CHAPTER

1

Concepts of Motion

Recommended class days: 3

Introduction and Part I Overview

The book's preface to the student, *From Me to You*, is intended for students to read, and you should list it explicitly on your assignment sheet (because otherwise students *won't* read it), but there's no need to spend class time on it.

Each of the eight parts of the textbook opens with an *Overview* and closes with a hierarchical *Knowledge Structure*. 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*. Many 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) and *why*.

Chapter Previews and Summaries

Each chapter of the book opens with a visual Chapter Preview—a feature that was introduced in the third edition of *Physics for Scientists and Engineers*—and closes with a visual Chapter Summary. It's worthwhile to call students' attention to these in Chapter 1. The previews, a form of what educational theorists call an *advance organizer*, are a cognitive strategy to promote the learning and retention of new information by providing readers with the beginnings of a knowledge structure. A few minutes spent with the preview gives them a framework for sorting and ordering new information as they encounter it in the chapter.

The summaries are not a laundry lists of facts and equations. Instead, each is a structured, hierarchical look back at the chapter. In other words, a "big picture" view that helps students apply their knowledge in new situations. Students cannot skip the chapter and simply use the summary to support an equation-hunting strategy to end-of-chapter homework. Rather, students who have read the chapter will find that the summary gives them the tools to dive into the chapter for the specific information they need to solve a problem.

Background Information

This 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 five chapters are devoted to establishing and clarifying just what we *mean* by the terms *force* and *motion*. As noted in the chapter 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.

Because of the conceptual difficulties students have with force and motion, the author has found it useful to delay the introduction of Newton's third law. Chapters 5 and 6 focus on understanding how a single particle responds to forces. Students learn only the first two of Newton's laws. Chapter 7 then introduces the third law to describe how two particles interact with each other. (The role of interactions is then pursued into the realm of momentum and energy conservation in Part II.) This separation of the second and third laws will be discussed more in Chapter 5. For now, 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:

- 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. Many 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 (see the discussion about vectors in the chapter "Teaching with *Physics for Scientists and Engineers*"). Formal definitions, such as $\vec{v}_{\text{avg}} = \Delta\vec{r}/\Delta t$, are nearly meaningless because most students can't interpret $\Delta\vec{r}$. Velocity and acceleration need to be introduced as *operational definitions*, and students need ample opportunities to apply the operations needed to find $\Delta\vec{r}$ and $\Delta\vec{v}$. This is especially true if the definition $\vec{a}_{\text{avg}} = \Delta\vec{v}/\Delta t$ is to make any sense. Much of this chapter is focused on developing and practicing specific *procedures* for determining velocity and acceleration vectors.

A second issue addressed in this chapter is the development of good problem-solving skills. The chapter 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). This chapter 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

- To understand and use the basic ideas of the *particle model*.
- To analyze the motion of an object by using *motion diagrams* as a tool.
- To differentiate between the concepts of position, velocity, and acceleration.
- To recognize the relationship between $\vec{v}$ and $\vec{a}$ when an object is speeding up, slowing down, or at a turning point.
- To gain initial experience with graphical addition and subtraction of vectors.
- To begin the process of learning to analyze problem statements and to translate the information into other representations.
- To learn about position-versus-time graphs and the sign conventions for one-dimensional motion.
- To understand the proper use of significant figures.

Pedagogical Approach

Rather than a traditional Chapter 1 on units and measurement, *Physics for Scientists and Engineers* dives right into the consideration of motion. The rationale is that students should immediately be aware that physics is about phenomena, not the memorization of facts and formulas. Information about units and measurements is introduced on an "as needed" basis in the chapters to come.

The approach to motion in this chapter—through the use of motion diagrams—is unconventional but straightforward. Students pick up the motion diagram idea quickly, but they need extensive practice before becoming adept at finding acceleration vectors. One difficulty is that students will leap to conclusions, drawing an acceleration vector they are "sure" is right without actually going through the steps of finding the correct vector. This chapter considers only linear acceleration; curvilinear acceleration is introduced in Chapter 4.

Vectors are introduced graphically, and you'll want students to practice doing some basic vector addition and subtraction (illustrated in Tactics Boxes 1.1 and 1.2) 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 is all about vectors—just draw a couple of vectors on the board, label them $\vec{A}$ and $\vec{B}$, then ask students to draw the vector $\vec{A}+\vec{B}$ and the vector $\vec{A}-\vec{B}$.

Note: It's worth explicitly calling students' attention to the Tactics Boxes. These boxes will help them develop specific skills.

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.

A concern to some instructors is that motion-diagram vectors are labeled $\vec{v}$ and $\vec{a}$ whereas all we've really defined are the average velocity $\vec{v}_{\text{avg}}$ and the average acceleration $\vec{a}_{\text{avg}}$. 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. To the contrary, classes using earlier editions of this textbook generated some of the highest-reported scores on both the Force Concept Inventory (conceptual understanding) and the Mechanics Baseline Test (quantitative problem solving).

It is important not to start doing any computations in this chapter. The focus is on identifying velocity and acceleration vectors for different kinds of motion and on starting to introduce different representations of motions. The "problems" in the examples and in the homework are for the purpose of learning to *describe* a problem statement with a pictorial or graphical representation. You should emphasize to students that they are not being asked to *solve* the problems at this time. There is a statement to that effect in the homework, but some students will overlook it and plunge right into half-remembered equations from high school.

A second goal of this chapter is to introduce the idea of *multiple representations of knowledge*. In particular, motion has the following descriptions:

- **Verbal**, as presented in typical end-of-chapter problems.
- **Pictorial**, as shown in motion diagrams, free-body diagrams, and pictures that establish coordinate systems and define symbols.
- **Graphical**, in position-, velocity-, and acceleration-versus-time graphs.
- **Mathematical**, through the relevant equations of kinematics and dynamics.

To acquire an accurate, intuitive sense of motion, students must learn to move back and forth between these different representations. This chapter begins with the verbal, pictorial, and graphical representations. Mathematical representations are added in Chapter 2.

A third goal is to introduce the idea of *models* and *modeling*, a topic with increased emphasis in this edition of *Physics for Scientists and Engineers*. Most real physical systems are extraordinarily complex. There are occasions—climate systems, or designing a jet engine—where all the details are important and an analysis requires complex numerical solutions. But in physics, and especially introductory physics, we strive to simplify situations so that we can use simple mathematics and focus our attention on the underlying physical principles. Models, whether they're constant-acceleration kinematics or simple harmonic motion, are prototypes that we can return to again and again because they're good, albeit not perfect, approximations to a great variety of more complex motions. Beginning students don't recognize the significance of models or know how to make the appropriate simplifications, so this is a topic worth revisiting throughout the first semester each time a new model is introduced.

Finally, this chapter introduces students to the four-part problem-solving strategy that will be used throughout the entire textbook. Students will take this strategy more seriously if they see you using it consistently in class. Although the Solve step won't come into play until Chapter 2, you can begin using the Model, Visualize, and Assess steps right away.

Using Class Time

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 author 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.

Three days may seem excessive for this chapter, but experience shows that it's not. Students have a much harder time visualizing motion and understanding acceleration than you may think. A little extra time spent here, laying the foundations, will pay for itself when we get to the mathematical description of motion.

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 on day 2 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, I put all logistical course information and a day-by-day schedule on a handout for the students. Then, when reviewing my expectations, I tell them that the first reading questions, due before Class 2, will cover both Chapter 1 *and* the handouts!

Although it's hard to have more than half of day 1 to really use, this is enough time to introduce the idea of a motion diagram by asking students to imagine stacking the frames of a video 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 video 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.

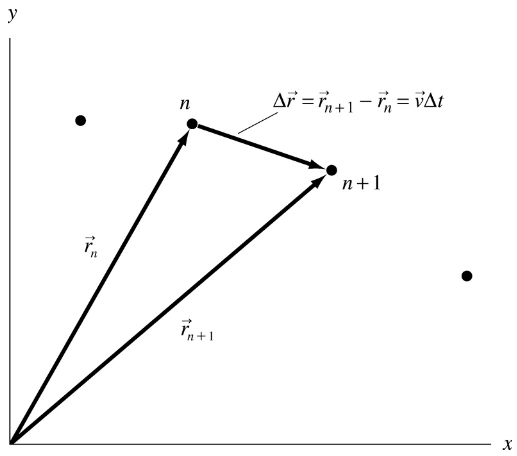
Once the basic idea is clear, have various students demonstrate speeding up, slowing down, or maybe both. To keep these initial motions as simple as possible, identify some points in the room (such as the ends of the lecture table) as being the edges of the camera's field of view. That way a student can speed up across the field of view, but students "won't see" and won't be distracted by his 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). 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 motions carefully, then draw a motion diagram using the particle model. A large strobe lamp, if available, can help clarify how objects move. Otherwise, roll balls down inclines so that they accelerate slowly, toss balls in a high parabolic trajectory so that they visibly slow but don't stop, roll a cart across a table with enough friction that it slows and stops, and so on. (This is a good place for a digression on the "start" and the "end" of the motion.) Ask students to focus on the *shape* of the trajectory and on how the speed changes.

As a lead-in to velocity, draw this figure on the board and ask ● ● ● ● ● students if the object is moving to the right, to the left, or if there's enough information to tell. After they all have agreed that they can't tell, you can introduce the velocity vector to indicate both the speed and direction of the motion. Remind them (they're supposed to have read the text, so don't do any *more* than remind) that velocity is defined as $\vec{v} = \Delta\vec{r}/\Delta t$, but for this to make sense they must be able to interpret $\Delta\vec{r}$.

It's good to give two or three examples of graphical vector addition and subtraction, then go over the diagram at the right. This defines the displacement $\Delta\vec{r}$ and, in the context of motion diagrams where all Δt are the same, shows that the velocity vector $\vec{v} = \Delta\vec{r}/\Delta t$ is directly proportional to $\Delta\vec{r}$. Thus the vector connecting two dots on a motion diagram can be interpreted as the velocity vector between those two frames. The speed part is obvious—dots further apart represent faster motion—but the concept of velocity also includes directional information. Students pick this up quickly, and you can return to a couple of earlier examples (balls on inclines, projectiles, etc.) to show the velocity vectors on the motion diagrams.



Note: It's worth commenting on the idea of an *operational definition*. You're defining $\vec{v}$ in terms of specific operations used to determine $\vec{v}$.

If you ask whether the velocity can change during motion, most students will only think of speed changes for one-dimensional motion. Note that this is correct, and draw the velocity vectors of something like an accelerating car, but then ask them to draw a bird's-eye view of a car going around a highway curve at constant speed. Thus there are two ways—speed or direction—in which the velocity can change. This chapter focuses only on change of speed—linear acceleration. We'll return to change of direction in Chapter 4.

The definition of acceleration, $\vec{a} = \Delta\vec{v}/\Delta t$, is designed to parallel the definition of velocity. All well and good, but they need to know two things. First, acceleration is the basic quantity we will need to relate force and motion. Second, visualizing and understanding acceleration *is* rather hard, but that's why we've been developing the motion diagram tool. Acceleration is another operational definition, and you can use motion diagrams to determine the acceleration by going through a sequence of steps to find $\Delta\vec{v}$.

Start with examples similar to Tactics Box 1.3 or the insets in Figure 1.15 that use just three points in a motion diagram. Note that three points (three frames of the motion diagram) yield two velocity vectors and just a single acceleration vector, so $\vec{a}$ goes at the midpoint of the three. Use three-point examples that show speeding up and slowing down. Even in a large class, you can draw the three points (number them so the time-sequence is clear), then have students determine $\vec{a}$ and compare their answer with a neighbor. Stick to one-dimensional examples of speeding up and slowing down (curved motion is in Chapter 4) and emphasize the direction $\vec{a}$ points since this will be important in the sign conventions for a_x and a_y.

Day 3: To start, ask for a complete motion diagram for some motion that you can demonstrate in class. Hopefully, students will have practiced these ideas in the *Student Workbook* and can do this fairly quickly and accurately.

Now is a good time to consider the acceleration at a turning point. If possible, demonstrate a turning point using *horizontal* motion. Push a fan cart away from you that rolls some distance, then reverses and rolls back. Or use a cart connected via string and pulley to a hanging mass; push the cart so that it rolls away (lifting the mass), then reverses and rolls back. Ask for a motion diagram from the time you release the cart until it returns, but don't initially call attention to the turning point. Students should have seen textbook examples where the return path of the motion diagram is displaced sideways, for clarity, but you might want to call this to their attention. After seeing their responses, you can home in on the question of the velocity and acceleration at the turning point. Even with the motion diagram construction, many students are reluctant to believe there is an acceleration at the turning point. So be prepared with verbal arguments as well, such as "How would it get away from the turning point if $\vec{v}$ and $\vec{a}$ were both zero?" If time permits, you can follow up with the motion of a ball that rolls up and down an incline, then a ball tossed straight upward.

A three-day presentation of this chapter will leave very little time to introduce position-versus-time graphs, the pictorial representation, or the basic problem-solving strategy on p. 21. Fortunately, students can pick this up fairly well from the text, and you can reinforce these ideas when you get to serious problem solving in Chapter 2. Nonetheless, you should try to get in one example of a position graph and one of analyzing a problem statement with a pictorial representation. A three-and-a-half or four-day presentation will allow you to do several problem-statement analyses, including additional motion diagram and graphing practice.

Class examples of a problem-statement analysis should be very simple, such as "Jane slams on her brakes while driving 30 mph and skids to a halt in 60 feet. How long does it take her to come to a stop?" The initial emphasis is on learning the proper way to draw a pictorial representation. It is important for students to be aware that they are to sketch the object *only* at the beginning and the end of the motion, as well as at points where the nature of the motion changes, because those are the points in the motion to which we're going to assign symbols. Some students have a hard time distinguishing between the motion diagram, which shows the object at many positions, and the pictorial representation, which shows the object only at a few critical positions.

The discussion of significant figures is best assigned for reading. You can talk about and demonstrate significant figures while solving example problems in Chapter 2; a lecture on significant figures has little demonstrable value. Don't overemphasize significant figures. This textbook generally uses 2 or 3, depending on the context. It's important to learn that 1 is too few (except for rough estimates) and 5 or more is too many. Otherwise, being overly pedantic on significant figures gets in the way of more important things students should be focusing on.

Sample Exam Questions

Sample exam questions for Chapters 1–2 are at the end of Chapter 2.