2 Motion in One Dimension

Recommended class days: 3

> *Of all the intellectual hurdles which the human mind has confronted and has overcome in the last fifteen hundred years, the one which seems to me to have been the most amazing in character and the most stupendous in the scope of its consequences is the one relating to the problem of motion.*
>
> Herbert Butterfield—*The Origins of Modern Science*

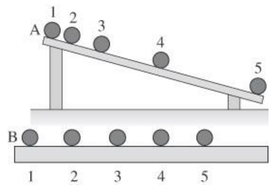
Background Information

For students, Chapter 2 is a large and difficult chapter. Although to physicists the chapter says little more than $v = \Delta x/\Delta t$ and $a = \Delta v/\Delta t$, these are symbolic expressions for difficult, abstract concepts. Student ideas about force and motion are largely non-Newtonian, and they cannot begin to grasp Newton's laws without first coming to a better conceptual understanding of motion.

As Butterfield notes in the above quote, the "problem of motion" was an immense intellectual hurdle. Galileo was perhaps the first to understand what it means to *quantify* observations about nature and to apply mathematical analysis to those observations. He was also the first to recognize the need to separate the *how* of motion—kinematics—from the *why* of motion—dynamics. These are very difficult ideas, and we should not be surprised that kinematics is also an immense intellectual hurdle for students.

Student difficulties with kinematics have been well researched (Trowbridge and McDermott, 1980 and 1981; Rosenquist and McDermott, 1987; McDermott et al., 1987,; Thornton and Sokoloff, 1990). Arons (1990) gives an excellent summary and makes many useful suggestions for teaching kinematics. Student difficulties can be placed in a few general categories, presented belowin the following paragraphs, along with suggestions for dealing with such difficulties.

Difficulties with concepts: Students have a rather undifferentiated view of motion, without clear distinctions between position, velocity, and acceleration. Chapter 1 gives them a start at making these distinctions, but they'll need additional practice.



Here's an example of the type of difficulty students experience. In one study, illustrated in the previous figure ~~above~~, students were shown a diagram illustrating the motion of two balls on two separate tracks. Ball A is released from rest and rolls down an incline while ball B rolls horizontally at constant speed. Ball B overtakes ball A near the beginning, as the motion diagram shows, but later ball A overtakes ball B. Students were asked to identify the time or times (if any) at which the two balls have the same speed. Prior to instruction, roughly half the students in a calculus-based physics class identified frames 2 and 4, when the balls have equal *positions*, as being times when they ~~have~~ have equal *speeds*.

Similarly, students often identify situations in which two objects have the same *speed* as indicating that the objects have the same *acceleration.* Confusion of velocity and acceleration is particularly pronounced at a turning point, where a majority of students think that the acceleration is zero. McDermott and her co-workers found that roughly 80% of students beginning calculus-based physics make errors when asked to identify or compare accelerations, and that the error rate was still roughly 60% after conventional instruction. Thornton and Sokoloff (1990) report very similar pre-instruction and post-instruction error rates for students' abilities to interpret acceleration graphically.

In addition~~:~~

- ~~Students~~ students have a very difficult time with the idea of *instantaneous* quantities.
- ~~Students~~ students are often confused by the significance of positive and negative signs, especially for velocity and acceleration. Many students interpret positive and negative accelerations as *always* meaning that the object is speeding up or slowing down. This seems to be an especially difficult idea to change.

Difficulties with graphs: Nearly all students can graph a set of data or can read a value from a graph. Their difficulties are with *interpreting* information presented graphically. In particular~~:~~

- ~~Many~~ many students don't know the meaning of "Graph *a*-versus-*b*." They graph the first quantity on the horizontal axis, ending up with the two axes reversed.

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- ~~Many~~ many students think that the slope of a straight-line graph is found from y/x (using any point on the graph) rather than $\Delta y / \Delta x$.
- ~~Students~~ students don't recognize that a slope has *units* or how to determine those units.
- ~~Many~~ many students don't understand the idea of the "slope at a point" on a curvilinear graph. They cannot readily compare the slopes at different points.
- ~~Very~~ very few students are familiar with the idea of "area under a curve." Even students who have already studied calculus, and who "know" that an integral can be understood as an area, have little or no idea how to use this information if presented with an actual curve.
- ~~Many~~ many students interpret "slope of a curve" or "area under a curve" literally, as the graph is drawn, rather than with reference to the scales and units along the axes. To them, a line drawn at 45° *always* has a slope of 1 (no units), and they may answer an area-under-the-curve question with "about three square inches."
- ~~Students~~ students don't recognize that an "area under the curve" has *units* or how the units of an "area" can be something other than area units. We tell them, "Distance traveled is the area under the *v*-versus-*t* curve." But distance is a length? How can a length equal an area?

It is ~~be~~ worthwhile to give students practice drawing and interpreting graphs. These are skills that are best learned by practice followed by feedback. The *Student Workbook* has many exercises you can use for such practice. For large lecture courses, this type of exercise is a natural fit for a recitation section, but it could be done during lecture, for instance as "clicker questions," either those suggested below or based on exercises in the Workbook.

Difficulties relating graphs to motion: Nearly all students have a very difficult time relating the *physical ideas* of motion to a *graphical representation* of motion. If students observe a motion—a ball rolling down an incline, for example—and are then asked to draw an *x*-versus-*t* graph, many will draw a *picture* of the motion as they saw it. Confusion between graphs and pictures underlies many of the difficulties of relating graphs to motion. Experience has shown that learning how to graph motion is a good way for students to develop conceptual understanding of motion. For this reason, Chapter 2 places special stress on the graphical interpretation of motion, and the second edition has added problems that require students to draw and interpret graphs.

Part of the difficulty with student comprehension is that we often measure position along a *horizontal* axis but graph the position on a *vertical* axis. This choice is never explained~~,~~ because it

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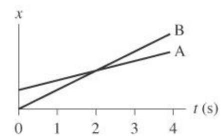
seems obvious to physicists, but it's a confusing issue for students who aren't sure what a function is or how graphs are interpreted.



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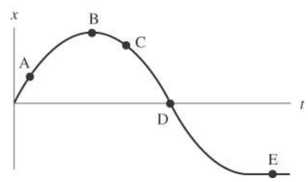
Confusion between position and velocity, and difficulty interpreting slopes, can be illustrated with a simple example. The previous graph ~~above~~ shows the motion of two objects A and B. Students are asked: Do A and B ever have the same speed? If so, at what time? A significant fraction will answer that A and B have the same speed at $t = 2$ s, confusing a common height with common slope.



Clearing up this confusion takes practice. One of the "clicker" questions presented in the lecture plans ~~below~~ uses the ~~above~~ previous position-versus-time graph. If students are asked at which lettered point or points the object is moving fastest, at rest, slowing down, etc., they initially have difficulty. But you'll find that most students can master questions similar to these with a small amount of instruction
and practice.

A much more difficult problem for most students, and one that takes more practice, is changing representations from one type of graph to another. For example, students might be given the following *x*-versus-*t* graph shown ~~below~~ on the left and asked to draw the corresponding v_x-versus-*t* graph. When first presented with such a problem, almost no students can generate the correct velocity graph shown on the right. Many feel that a "conservation of shape" law applies and redraw the position graph—perhaps translated up or down—as a velocity graph. They need a careful explanation, through several examples, of how the *slope* of the position graph becomes the *value* of the velocity graph at the same *t*. Changing from a velocity graph back to a position graph is even more difficult—which is why Chapter 2 spends a good deal of time explaining how to perform such translations.

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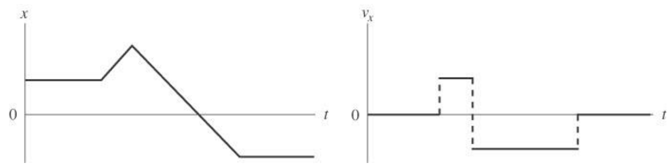

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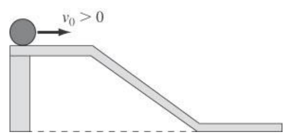
To tie all aspects of a student's understanding of kinematics together, McDermott and her group presented students with situations of a ball rolling along a series of level and inclined tracks, for instance the following graph ~~below.~~:



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The students were then asked to draw *x*-versus-*t*, v_x-versus-t, and a_x-versus-t graphs of the motion, with the graphs stacked vertically so that a vertical line connected equal values of *t* on each of the three graphs. Students in a conventional physics class were presented—*after kinematics instruction*—with the simple track shown in the figure. Only 1 student of 118 gave a completely correct response. Many students draw wildly incorrect graphs for questions like these, indicating an inability to translate from a visualization of the motion to a graphical description of the motion.

Difficulties with terminology: Arons (1990) has written about student difficulties with the term *per*. Many students have difficulty giving a verbal explanation of what "20 meters per second" *means*—especially for an instantaneous velocity that is only "20 meters per second" for "an instant." Students will often say things such as "acceleration is delta *v* over delta *t*," but they frequently *don't* use the word "over" in the sense of a ratio but rather to mean "during the interval." This term is dealt with explicitly in the text, part of our general approach to make the implicit assumptions made by physicists explicit for students studying this material for the first time.

Another difficult terminology issue for students is our use of the words *initial* and *final*. Sometimes we use *initial* to mean the initial conditions with which a problem starts, and *final* refers to the end of the problem. But then we use $\Delta x = x_{\text{final}} - x_{\text{initial}}$ and $\Delta v = v_{\text{final}} - v_{\text{initial}}$ when we're looking at how position and velocity change over *small* intervals Δt. Students often don't recognize the distinction between these uses.

Finally, students often don't make the same *assumptions* we do about the beginning and ending points of a problem. We interpret "Bob throws a ball at 20 m/s …" as a problem that starts with Bob releasing the ball. Students often want to include his throw as part of the problem. Similarly, a question to "find the final speed of a ball dropped from a height of 10 m" will get many answers of "zero," because that really is the *final* speed. These are not insurmountable issues, but you need to be aware that students don't always interpret a problem statement as a physicist would, and address these assumptions in lecture.

Difficulties with mathematics: Many students are not sure what a *function* is. They don't really understand the notation $x(t)$ or our discussion of "position as a function of time." A significant fraction of students interpret $x(t)$ as meaning *x times t*, as it would in an expression such as $a(b+c)$. Instructors need to give explicit attention to this issue.

Students are easily confused with changes in notation. Math courses tend to work with functions $y(x)$, with x the independent variable. In physics, we use functions $x(t)$, with x the dependent variable. Despite how trivial this seems, instructors should be aware that many students are confused by the different notation and need assistance with this.

Student Learning Objectives

In covering the material of this chapter, students will learn to

- ~~Begin~~ begin describing problems in many different representations: ~~Graphical~~graphical, pictorial, mathematical.
- ~~Develop~~ develop their understanding of the kinematic variables position, velocity, and acceleration.
- ~~Solve~~ solve basic problems of motion in one dimension, including objects falling under the influence of gravity.

Pedagogical Approach

This chapter treats one-dimensional motion only. Although the basic kinematic quantities x, v_x, and a_x (or y, v_y, and a_y) are components of vectors, a full discussion of vectors is not needed for one-dimensional motion, and we do not discuss these quantities using the term "component." The major issue is whether each of these quantities is positive or negative, and that only depends on the direction

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along the axis. This is easily determined with a motion diagram. Students will need practice associating a verbal description of the motion with the proper signs, especially for acceleration.

Note: In this textbook, $v = |\vec{v}|$ is the magnitude of the velocity vector, or speed, and $a = |\vec{a}|$ is the magnitude of the acceleration. Components of vectors, such as v_x or a_y, always use explicit *x*- and *y*-subscripts. It can seem cumbersome, but it is important to use this full notation, including subscripts, otherwise students will be confused by the (admittedly rather common) practice in one-dimensional motion of using *v* both for velocity (a signed quantity) and for speed.

This chapter aims to provide the conceptual foundations of kinematics, but also to help students develop a systematic approach to analyzing problems. As we experienced problem solvers know, you don't start solving a problem by putting numbers in an equation; more often than not, you start by drawing a picture. To this end, the text emphasizes *multiple representations of knowledge.* In particular, motion has the following descriptions:

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- **Verbal**, as presented in typical end-of-chapter problems.
- **Diagrammatic**, with position, velocity, and acceleration shown in a motion diagram.
- **Pictorial**, showing beginning and ending points as well as coordinates and symbols.
- **Graphical**, as shown in position-, velocity-, and acceleration-versus-time graphs.
- **Mathematical**, through the relevant equations of kinematics.

To acquire an accurate, intuitive sense of motion, students must learn to move back and forth between these different representations. Diagrams, pictures, and graphs are especially stressed. The number and variety of representations that are used in the textbook examples are certainly more than students will use in doing their homework assignments, but if we can get them to slow down and draw some sort of representation—a graph, a pictorial representation, a diagram—before simply plugging numbers into an equation, even for the somewhat simple problems of this chapter, this discipline will serve them well in the chapters to come.

Much of this chapter is focused on learning the different representations of kinematic knowledge. The connection between motion diagrams and graphs is strongly emphasized. Students learned a bit about motion diagrams in Chapter 1, and they should now be able to draw a correct motion diagram for nearly any one-dimensional motion. This is a good intermediate stage in the process of interpreting a verbal description of motion. Students can see where velocities are big or small and where the motion speeds up or slows down. As they proceed into the less familiar territory of drawing graphs, you can keep calling their attention to whether or not the graph is consistent with the motion diagram. This approach is particularly useful for establishing correct signs.

The ultimate goal, of course, is for students to be able to work kinematics problems. But, more than this, paying so much attention to techniques of representing and solving problems in the rather straightforward area of kinematics will help students develop good habits that will help them as the material of the course becomes more complex. There is good evidence that initial attention to these issues leads students to become *better* problem solvers—not just for kinematics, but generally.

Suggested Lecture Outlines

Chapters 1, 2 and 3 make a continuous sequence that introduces not only basic physics concepts but also techniques and tools that the students will use for the rest of the course. Chapters 1 and 2 are very closely linked; some instructors may choose to treat the two as a unit, beginning by talking about motion in some detail, while introducing the less interesting (but no less important!) concepts of units and significant figures along the way.

Chapter 2 introduces the first Problem-Solving Strategy in the book. This book has a strong emphasis on teaching problem-solving skills, and Chapter 2 is the right place to introduce the first such strategy. Chapter 2 moves more slowly through basic one-dimensional kinematics than some books because we make a significant effort to stress the different ways that we expect students to represent and solve problems. We include extensive instruction in problem-solving strategies in this relatively straightforward section~~,~~ so that students will have some well-developed skills when they begin to hit material t~~which ~~hat is more conceptually challenging. We suggest a similar approach in your lectures.

If you take the time to introduce techniques of problem solving and kinematics in sufficient detail, you will likely find that you need the full three days we suggest for this chapter. If this is too much for your schedule, you might try combining Chapters 1 and 2 (as previously suggested~~ above~~), which could provide some efficiencies.

In teaching from this book, we will often suggest using the third of three days on a topic for applications and extensions. In this chapter, we suggest Day 3 as the day to discuss free fall—a great topic for applying the general material of the first part of the chapter to a specific, new type of problem. It's a chance to teach about free fall, but also a chance to review all of the concepts the students will have learned to this point.

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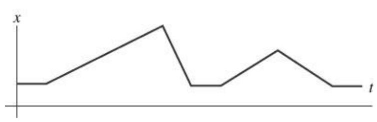
DAY 1: Basic concepts of one-dimensional motion. The best and the worst thing about teaching kinematics is that students already "know" a good deal about the subject. You can draw on their prior knowledge and experience, for it is extensive. But they will have many misconceptions. These misconceptions are based on years of experience, so they can be quite hard to change. Throughout your treatment of this material, but especially on the first day or two, it's worthwhile to ask many questions of the class~~,~~ to draw on and assess their prior knowledge. One possibility is to begin with a question that leads to ~~into~~ a class discussion.

Class Question: Which is faster, a man or a horse?

This is a question that is raised at the start of the chapter, and it's a good one for spurring a discussion that gives you insight into what your students know. It's also a good way to show that we have to be careful about the words we use and how we define them. What do we mean by "faster"? Higher average speed? Higher maximum speed? Quicker response time? Greater acceleration? Depending on which measure you choose, either the man or the horse might be ~~the~~ faster.

This is a good time to review the definitions of basic kinematic variables. A good way to start is with a demonstration, a classic activity in which a student is asked to move in a manner that matches a certain graph. This also works very well as a lab activity. The easiest way to do this is to use a computer, interface, and motion detector—all of which are becoming ubiquitous in physics instructional labs these days.

Demonstration: Distance Matching. A student walks back and forth in front of a motion detector, attempting to match a particular graph, like the following one ~~below~~. This is a nice graph because it has regions of constant—but very different—velocity.

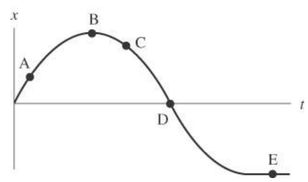


Have a student try this once, then have him or her discuss how he or she could do better. Then, have him or her try the motion one more time, or perhaps a third time—until a good match is obtained. After the student has made a reasonable attempt, have the student describe the motion~~,~~ in words—a different representation.

Most students can do pretty well matching a graph on the second try ~~after a practice run~~, and this is a good way to bring out the notions about kinematics that students already have. Most students have an intuitive sense that the speed is the slope of the distance-versus-time graph. After a trial run, they will move faster when the slope is greater. They also have a sense for the difference between positive and negative slopes; they will generally move in the correct direction. They almost always understand that zero slope corresponds to zero velocity, and will stand still. This will likely come out in discussion following this demonstration, and it is a good way to introduce these notions in a very natural way.

After this introductory exercise, it's useful to give the students a chance to practice—and you a chance to assess their understanding. You could start with one of the graphs noted in the background information section.~~:~~

Clicker Question: A car moves along a straight stretch of road. The following graph ~~below~~ shows the car's position as a function of time:~~.~~



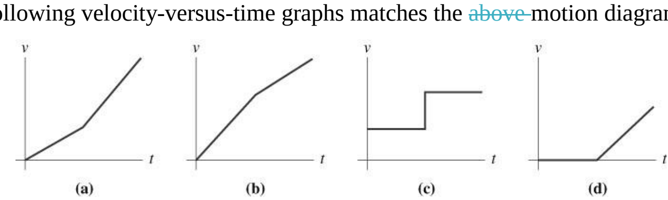
At what point (or points) do the following conditions apply?

- ___The displacement is zero
- ___The speed is zero
- ___The speed is increasing
- ___The speed is decreasing

After this, it's worthwhile to continue with questions involving connections between different representations. As with all of the clicker questions presented in this guide, however you present them—using a response system or not—it is important that students are active, that they work the problems themselves. Don't simply discuss the solution.

Clicker Question: Here is a motion diagram of a car moving along a straight stretch of road:~~.~~

Which of the following velocity-versus-time graphs matches the ~~above~~ motion diagram?



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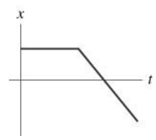
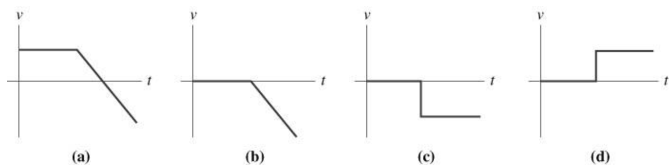
Another element stressed in the chapter is the connection between position graphs and velocity graphs. How to convert between the two is a topic worthy of some class discussion. Here are some clicker questions that you can use to assess student understanding before or after you discuss this topic:

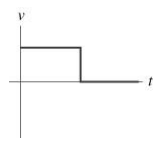
Clicker Question: A graph of position versus time for a basketball player moving down the court appears as follows:



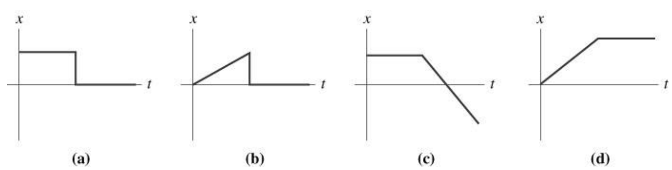
Which of the following velocity graphs matches the ~~above~~ position graph?



Clicker Question: A graph of velocity versus time for a hockey puck shot into a goal appears as follows:



Which of the following position graphs matches the ~~above~~ velocity graph?



Questions like those ~~above~~ just asked might well reveal some of the finer points of kinematics that your students don't understand, like those mentioned ~~in the above sections~~previously. It is worthwhile to ~~do~~ ask further questions and perform demonstrations, basing your choices on the understanding that your students have, and what points are still troubling for them.

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After this, it's time for some straight lecture—presenting definitions and equations~~,~~ to solidify the lessons of the active learning that just took place. Once you have these details in place, you can begin to solve problems.

Students like to think that solving a physics problem means picking the right equation and plugging in numbers. Much of what we need to do in the introductory course is to convince students that they need to take a more thoughtful approach to problem solving. At this point, it's time to introduce an equation and use it to solve a problem. But the problem should be solved carefully and fully, drawing a graph, reasoning from the graph, using the equation, and then assessing the final result. It's time to start using the Prepare-Solve-Assess sequence for solving problems in earnest.

Go over the full problem-solving strategy, the different steps, and why they are important, then use it to solve a problem. (Note that this is a bit earlier than the problem-solving strategy is introduced in the book, but this is a natural time for it in your classroom presentation.)

Introduce the basic equation for one-dimensional motion at constant velocity:

$$v_x = \frac{\Delta x}{\Delta t} = \text{constant}, \ \Delta x = v_x \Delta t$$

then use this equation to solve a problem fully, without diving right into the "solve" step. Here is an example that has a good level of detail. It's simple, but including ~~a~~ visual elements—such as a pictorial representation and a graph—make the solution much more straightforward.

Example: A soccer player is 15 m from her opponent's goal. She kicks the ball hard; after 0.50 s, it flies past a defender who stands 5 m away, and continues toward the goal. How much time does the goalie have to move into position to block the kick from the moment the ball leaves the kicker's foot?

If there is time, you may wish to do another example or two illustrating the problem-solving strategy, but you might well find that this day, spent in discussion and development of basic concepts, is already quite full.

DAY 2: Motion with Changing Velocity. Once we introduce changing velocity, we have the possibility to solve much more interesting problems, but be aware that the concept of acceleration causes students a good deal of confusion. Another key concept for Day 2 is the difference between average velocity and instantaneous velocity—another potentially confusing topic.

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Start with a discussion of the difference between average and instantaneous speed, something of which the students will already have a good conceptual grasp ~~of~~. One possibility is to start with a class discussion.

Discussion Question: A man drives the 60 miles from Omaha to Lincoln, Nebraska, in exactly ~~one~~ 1 hour. Later, he gets a ticket in the mail from a speed camera that shows his car clocked at 75 mph, over the limit. He protests, arguing that because it took him one hour to cover the 60 miles, ~~he~~ his speed was exactly 60 mph, no more. Does he have a case?

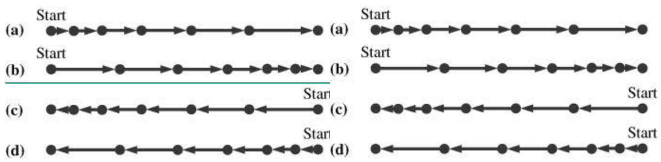
This quickly brings up the distinction between average and instantaneous speed. Your students already have some understanding of the difference. They know that their speedometer (and speed cameras!) measure instantaneous speed, and they also have some sense of average speed. But their notions are a bit hazy, and require some clarification.

Next, you can discuss how you measure an “instantaneous” speed. Students likely know that the speed is computed as a displacement divided by a time interval, and that, if the time interval is short, the speed is “instantaneous.” You can also bring up how we get instantaneous velocity from a graph. Students know that the slope of a distance-versus-time graph is a velocity, so a graph with a changing slope means motion with changing velocity. Show a graph of such a motion (the chapter uses data for a drag racer) and discuss the details.

Next, bring up the concept of acceleration, and what it means. You should stress the meaning of the units; we are fond of writing m/s^2, but you should remind students that this is shorthand for “meters per second per second”—and remind them of the meaning of “per” in this context. A practical example of this helps as well. The car data presented in the chapter works well for this. The Porsche, which accelerates at $7.5\ \text{m/s}^2$, moves at $0\ \text{m/s}$ at $t = 0\ \text{s}$, $7.5\ \text{m/s}$ at $t = 1\ \text{s}$, and so on.

It is worth spending some time clarifying the different signs of acceleration and velocity. As noted above, students generally think of acceleration as “speeding up”~~;~~” the idea that, for an object moving with a negative velocity, a reduction in speed could correspond to a positive acceleration is very confusing, and worth some elaboration. Here are some clicker questions that can help spur such discussion.

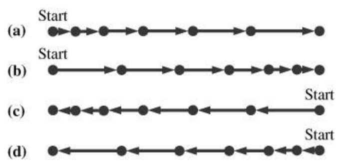
Clicker Question: These four motion diagrams show the motion of a particle along the *x*-axis. Rank these motion diagrams by the magnitude of the acceleration. There may be ties.



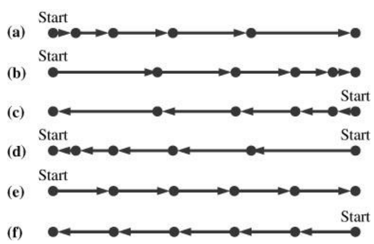
Clicker Question: These four motion diagrams show the motion of a particle along the *x*-axis.

A. Which motion diagrams correspond to a positive acceleration?

B. Which motion diagrams correspond to a negative acceleration?

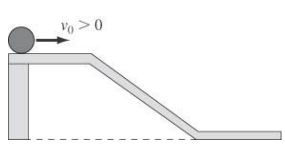


Clicker Question: These six motion diagrams show the motion of a particle along the *x*-axis. Rank the accelerations corresponding to these motion diagrams, from most positive to most negative. There may be ties.



Next, it's time to return to the idea of graphs, with graphs involving changing velocities. Acceleration is the slope of the velocity-versus-time graph, a direct analogy to velocity being the slope of the position-versus-time graph. The "ball on a ramp" example from the background information section makes a good way to introduce these ideas.

Example: A ball moving to the right traverses the ramp shown below. Sketch a graph of the velocity versus time, and, directly below it, using the same scale for the time axis, sketch a graph of the acceleration versus time.



After a thorough discussion of these concepts and representations, you can introduce the equations for motion in one dimension. After introducing these equations, you can do some real, significant problems.

Before ~~-~~you dig into more quantitative problems, remind the students of the most crucial step of the problem-solving strategy: drawing a picture. Not just any picture, of course; Tactics Box 2.2 describes how to draw a pictorial representation. After this, the book then goes on to discuss the full visual overview that should accompany any problem.

We picked the name “visual overview” to stress that students should be drawing pictures: motion diagrams, pictorial representations, graphs.... The act of setting up the visual overview is the most important part of solving a problem, as we repeatedly stress. In future chapters, the visual overview will grow more complex~~,~~ with the addition of force-identification diagrams and free-body diagrams. But even for such simple problems as we consider in Chapter 2, the visual overview is a very key element.

Start with a relatively straightforward example for which you can illustrate the process of translating from words to pictures (explicitly noting the assumptions that you make) and then from pictures to equations that ~~which~~ can then be solved. In the following example~~,~~ you’ll want to pay particular attention to what is the start and the end of the problem.

Example: Tennis balls are tested by measuring their bounce when dropped from a height of approximately 2.5 m. What is the final speed of a ball dropped from this height?

After this, we suggest that you do some more complex examples for which the different pieces of the visual overview give crucial information that help to solve the problem so that creating the visual overview doesn’t seem like an empty exercise. Here are two context-rich examples related to text material that are much more easily solved if the elements of the visual overview are present.

Example: A train is approaching a town at a constant speed of 12 m/s. The town is 1.0 km distant. After 30 seconds, the conductor applies the brakes. What acceleration is necessary to bring the train to rest exactly at the edge of town?

A pictorial representation and a velocity graph are a great help in working out the solution to this example. For even more complex examples, the graphs are even more important.

Example: The chapter begins and ends with a discussion of the possible outcome of a race between a human and a horse. In fact, there have been some well publicized sprints between football players and horses carrying jockeys. In order to render the contest more sporting, the human is given a head start. We can make a rough model of a short sprint as a period of constant acceleration followed by a period of

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Formatted: Font: Times New Roman, Not Bold, Font color: Black constant speed. In this model, a very good human sprinter can accelerate at 12 m/s^2 for 1.0 s; a horse can accelerate at 6.0 m/s^2 for 4.0 s. Suppose a man and a horse of these abilities are competing in a race of 400 m; how much of a head start would the man need in order to just tie the horse?

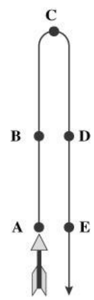
DAY 3: Free Fall. The new problem-solving concepts and techniques introduced are worthy of more discussion. Visualizing problems with motion diagrams, pictorial representations, and graphs is something new, even for students who have ~~had~~ taken physics courses before. As you know, and as we discussed ~~above~~previously, students will want to glean numbers from the statement of a problem, find an equation, and start plugging and chugging. We are trying to teach them new habits that will serve them well in future chapters, and doing some examples in great detail is a good way to ~~do~~ accomplish this.

For this reason, we suggest spending Day 3 on the topic of free fall. Free fall is a short section in the book, about four pages. But it's a great topic to use as a springboard for solving problems, and that's what most of Day 3 should be spent doing: solving problems with full visual overviews, following the problem-solving strategies of the chapter.

First, start with an overview of the concept of free fall. This is easy to state: All objects~~,~~ moving under the influence of gravity and no other forces~~,~~ accelerate at $\vec{a}_{\text{free fall}} = (9.8\text{ m/s}^2,\text{ downward})$. But students have some difficulties applying this concept in practice, and their difficulties are a result of their underlying confusion about motion, their tendency to confuse velocity and acceleration.

With this in mind, it's worthwhile to have some clicker questions that test their understanding of free fall. After each question, take some time for discussion of the answers; the "wrong" answers that students choose provide excellent insight as to the misconceptions that students harbor.

Clicker Question: An arrow is launched vertically upward. It moves straight up to a maximum height, then falls to the ground. The trajectory of the arrow is noted. At which point of the trajectory is the arrow's acceleration the greatest? The least? Ignore air resistance; the only force acting is gravity.



Clicker Question: An arrow is launched vertically upward. It moves straight up to a maximum height, then falls to the ground. The trajectory of the arrow is noted. Which graph best represents the vertical velocity of the arrow as a function of time? Ignore air resistance; the only force acting is gravity.

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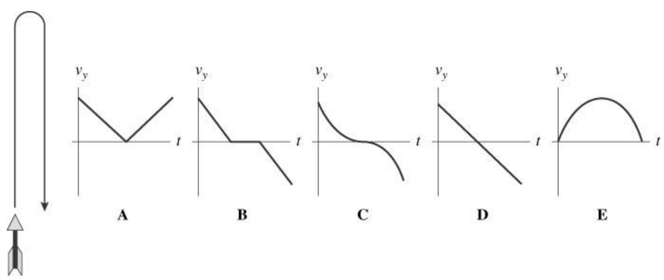

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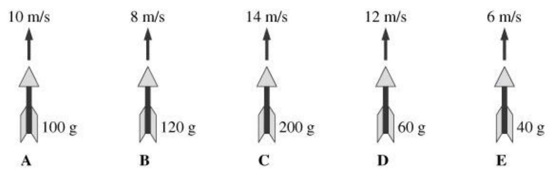
Clicker Question: The following figure below shows five arrows with differing masses that were launched straight up with the noted speeds. Rank the arrows, from greatest to least, on the basis of the maximum height the arrows reach. Ignore air resistance; the only force acting is gravity.



After clarifying the important elements of the basic physics, the rest of the day should be spent on free-fall examples that give you an opportunity to illustrate the problem-solving strategies and the creation of a full visual overview. Here are some examples using realistic numbers and real situations that you can adapt for your class.

Example: Spud Webb, height 5'7", was one of the shortest basketball players in the NBA. But he had an impressive vertical leap: He was reputedly able to jump 110 cm off the ground. To jump this high, with what speed would he leave the ground?

Example: A football is punted straight up into the air; it hits the ground 5.2 s later. What was the greatest height reached by the ball? With what speed did it leave the kicker's foot?

Example: Passengers on ~~The~~ the Giant Drop, a free-fall ride at Six Flags Great America, sit in cars that are raised to the top of a tower. The cars are then released for 2.6 s of free fall. How fast are the passengers moving at the end of this speeding up phase of the ride? If the cars in which they ride then come to rest in a time of 1.0 s, what is the acceleration (magnitude and direction) of this slowing down phase of the ride? Given these numbers, what is the minimum possible height of the tower?

Example: A pole vaulter is nearly motionless as he clears the bar~~,~~ set 5.2 m above the ground. He then falls onto a thick pad. The top of the pad is 75 cm above the ground; it compresses by 50 cm as ~~he~~ the pole vaulter comes to rest. What is his acceleration as he comes to rest on the pad?

Other Resources

In addition to the specific suggestions made above in the daily lecture outlines, here are some other suggestions for demonstrations, examples, questions, and additional topics that you could weave into your class time.

Suggested Demonstrations

In addition to the motion exercises noted above, there are some other good demonstrations that can be done for this material, though not as many as in other chapters. Here are some of our favorites:

Free fall, Part I. Aristotle's concept of natural motion was that all objects would return to their natural positions on the earth. Heavier objects would have a greater impetus to do this, and so would fall faster: If you drop two objects, one with twice the mass of the other, the object that is twice as heavy should reach the ground in half the time. Jump off a chair, dropping a ~~US~~ nickel at the same time. You will take about 0.3 s to reach the ground. To Aristotle's way of thinking, the 5 g nickel, with about 1/10,000 of your mass, should take 10,000 times longer to hit the ground—3000 s, or the length of a 50-minute lecture. The nickel hits the ground a bit sooner than this, making a nice jumping~~-~~off point for discussing how free fall really works.

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Free fall, Part II. If you take a long string and tie nuts or bolts to it with the right increasing separation, when the string is dropped~~,~~ the collisions of the metal pieces with the floor will make a series of sounds that are evenly spaced. Humans are good at detecting such equal spacing, so this can be a dramatic way to show the acceleration of gravity.

Catch me if you can. There are many movies that involve free fall, usually in a way that isn't physically correct. A clip from such a movie can be a good way to set up a problem. For instance, in *Superman II,* a boy falls over the edge of Niagara Falls, height 51 m. Clark Kent notes ~~his~~ the boy's plight, looks for a place to change, changes clothes, and flies to save him. This all takes about 30 s. You can show this clip and then ask your students to calculate either 1) how far the boy would fall during this time, ignoring air resistance, or 2) how long Superman would actually have to come to his aid.

Sample Reading Quiz Questions

1. The slope at a point on a position-versus-time graph of an object is the
   ~~A~~a. ~~the~~ object's speed at that point.
   ~~B~~b. ~~the~~ object's average velocity at that point.
   ~~C~~c. ~~the~~ object's instantaneous velocity at that point.
   ~~D~~d. ~~the~~ object's acceleration at that point.
   ~~E~~e. ~~the~~ distance traveled by the object to that point.
2. The area under a velocity-versus-time graph of an object is
   ~~A~~a. the object's speed at that point.
   ~~B~~b. the object's acceleration at that point.
   ~~C~~c. the distance traveled by the object.
   ~~D~~d. the displacement of the object.
   ~~E~~e. This topic was not covered in this chapter.
3. A 1-pound ball and a 100-pound ball are dropped from a height of 10 feet at the same time. In the absence of air resistance
   ~~A~~a. the 1-pound ball wins the race.
   ~~B~~b. the 100-pound ball wins the race.
   ~~C~~c. the two balls end in a tie.

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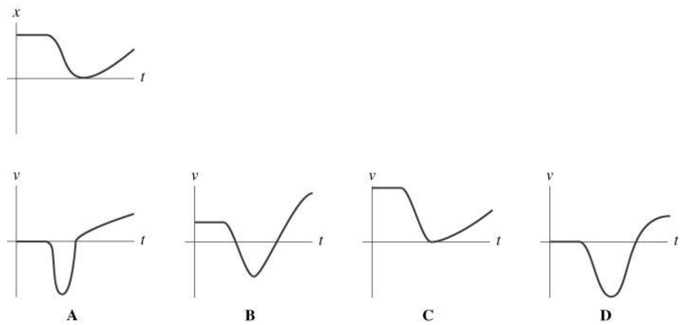
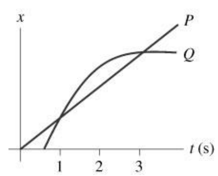
~~D~~d. there's not enough information to determine which ball wins the race.

Additional Student Response System ("Clicker") Questions

1. A particle moves with the position-versus-time graph shown. Which graph best illustrates the velocity of the particle as a function of time?



2. Masses P and Q move with the position graphs shown. Do P and Q ever have the same velocity? If so, at what time or times?



~~A~~a. P and Q have the same velocity at 2 s.

~~B~~b. P and Q have the same velocity at 1 s and 3 s.

~~C~~c. P and Q have the same velocity at 1 s, 2 s, and 3 s.

~~D~~d. P and Q never have the same velocity.

3. Mike jumps out of a tree and lands on a trampoline. The trampoline sags 2 feet before launching Mike back into the air.

At the very bottom, where the sag is the greatest, Mike's acceleration is~~:~~

~~A~~a. ~~Upward~~upward.

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~~B~~b. ~~Downward~~downward.

~~C~~c. ~~Zero~~zero.

Additional Examples

1. When you stop a car on very slick icy pavement, the acceleration of your car is approximately $-1.0\ \text{m/s}^2$. If you are driving on icy pavement at 30 m/s (about 65 mph) and you hit the brakes, how much distance will your car travel before coming to rest?
2. As we will see in a future chapter, the time for a car to come to rest in a collision is always about 0.1 s. Ideally, the front of the car will crumple as this happens, with the passenger compartment staying intact. If a car is moving at 15 m/s and hits a fixed obstacle, coming to rest in 0.10 s, what is the acceleration? How much does the front of the car crumple during the collision?

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One Step Beyond: Animal Leaps

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Steven Vogel has done a number of interesting analyses in which he applies physics concepts to living systems. In one paper, he notes that investigators as early as Galileo hypothesized that all animals should be capable of jumping to about the same height, meaning they must have similar launch speeds. [Vogel, S. (2005). "Living in a physical world III. Getting up to speed." *J. Biosci.* 30(3), 303–312]. An analysis of the kinematics of animal jumps is a nice application of the principles of this chapter.

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The equal leap hypothesis isn't quite true; mice can jump quite high, while elephants can't jump at all. But it does turn out that animals over a very wide range of sizes that are good jumpers can perform approximately the same vertical leap. In principle, the reasons for this are straightforward. Suppose we use L to denote the linear size of an animal. The animal's mass is just proportional to L^3. The force its muscles can supply is proportional to the cross-sectional area of the muscles, and so will be proportional to L^2. The acceleration possible during a jump, $a = F/m$, is thus proportional to $1/L$. But the distance over which the force can be applied as the legs are extended during a jump will be proportional to L. Larger animals are capable of lesser accelerations, but can apply these over a greater distance. To a first approximation, the final speed in a jump should be about the same, regardless of size.

Vogel gives numbers for a few excellent jumpers to make this case. An antelope can extend its long legs by 1.5 m during a jump, accelerating at 16 m/s^2 during this extension. A much smaller animal, a bushbaby (a very small primate), can extend its legs by much less— only about 16 cm—but it undergoes a much larger acceleration of 140 m/s^2. The net result is that the two animals have about the same vertical leap. A quick calculation, which you can do with your students, shows that the ~~galago~~ bushbaby has a vertical leap of 2.3 m, and the much-larger antelope has a very similar vertical leap of 2.4 m. (Humans are nearly as proficient; a world-class standing high jump will be just shy of 2.0 m, but the jumper's center of gravity rises by much less than this.)

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At some point, the muscle scaling argument breaks down. A click beetle could, in the absence of air resistance, leap to a height similar to that of the antelope or the bushbaby. The extension distance of less than 1 cm requires an acceleration of 3800 m/s^2 to achieve this jump height. Muscle power alone is simply not capable of providing this acceleration. Other mechanisms apply that allow for the truly amazing leap of this small creature.

Of course, beetles and other animals don't usually jump straight up. In the next chapter, we will look at broad jumps, in which animals jump for maximum horizontal distance.

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