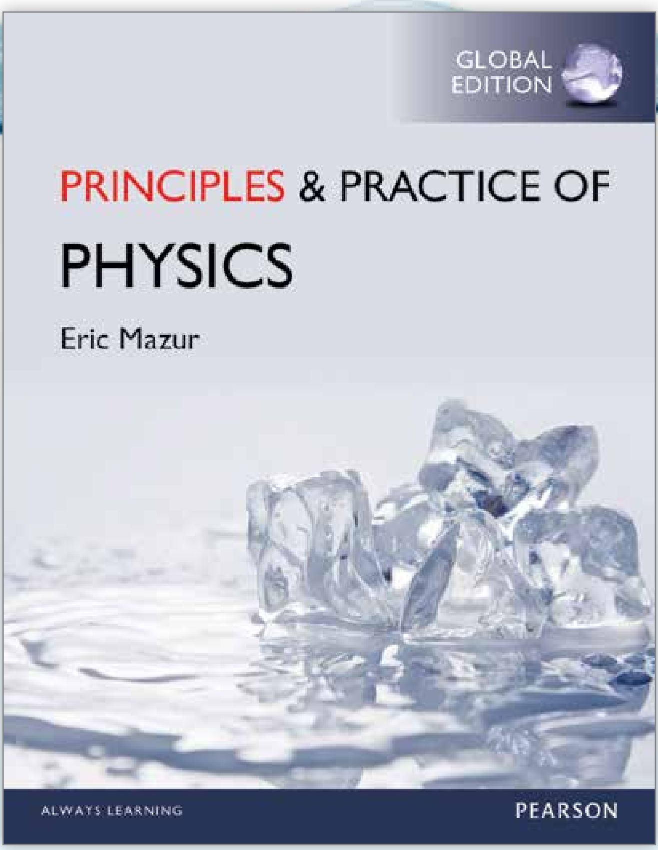
# PUTTING PRINCIPLES FIRST

ALWAYS LEARNING

PEARSON

# New learning architecture

The division into *Principles* and *Practice* volumes fosters better learning of both physics principles and problem solving.

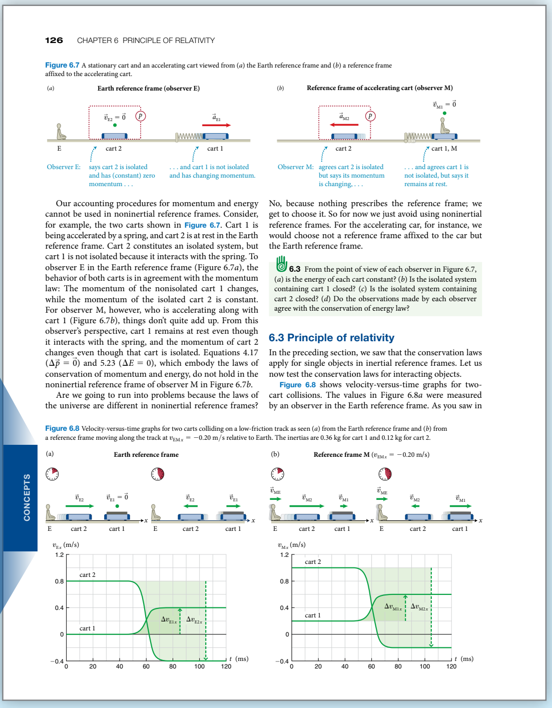


## The *Principles* volume teaches the physics.

Each Principles chapter is divided into a **CONCEPTS** section and a **QUANTITATIVE TOOLS** section.

The **CONCEPTS** section develops the ideas in qualitative terms, using words and pictures to build from specific observations to general principles.

**CONCEPTS**



126 CHAPTER 6 PRINCIPLE OF RELATIVITY

**Figure 6.7** A stationary cart and an accelerating cart viewed from (*a*) the Earth reference frame and (*b*) a reference frame affixed to the accelerating cart.

Our accounting procedures for momentum and energy cannot be used in noninertial reference frames. Consider, for example, the two carts shown in **Figure 6.7**. Cart 1 is being accelerated by a spring, and cart 2 is at rest in the Earth reference frame. Cart 2 constitutes an isolated system, but cart 1 is not isolated because it interacts with the spring. To observer E in the Earth reference frame (Figure 6.7*a*), the behavior of both carts is in agreement with the momentum law: The momentum of the nonisolated cart 1 changes, while the momentum of the isolated cart 2 is constant. For observer M, however, who is accelerating along with cart 1 (Figure 6.7*b*), things don't quite add up. From this observer's perspective, cart 1 remains at rest even though it interacts with the spring, and the momentum of cart 2 changes even though that cart is isolated. Equations 4.17 ($\Delta\vec{p} = \vec{0}$) and 5.23 ($\Delta E = 0$), which embody the laws of conservation of momentum and energy, do not hold in the noninertial reference frame of observer M in Figure 6.7*b*.

Are we going to run into problems because the laws of the universe are different in noninertial reference frames? No, because nothing prescribes the reference frame; we get to choose it. So for now we just avoid using noninertial reference frames. For the accelerating car, for instance, we would choose not a reference frame affixed to the car but the Earth reference frame.

**6.3** From the point of view of each observer in Figure 6.7, (*a*) is the energy of each cart constant? (*b*) Is the isolated system containing cart 1 closed? (*c*) Is the isolated system containing cart 2 closed? (*d*) Do the observations made by each observer agree with the conservation of energy law?

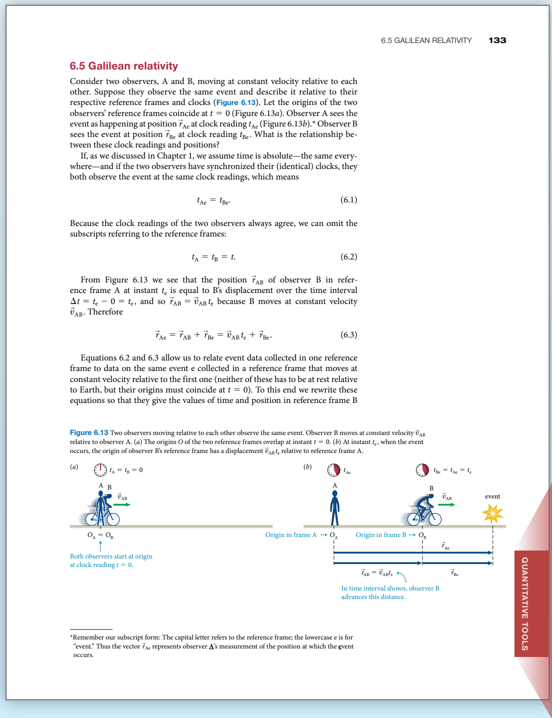
### 6.3 Principle of relativity

In the preceding section, we saw that the conservation laws apply for single objects in inertial reference frames. Let us now test the conservation laws for interacting objects.

**Figure 6.8** shows velocity-versus-time graphs for two-cart collisions. The values in Figure 6.8*a* were measured by an observer in the Earth reference frame. As you saw in

**Figure 6.8** Velocity-versus-time graphs for two carts colliding on a low-friction track as seen (*a*) from the Earth reference frame and (*b*) from a reference frame moving along the track at $v_{EMx} = -0.20$ m/s relative to Earth. The inertias are 0.36 kg for cart 1 and 0.12 kg for cart 2.

CONCEPTS



6.5 GALILEAN RELATIVITY 133

### 6.5 Galilean relativity

Consider two observers, A and B, moving at constant velocity relative to each other. Suppose they observe the same event and describe it relative to their respective reference frames and clocks (**Figure 6.13**). Let the origins of the two observers' reference frames coincide at $t = 0$ (Figure 6.13*a*). Observer A sees the event as happening at position $\vec{r}_{Ae}$ at clock reading $t_{Ae}$ (Figure 6.13*b*).* Observer B sees the event at position $\vec{r}_{Be}$ at clock reading $t_{Be}$. What is the relationship between these clock readings and positions?

If, as we discussed in Chapter 1, we assume time is absolute—the same everywhere—and if the two observers have synchronized their (identical) clocks, they both observe the event at the same clock readings, which means

$$t_{Ae} = t_{Be}. \tag{6.1}$$

Because the clock readings of the two observers always agree, we can omit the subscripts referring to the reference frames:

$$t_A = t_B = t. \tag{6.2}$$

From Figure 6.13 we see that the position $\vec{r}_{AB}$ of observer B in reference frame A at instant $t_e$ is equal to B's displacement over the time interval $\Delta t = t_e - 0 = t_e$, and so $\vec{r}_{AB} = \vec{v}_{AB}\,t_e$ because B moves at constant velocity $\vec{v}_{AB}$. Therefore

$$\vec{r}_{Ae} = \vec{r}_{AB} + \vec{r}_{Be} = \vec{v}_{AB}\,t_e + \vec{r}_{Be}. \tag{6.3}$$

Equations 6.2 and 6.3 allow us to relate event data collected in one reference frame to data on the same event e collected in a reference frame that moves at constant velocity relative to the first one (neither of these has to be at rest relative to Earth, but their origins must coincide at $t = 0$). To this end we rewrite these equations so that they give the values of time and position in reference frame B

**Figure 6.13** Two observers moving relative to each other observe the same event. Observer B moves at constant velocity $\vec{v}_{AB}$ relative to observer A. (*a*) The origins *O* of the two reference frames overlap at instant $t = 0$. (*b*) At instant $t_e$, when the event occurs, the origin of observer B's reference frame has a displacement $\vec{v}_{AB}t_e$ relative to reference frame A.

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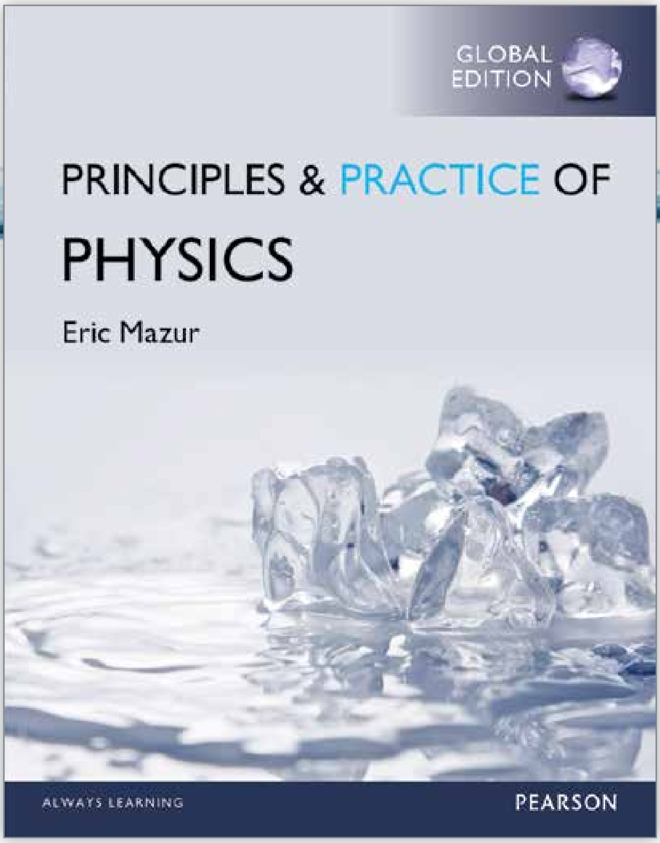
*Remember our subscript form: The capital letter refers to the reference frame; the lowercase e is for "event." Thus the vector $\vec{r}_{Ae}$ represents observer **A**'s measurement of the position at which the **e**vent occurs.

QUANTITATIVE TOOLS

**QUANTITATIVE TOOLS**

The **QUANTITATIVE TOOLS** section formalises the ideas mathematically.



The *Practice* volume teaches the skills needed to apply physics to the task of solving problems.

QUESTIONS AND PROBLEMS 99

32. In a three-car crash, car A bumps into the back end of car B, which then goes forward and bumps into the back end of car C. Is the distance that car B moves between the collisions the same in all inertial reference frames? ••
33. Riding up an escalator while staying on the same step for the whole ride takes 30 s. Walking up the same escalator takes 20 s. How long does it take to walk down the up escalator? ••
34. A woman is on a train leaving the station at 4.0 m/s, while a friend waving goodbye runs alongside the car she's in. (*a*) If the friend is running at 6.0 m/s and moving in the same direction as the train, how fast must the woman walk, and in which direction, to keep up with him? (*b*) Once the train has reached a speed of 10 m/s, how fast must the woman walk, and in which direction, to keep up with her friend? ••
35. Airline pilots who fly round trips know that their round-trip travel time increases if there is any wind. To see this, suppose that an airliner cruises at speed $v$ relative to the air. (*a*) For a flight whose one-way distance is $d$, write an expression for the interval $\Delta t_{\text{calm}}$ needed for a round trip on a windless day. Ignore any time spent on the ground, and assume that the airliner flies at cruising speed for essentially the whole trip. (*b*) Now assume there is a wind of speed $w$. It doesn't matter which way the wind is blowing; all that matters is that it is a

tail wind in the opposite
r the time interval $\Delta t_{\text{wind}}$
this wind is blowing. Then
to

$\left(\frac{w}{v}\right)^2\Big]$

ıst step, you may need to
n $z \ll 1$.) •••

asured when the object is
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ured by an observer mov-
t velocity $\vec{v}$ in the positive
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of Earth is the center of

center of mass of the sys-
ee disks are made of sheet
the diameters are 1.0 m,
calculation for three solid
l and having the same di-

parate rafts 10 m apart in
a small beach toy floating
rl and her raft have twice

the inertia of the boy and his raft. The rafts are connected by a rope 12 m long, so she decides to pull on the rope, drawing the rafts together until she can reach the toy. Which raft gets to the toy first? How much distance is there between the two rafts when the first one reaches the toy? ••

40. The two cubes in Figure P6.40 have different inertias. The cubes are connected to each other by a spring, and a hammer strikes them in the two ways, (*a*) and (*b*), shown in the figure. Assuming that the same impulse is transferred from the hammer, does the center-of-mass motion after the collision depend on which cube is struck first? ••

Figure P6.40

41. Determine the position of the center of mass of the baton shown in Figure P6.41, taking the origin of your coordinate axis to be (*a*) the center of the larger ball, (*b*) the center of the smaller ball, and (*c*) a point 1.0 m to the left of the larger ball. How much calculation was required for each of the three parts of this problem? ••

Figure P6.41

42. The empty cubical box shown in Figure P6.42 has no top face; that is, the box is made up of only five square faces. If all five faces have the same inertia, at what height above the bottom of the box is the center of mass? ••

Figure P6.42

43. How can you tell from the motion of the center of mass of an isolated system whether the reference frame from which the motion is measured is inertial? ••
44. Determine the center of mass of a pool cue whose diameter decreases smoothly from 40 mm to 10 mm over its 1.40-m length (Figure P6.44). Assume that the cue is made from solid wood, with no hidden weights inside. (Hint: See Appendix D for the center-of-mass computation for extended objects. You will find it easier to do the integral for a complete cone. The pool cue is a truncated cone—that is, a cone with its conical tip removed. Slicing off a piece is like adding negative inertia.) •••

Figure P6.44

WORKED AND GUIDED PROBLEMS 91

## Worked and Guided Problems

### Procedure: Applying Galilean relativity

In problems dealing with more than one reference frame, you need to keep track not only of objects, but also of reference frames. For this reason, each quantity is labeled with two subscripts. The first subscript denotes the observer; the second denotes the object of interest. For example, if we have an observer on a train and also a car somewhere on the ground but in sight of the train, then $\vec{a}_{\text{Tc}}$ is the train observer's measurement of the acceleration of the car. Once you understand this notation and a few basic operations, working with relative quantities is easy and straightforward.

s given in the problem,
tation.
d to determine in the

3. Use subscript cancellation (Eq. 6.13) to write an equation for each quantity you need to determine, keeping the first and the last subscripts on each side the same. For example, in a problem where you need to determine $\vec{v}_{\text{Tc}}$ involving a moving observer B, write

$$\vec{v}_{\text{Tc}} = \vec{v}_{\text{TB}} + \vec{v}_{\text{Bc}}.$$

4. If needed, use subscript reversal (Eq. 6.15) to eliminate any unknowns.
5. Use the kinematics relationships from Chapters 2 and 3 to solve for any remaining unknowns, making sure you stay in one reference frame.

You can use this procedure and the subscript operations for any of the three basic kinematic quantities (position, velocity, and acceleration).

*s chapter but are not associated with any particular section.*
*others you should work out by following the guidelines provided.*

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to a track meet, a sprinter
running down the aisle. In
rinter starts from rest and
0 s, he has accelerated to a
at a constant 30 m/s rela-
does an observer standing
inter's initial velocity, final

ate information from the
reference frame E, which
locity and acceleration. As
ing attention to the direc-

Because the train does not accelerate, T is an inertial reference frame, as is the Earth reference frame E. We are given enough information to calculate the sprinter's initial velocity $\vec{v}_{\text{Ts,i}}$, final velocity $\vec{v}_{\text{Ts,f}}$, and acceleration $\vec{a}_{\text{Ts}}$ measured by an observer at rest in the train reference frame, and we need to determine what the trackside observer measures for these three quantities, which we denote as $\vec{v}_{\text{Es,i}}$, $\vec{v}_{\text{Es,f}}$, and $\vec{a}_{\text{Es}}$ because they are being measured in the Earth reference frame.

❷ **DEVISE PLAN** As Figure WG6.1 shows, we define the positive $x$ direction as the direction in which the train is moving. The train is therefore moving with a velocity that has $x$ component $v_{\text{ET}x} = +30\,\text{m/s}$ as measured by the observer in the Earth reference frame. (And to a passenger on the train, the trackside observer moves along the $x$ axis with a velocity that has $x$ component $v_{\text{TE}x} = -30\,\text{m/s}$.)

We need to transform velocity information from the T reference frame to the E reference frame, and so we use Eq. 6.14 with the subscripts appropriate to this problem:

$$\vec{v}_{\text{Es}} = \vec{v}_{\text{ET}} + \vec{v}_{\text{Ts}}. \tag{1}$$

For the sprinter's acceleration, we note from Eq. 6.11 that the two inertial reference frames give the same result:

$$\vec{a}_{\text{Es}} = \vec{a}_{\text{Ts}}.$$

We can use Eq. 1 for both the sprinter's initial velocity and his final velocity measured by the trackside observer. To calculate the acceleration this observer measures, we do not have enough information to take the time derivative of the velocity because we know

PRACTICE

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## Chapter Summary

### Inertial reference frames (Sections 6.1–6.4, 6.6)

**Concepts** A **reference frame** is a combination of a reference axis that defines a direction in space and a reference point that defines the origin from which motion is measured. The **Earth reference frame** is a reference frame at rest relative to Earth.

An **inertial reference frame** is one in which the **law of inertia** holds, which means a reference frame in which an isolated object remains either at rest or in motion at constant velocity.

The **principle of relativity** states that the laws of the universe are the same in all inertial reference frames.

The **zero-momentum reference frame** for a system of objects is the reference frame in which the momentum of the system is zero. The velocity of this reference frame is equal to the velocity of the center of mass of the system.

**Quantitative Tools** The position $\vec{r}_{\text{cm}}$ of the **center of mass** of a system of objects of inertias $m_1, m_2, \ldots$ located at positions $\vec{r}_1, \vec{r}_2, \ldots$ is

$$\vec{r}_{\text{cm}} \equiv \frac{m_1\vec{r}_1 + m_2\vec{r}_2 + \cdots}{m_1 + m_2 + \cdots}. \tag{6.24}$$

The **center-of-mass velocity** of a system of objects is

$$\vec{v}_{\text{cm}} \equiv \frac{d\vec{r}_{\text{cm}}}{dt} = \frac{m_1\vec{v}_1 + m_2\vec{v}_2 + \cdots}{m_1 + m_2 + \cdots}. \tag{6.26}$$

This is also the velocity of the **zero-momentum reference frame** for this system.

### Relative motion (Section 6.5)

**Concepts** The **Galilean transformation equations** allow us to transform quantities measured in one inertial reference frame into their values in another inertial reference frame when the two reference frames are moving at constant relative velocity. The transformation equations tell us that *time intervals*, *lengths*, and *accelerations* are the same in any two inertial reference frames moving at constant relative velocity.

**Quantitative Tools** The **Galilean transformation equations** relate the time $t$ and position $\vec{r}_{\text{e}}$ for an event (e) measured in an inertial reference frame A to these quantities measured for the event in any other inertial reference frame B. If the reference frames have a constant relative velocity $\vec{v}_{\text{AB}}$ and have their origins coinciding at $t = 0$, the transformation equations are

$$t_{\text{B}} = t_{\text{A}} = t \tag{6.4}$$

and

$$\vec{r}_{\text{Be}} = \vec{r}_{\text{Ae}} - \vec{v}_{\text{AB}}t_{\text{e}}. \tag{6.5}$$

As a consequence of these equations, the velocity $\vec{v}_{\text{Ao}}$ of an object (o) measured in an inertial reference frame A is related to the object's velocity measured in any other inertial reference frame B by

$$\vec{v}_{\text{Ao}} = \vec{v}_{\text{AB}} + \vec{v}_{\text{Bo}}. \tag{6.14}$$

The transformation equations also give the relationship between accelerations measured in any two inertial reference frames A and B:

$$\vec{a}_{\text{Ao}} \equiv \vec{a}_{\text{Bo}}. \tag{6.11}$$

### Convertible kinetic energy (Section 6.7)

**Concepts** The **translational kinetic energy** of a system is the kinetic energy associated with the motion of its center of mass. For an isolated system, this kinetic energy is **nonconvertible** because it cannot be converted to internal energy (if it were, the momentum of the system would not be constant).

The **convertible kinetic energy** of an isolated system is the portion of the system's

**Quantitative Tools** The **translational (nonconvertible) kinetic energy** $K_{\text{cm}}$ of a system is

$$K_{\text{cm}} \equiv \tfrac{1}{2}mv_{\text{cm}}^2, \tag{6.32}$$

where $m$ is the system's inertia and $v_{\text{cm}}$ is the speed of its center of mass.

The **convertible kinetic energy** of a two-particle system is

$$K_{\text{conv}} = \tfrac{1}{2}\mu v_{12}^2, \tag{6.40}$$

PRACTICE

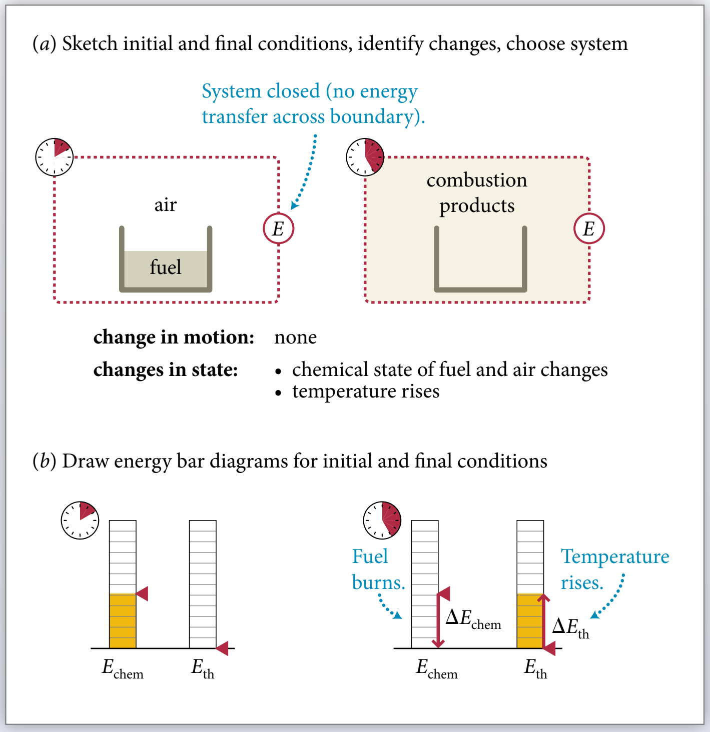
Among other features, the Practice volume contains a **CHAPTER SUMMARY**, **MULTI-CONCEPT WORKED EXAMPLES**, and **PROBLEM SETS**.

# Physics on a
# contemporary foundation

This text builds physics on foundational concepts to help students develop an understanding that is stronger, deeper, and fundamentally simpler than provided by traditional texts.

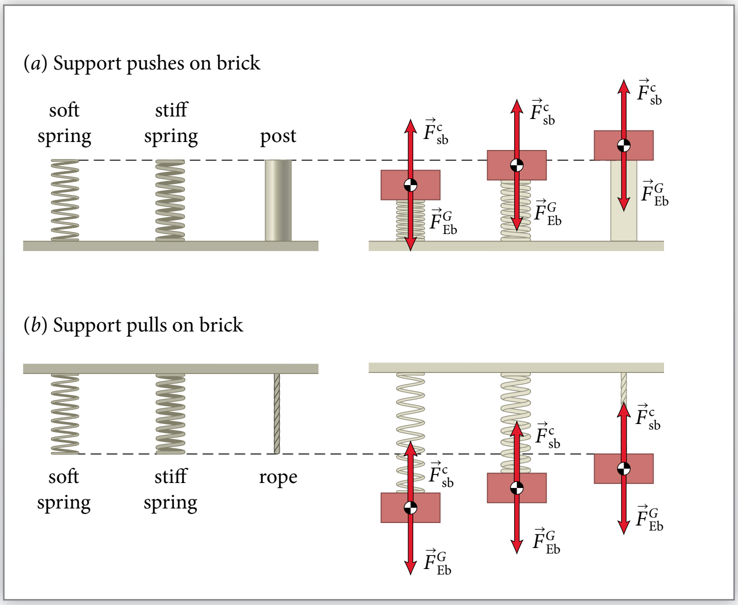
## Contents

## Early emphasis on conservation laws



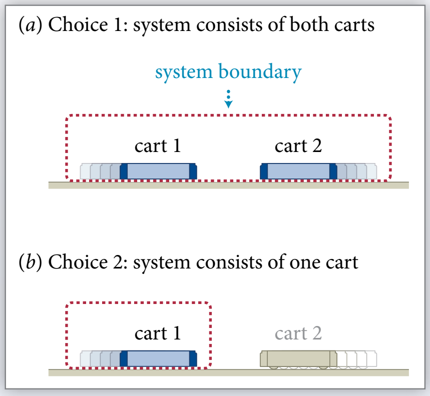
(Figure 5.9)

## The core ideas of mechanics are developed in one dimension



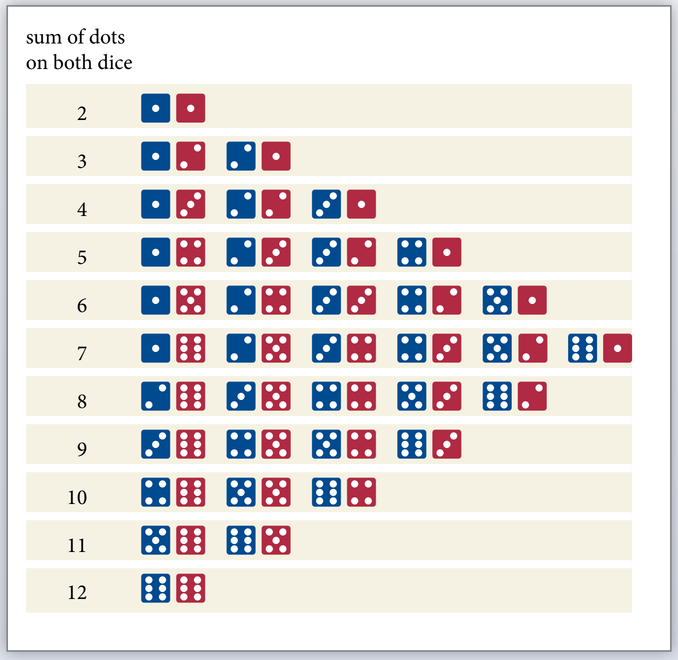
(Figure 8.9)

## Strong emphasis on the concept of a system



(Figure 4.12)

## Statistical treatment of thermodynamics

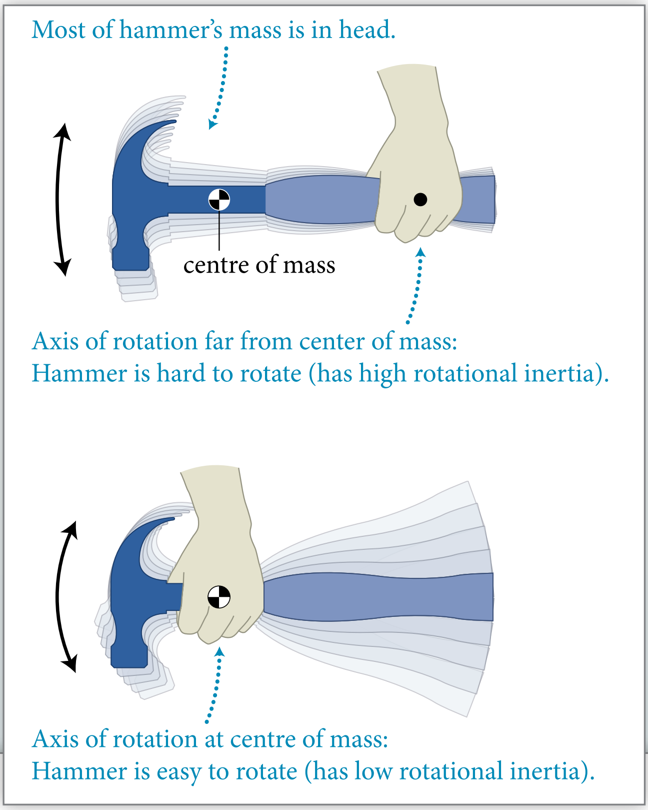


(Figure 19.2)

# Research-based instruction

This text uses a range of research-based instructional techniques.

(Figure 11.19)



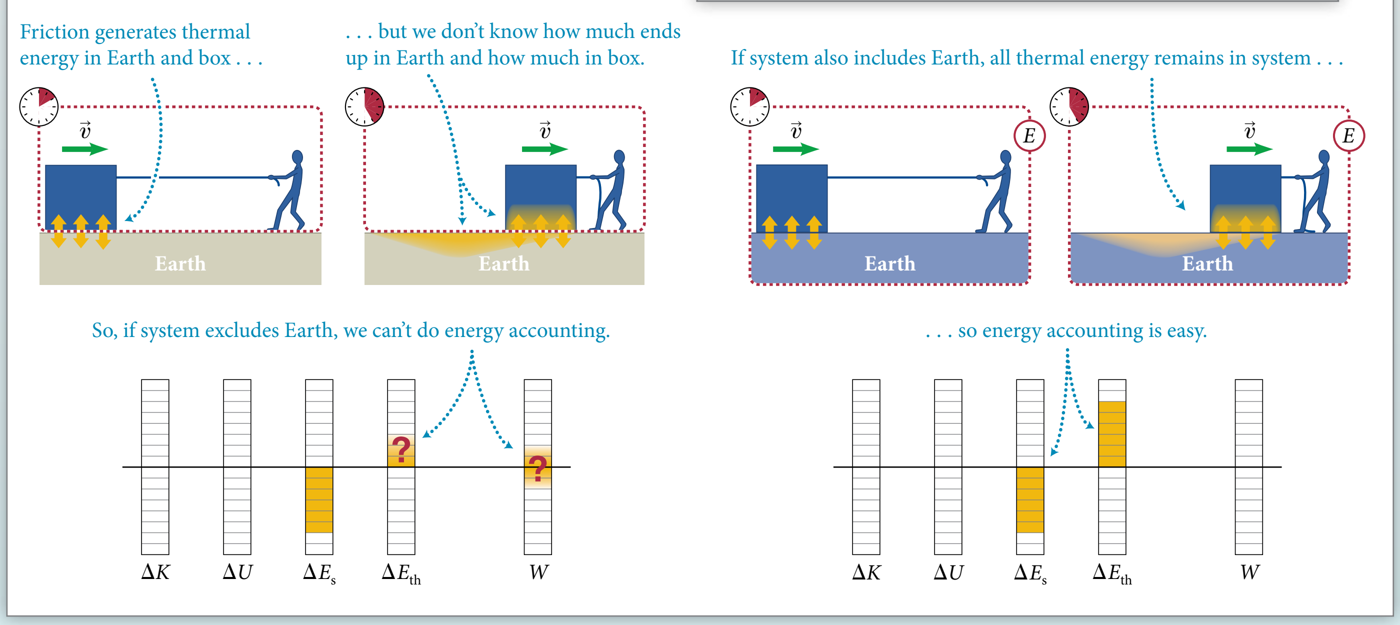
## Strong connection to experiment and experience

This text develops ideas from observations and experiments, instead of stating principles and then showing that they conform to reality.

## Strong visual instruction

The figures are designed to work as visual explanations, presenting ideas in visual terms. For example, they

- incorporate explanation
- are intentionally schematic to reduce cognitive load
- use multiple representations to help students visualise quantitative information
- illustrate the process of physical reasoning

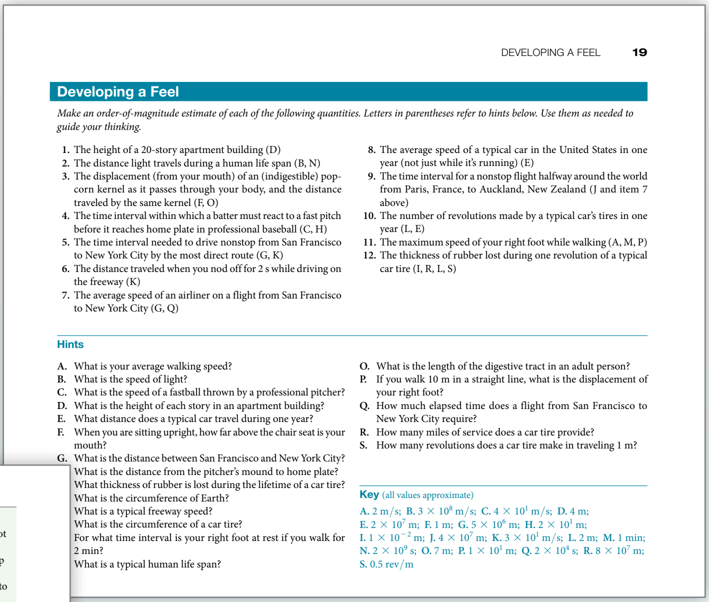


(Figure 9.11)

# Integrated
# student engagement

Self-check and engagement features are integrated closely into the learning program. Among others, they include the following:

**DEVELOPING A FEEL** in the ***Practice*** volume helps students to develop a quantitative feel for the quantities introduced in the chapter and learn to make valid assumptions and estimates.



DEVELOPING A FEEL 19

## Developing a Feel

*Make an order-of-magnitude estimate of each of the following quantities. Letters in parentheses refer to hints below. Use them as needed to guide your thinking.*

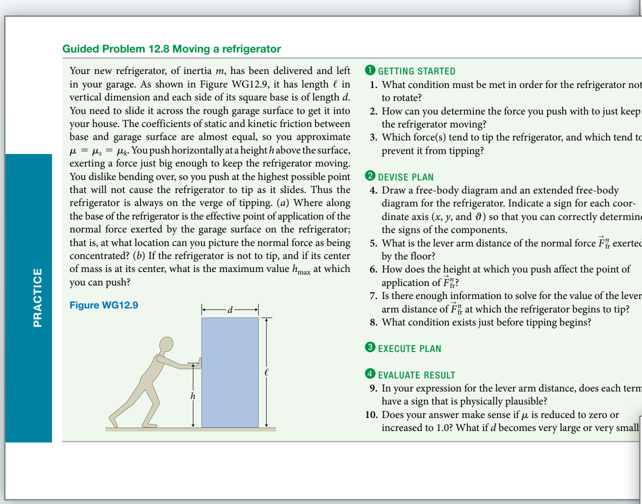
1. The height of a 20-story apartment building (D)
2. The distance light travels during a human life span (B, N)
3. The displacement (from your mouth) of an (indigestible) popcorn kernel as it passes through your body, and the distance traveled by the same kernel (F, O)
4. The time interval within which a batter must react to a fast pitch before it reaches home plate in professional baseball (C, H)
5. The time interval needed to drive nonstop from San Francisco to New York City by the most direct route (G, K)
6. The distance traveled when you nod off for 2 s while driving on the freeway (K)
7. The average speed of an airliner on a flight from San Francisco to New York City (G, Q)
8. The average speed of a typical car in the United States in one year (not just while it's running) (E)
9. The time interval for a nonstop flight halfway around the world from Paris, France, to Auckland, New Zealand (J and item 7 above)
10. The number of revolutions made by a typical car's tires in one year (L, E)
11. The maximum speed of your right foot while walking (A, M, P)
12. The thickness of rubber lost during one revolution of a typical car tire (I, R, L, S)

### Hints

A. What is your average walking speed?
B. What is the speed of light?
C. What is the speed of a fastball thrown by a professional pitcher?
D. What is the height of each story in an apartment building?
E. What distance does a typical car travel during one year?
F. When you are sitting upright, how far above the chair seat is your mouth?
G. What is the distance between San Francisco and New York City?
What is the distance from the pitcher's mound to home plate?
What thickness of rubber is lost during the lifetime of a car tire?
What is the circumference of Earth?
What is a typical freeway speed?
What is the circumference of a car tire?
For what time interval is your right foot at rest if you walk for 2 min?
What is a typical human life span?
O. What is the length of the digestive tract in an adult person?
P. If you walk 10 m in a straight line, what is the displacement of your right foot?
Q. How much elapsed time does a flight from San Francisco to New York City require?
R. How many miles of service does a car tire provide?
S. How many revolutions does a car tire make in traveling 1 m?

**Key** (all values approximate)

**A.** 2 m/s; **B.** $3 \times 10^8$ m/s; **C.** $4 \times 10^1$ m/s; **D.** 4 m; **E.** $2 \times 10^7$ m; **F.** 1 m; **G.** $5 \times 10^6$ m; **H.** $2 \times 10^1$ m; **I.** $1 \times 10^{-2}$ m; **J.** $4 \times 10^7$ m; **K.** $3 \times 10^1$ m/s; **L.** 2 m; **M.** 1 min; **N.** $2 \times 10^9$ s; **O.** 7 m; **P.** $1 \times 10^1$ m; **Q.** $2 \times 10^4$ s; **R.** $8 \times 10^7$ m; **S.** 0.5 rev/m



PRACTICE

### Guided Problem 12.8 Moving a refrigerator

Your new refrigerator, of inertia $m$, has been delivered and left in your garage. As shown in Figure WG12.9, it has length $\ell$ in vertical dimension and each side of its square base is of length $d$. You need to slide it across the rough garage surface to get it into your house. The coefficients of static and kinetic friction between base and garage surface are almost equal, so you approximate $\mu = \mu_s = \mu_k$. You push horizontally at a height $h$ above the surface, exerting a force just big enough to keep the refrigerator moving. You dislike bending over, so you push at the highest possible point that will not cause the refrigerator to tip as it slides. Thus the refrigerator is always on the verge of tipping. (*a*) Where along the base of the refrigerator is the effective point of application of the normal force exerted by the garage surface on the refrigerator; that is, at what location can you picture the normal force as being concentrated? (*b*) If the refrigerator is not to tip, and if its center of mass is at its center, what is the maximum value $h_{max}$ at which you can push?

Figure WG12.9

➊ GETTING STARTED

1. What condition must be met in order for the refrigerator not to rotate?
2. How can you determine the force you push with to just keep the refrigerator moving?
3. Which force(s) tend to tip the refrigerator, and which tend to prevent it from tipping?

➋ DEVISE PLAN

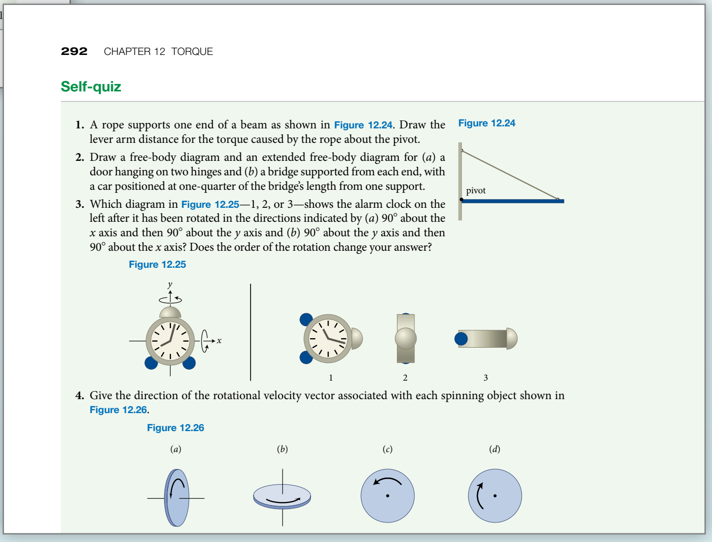
4. Draw a free-body diagram and an extended free-body diagram for the refrigerator. Indicate a sign for each coordinate axis ($x$, $y$, and $\vartheta$) so that you can correctly determine the signs of the components.
5. What is the lever arm distance of the normal force $\vec{F}^n_{fr}$ exerted by the floor?
6. How does the height at which you push affect the point of application of $\vec{F}^n_{fr}$?
7. Is there enough information to solve for the value of the lever arm distance of $\vec{F}^n_{fr}$ at which the refrigerator begins to tip?
8. What condition exists just before tipping begins?

➌ EXECUTE PLAN

➍ EVALUATE RESULT

9. In your expression for the lever arm distance, does each term have a sign that is physically plausible?
10. Does your answer make sense if $\mu$ is reduced to zero or increased to 1.0? What if $d$ becomes very large or very small

In the ***Practice*** volume, each fully solved Worked Problem is followed by a **GUIDED PROBLEM** that has a list of Socratic questions and suggestions in place of a full solution.



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### Self-quiz

1. A rope supports one end of a beam as shown in Figure 12.24. Draw the lever arm distance for the torque caused by the rope about the pivot.
2. Draw a free-body diagram and an extended free-body diagram for (*a*) a door hanging on two hinges and (*b*) a bridge supported from each end, with a car positioned at one-quarter of the bridge's length from one support.
3. Which diagram in Figure 12.25—1, 2, or 3—shows the alarm clock on the left after it has been rotated in the directions indicated by (*a*) 90° about the $x$ axis and then 90° about the $y$ axis and (*b*) 90° about the $y$ axis and then 90° about the $x$ axis? Does the order of the rotation change your answer?

Figure 12.24

Figure 12.25

4. Give the direction of the rotational velocity vector associated with each spinning object shown in Figure 12.26.

Figure 12.26

In ***Principles***, each Concepts section ends with a **SELF QUIZ** that lets students test their understanding of the material before proceeding.

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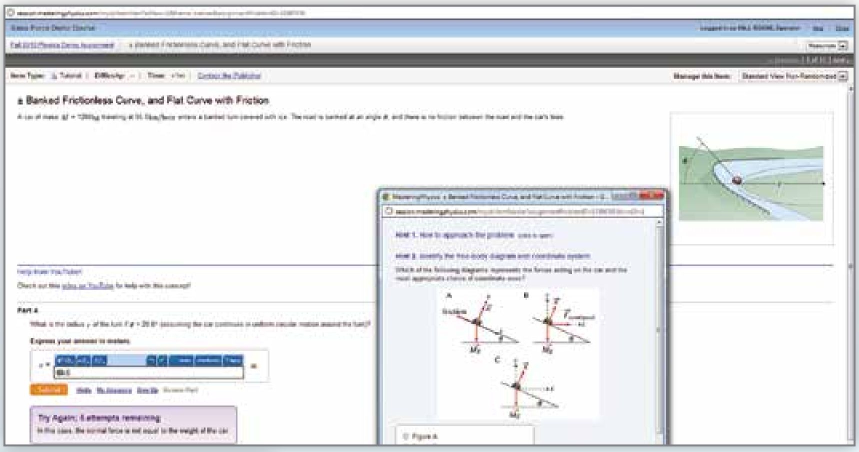
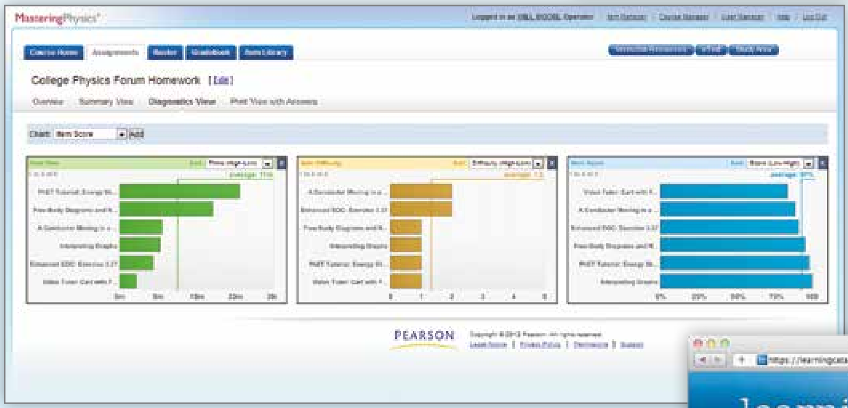
- Mastering's hallmark **HINTS** and **FEEDBACK** offer scaffolded instruction similar to what students would experience in an office hour.
- **HINTS** (declarative and Socratic) can provide problem-solving strategies or break the main problem into simpler exercises.
- **FEEDBACK** lets the student know precisely what misconception or misunderstanding is evident from their answer and offers ideas to consider when attempting the problem again.





The **GRADEBOOK DIAGNOSTICS** screen provides your favourite weekly diagnostics. With a single click, charts summarise the most difficult problems, vulnerable students, and grade distribution.

**LEARNING CATALYTICS™** is a "bring your own device" student engagement, assessment, and classroom intelligence system. With learning catalytics you can:

- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical-thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make learning catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

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