. Another important vector quantity is velocity. Recall that the displacement vector spans successive positions on a motion diagram. It points from "where you were" to "where you are now"; that is, it points in the direction of motion. But this is the *same* direction as the velocity, so the velocity vector points in the same direction as the displacement vector.

Now the magnitude—graphically, the length—of the velocity vector is the particle's speed. But we learned that speed = distance traveled/time interval. In a motion diagram, the time interval between successive points; is the same for all points, so we see that the speed is proportional to the distance between successive points; that is, it's proportional to the particle's displacement. So the length of the velocity vector is proportional to the length of the displacement vector. It's simplest to make it the *same* length as the displacement vector, meaning that you can draw the velocity vector as also spanning successive particle positions.

Example: Jack throws a ball at a 60° angle, measured from the horizontal. The ball is caught by Jim. Draw a motion diagram of the ball with velocity vectors.

Other Resources

In addition to the specific suggestions made in the daily lecture outlines, each section of this guide will finish with reading quiz questions, additional examples, and other information that you can weave into your class time.

Sample Reading Questions

1. What is the difference between speed and velocity?
   A. Speed is an average quantity while velocity is not.
   B. Velocity contains information about the direction of motion while speed does not.
   C. Speed is measured in mph, while velocity is measured in m/s.
   D. The concept of speed applies only to objects that are neither speeding up nor slowing down, while velocity applies to every kind of motion.
   E. Speed is used to measure how fast an object is moving in a straight line, while velocity is used for objects moving along curved paths.
2. The quantity 2.67×10^3 m/s has how many significant figures?
   A. 1
   B. 2
   C. 3
   D. 4
   E. 5
3. The correct SI units for distance and mass are
   A. Feet, pounds.
   B. Centimeters, grams.
   C. Meters, grams.
   D. Meters, kilograms.
4. If Sam walks 100 m to the right, then 200 m to the left, his net displacement vector
   A. Points to the right.
   B. Points to the left.
   C. Has zero length.
   D. Cannot tell without more information.
5. Velocity vectors point
   A. In the same direction as displacement vectors.
   B. In the opposite direction as displacement vectors.
   C. Perpendicular to displacement vectors.
   D. In the same direction as acceleration vectors.
   E. Velocity is not represented by a vector.