





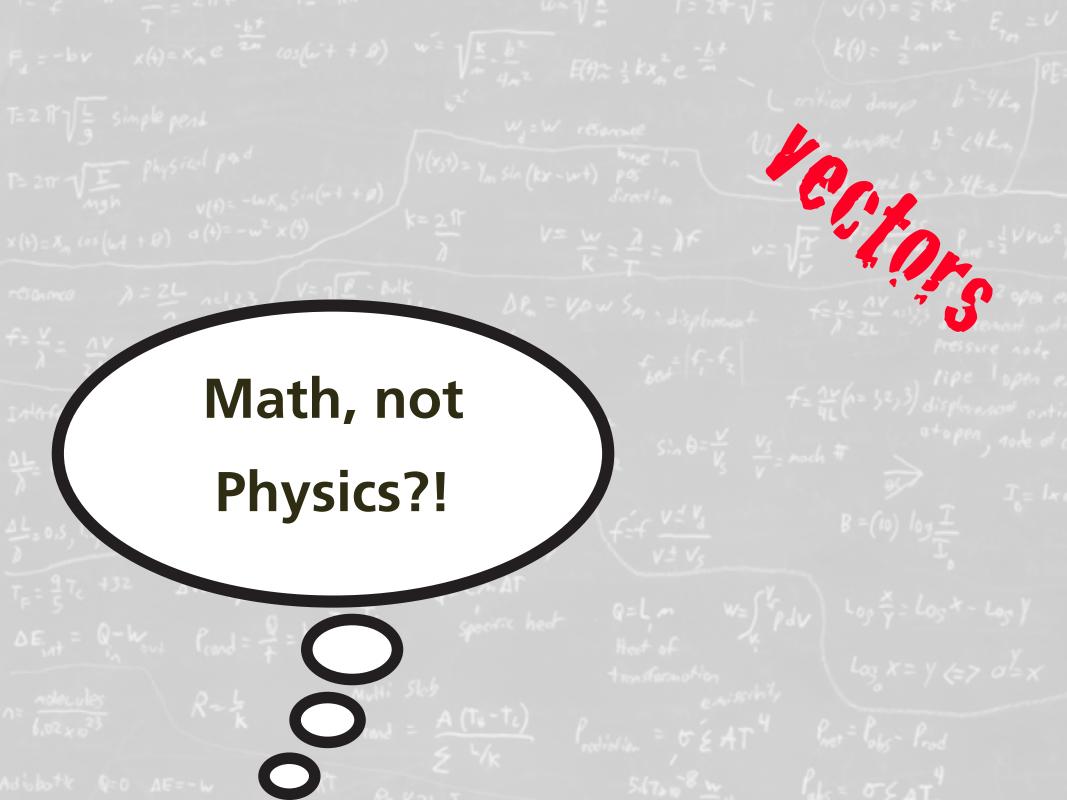


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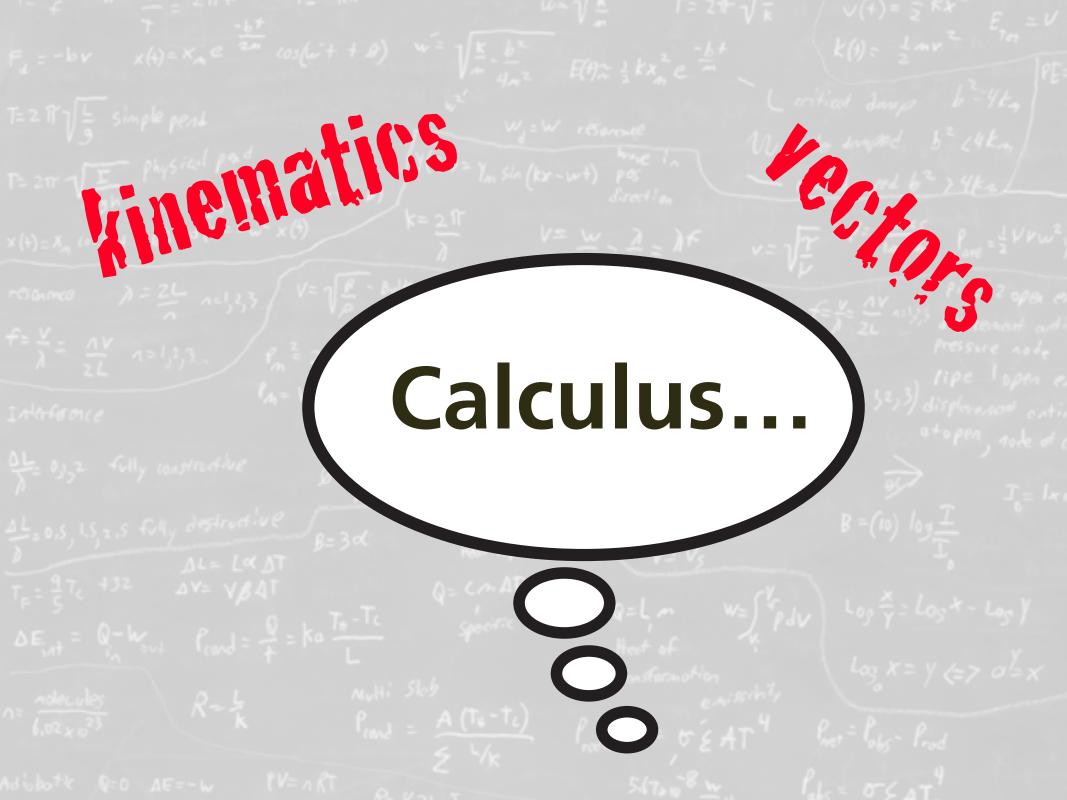
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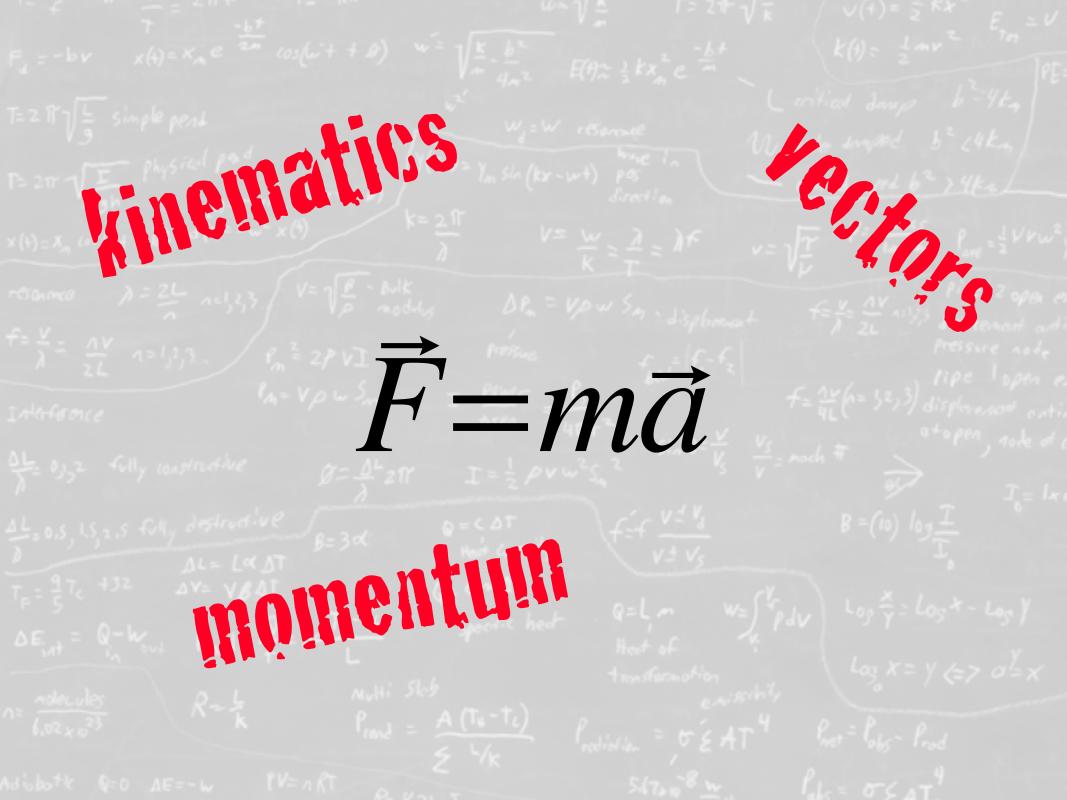
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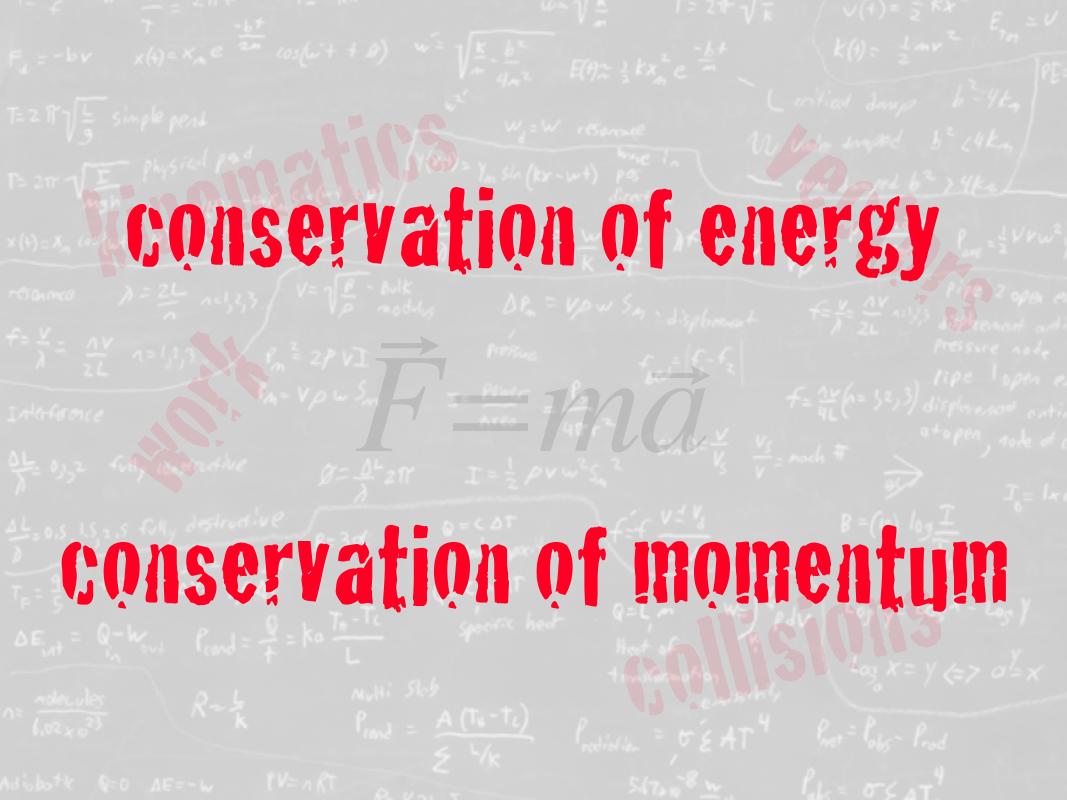
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## conservation of energy

## Just algebra!

## conservation of momentum

## conservation of energy

Why not START the easy way?

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#### The historical approach

- Newton's laws
- Momentum (and conservation)
- Collisions
- Work and energy
- Conservation of energy

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#### Ernst Mach (1838–1916)

- Collisions
- COLLEGE PHYSICS
- Conservation of momentum
- Newton's laws
- Work and energy
- Conservation of energy

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#### Ernst Mach (1838-1916)

- Collisions (experimental)
- Conservation of momentum (experimental)
- Newton's laws
- Work and energy
- Conservation of energy

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Halliday / Resnick / Walker
PHYSICS

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### COLLEGE PHYSICS

wouldn't it be nice if we could start simple?

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SERWAY | JEWETT

PHYSICS FOR SCIENTISTS
AND ENGINEERS

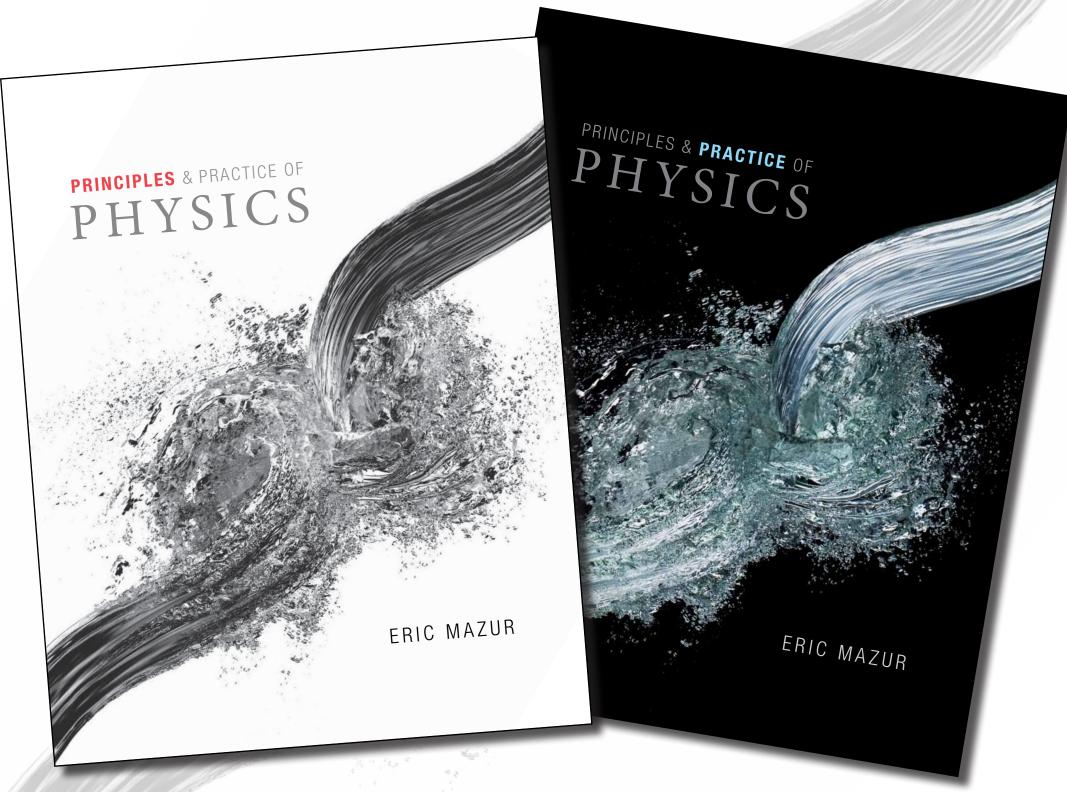
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## we can!



PRINCIPLES & PRACTICE OF

- Conservation of momentum
  - Conservation of energy
  - Interactions
  - Force
  - Work

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ERIC MAZUR

PRINCIPLES & PRACTICE OF

- Conservation of momentum (experimental)
  - Conservation of energy (experimental)
  - Interactions
  - Force
  - Work

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PRINCIPLES & PRACTICE OF

- Conservation of momentum (experimental)
- Conservation of energy
- Interactions
- Force
- Work

What about engineers?

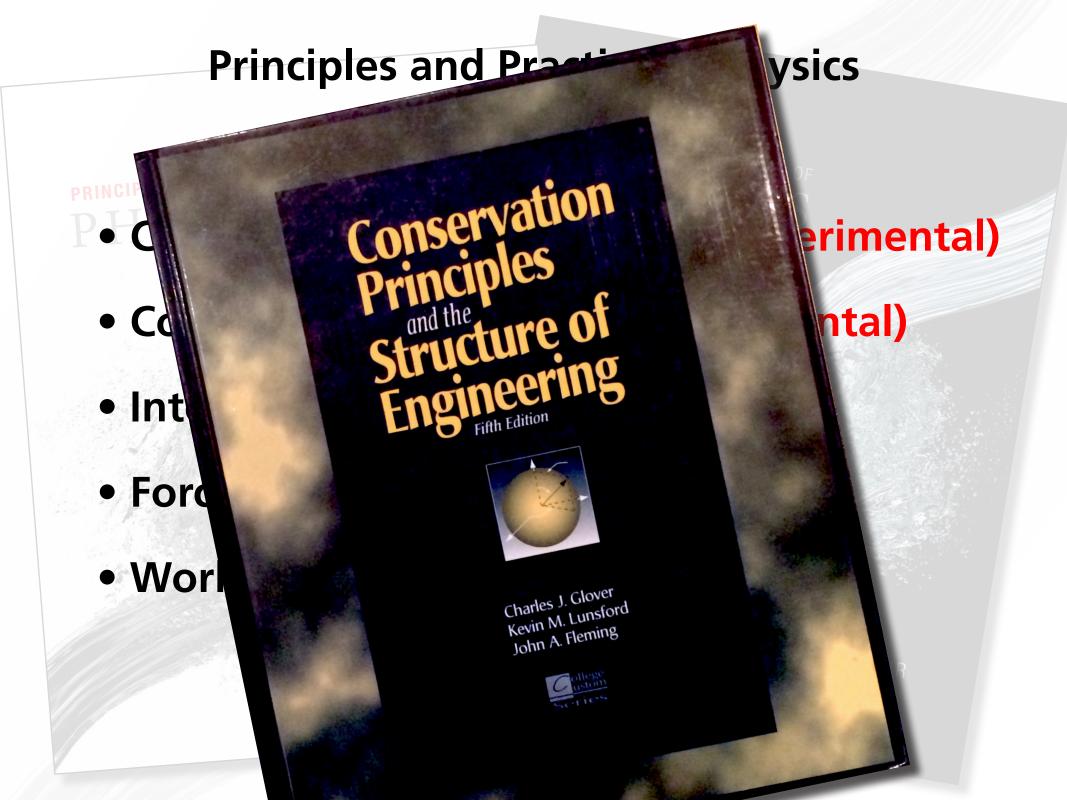
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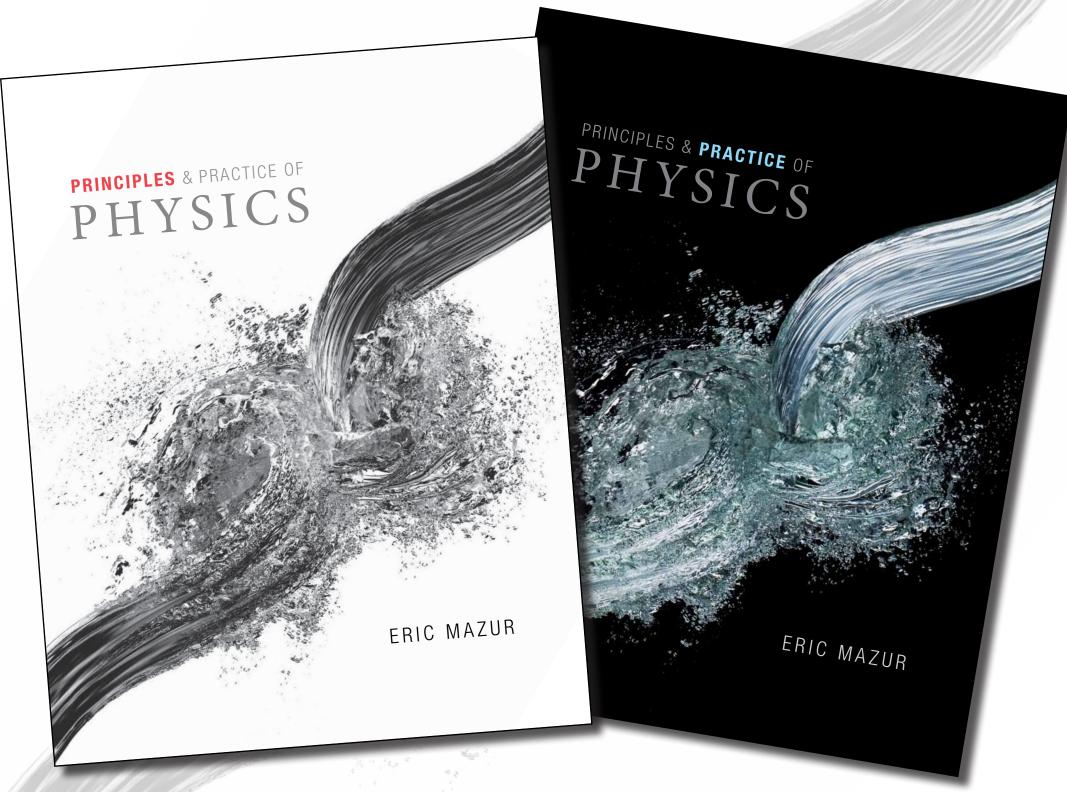
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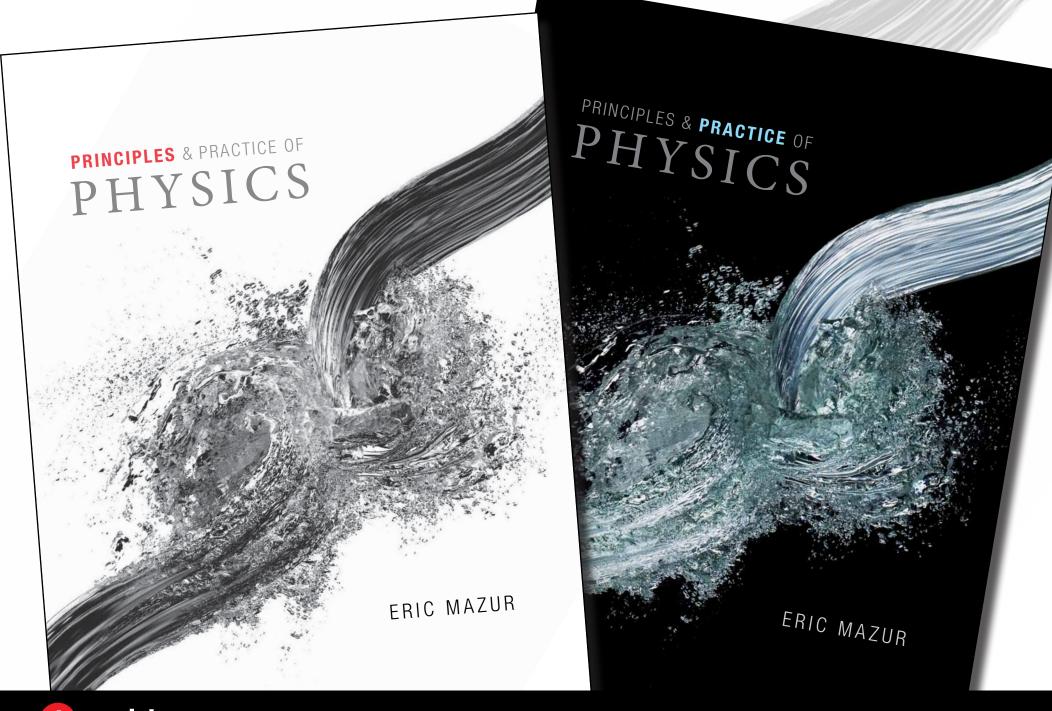
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  - Work

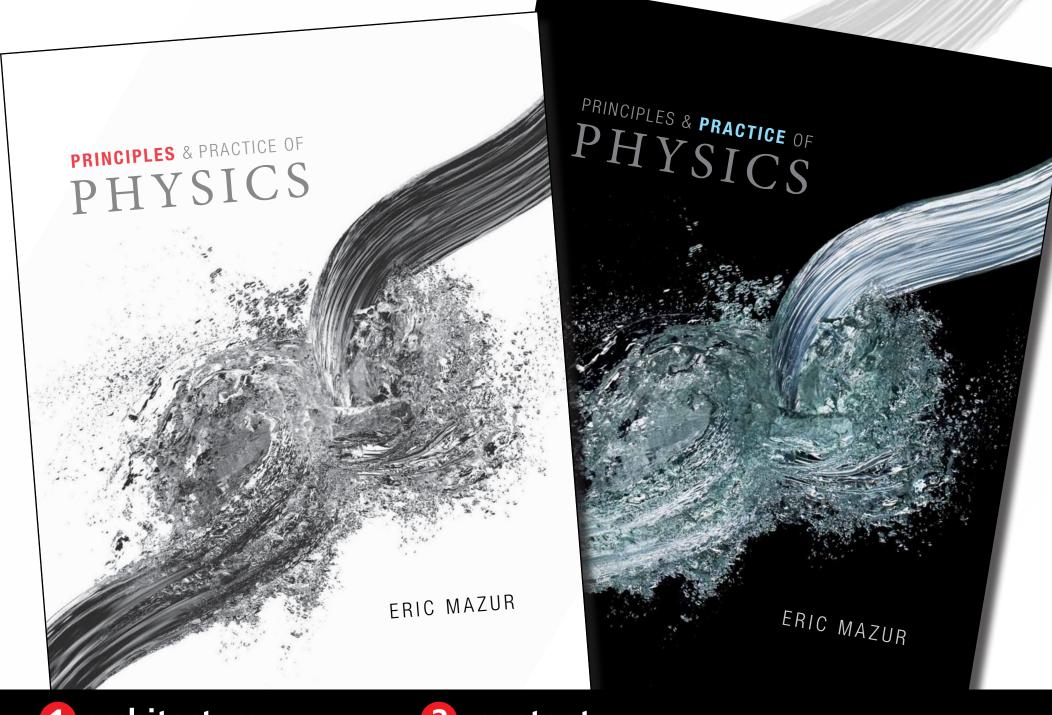
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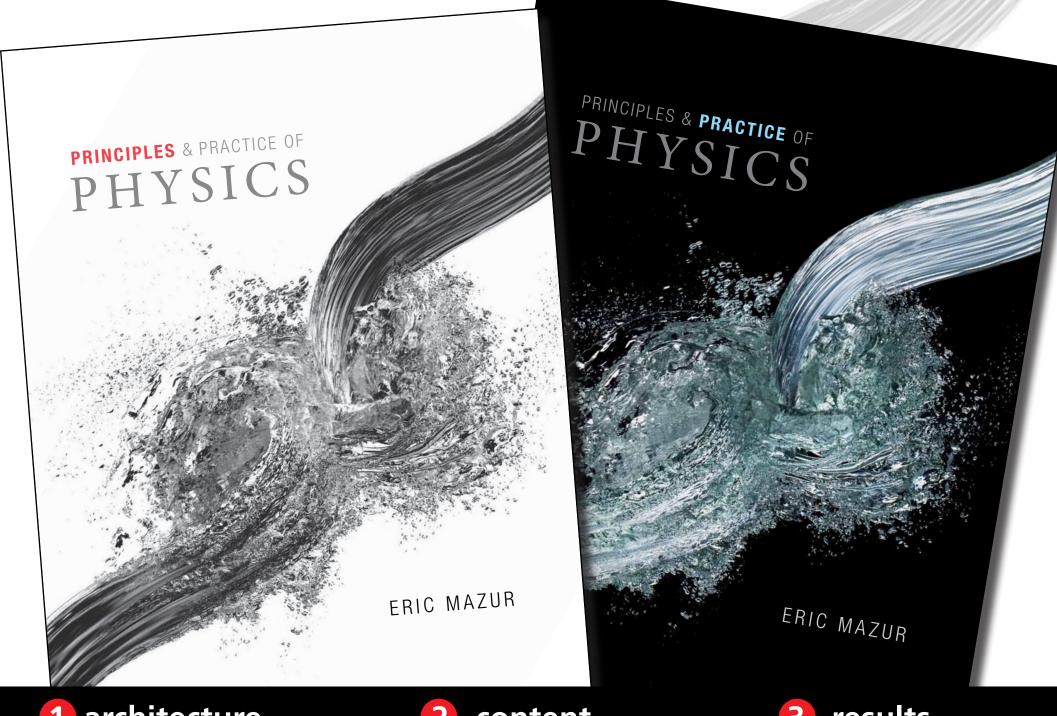






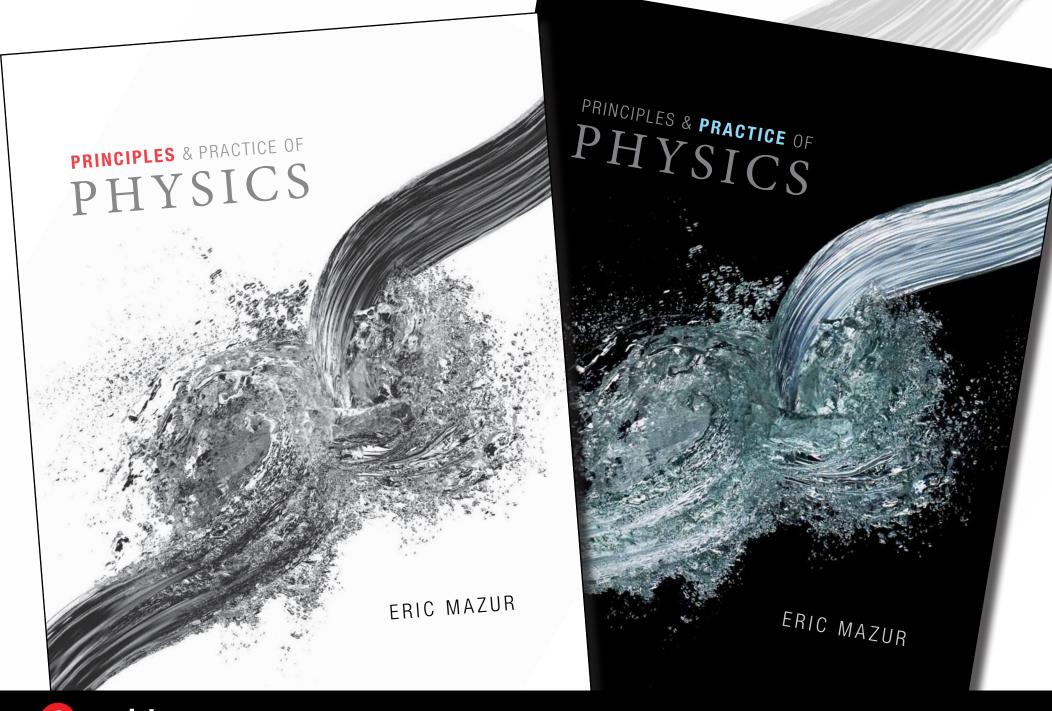


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content

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PRINCIPLES & PRACTICE OF PHYSIC

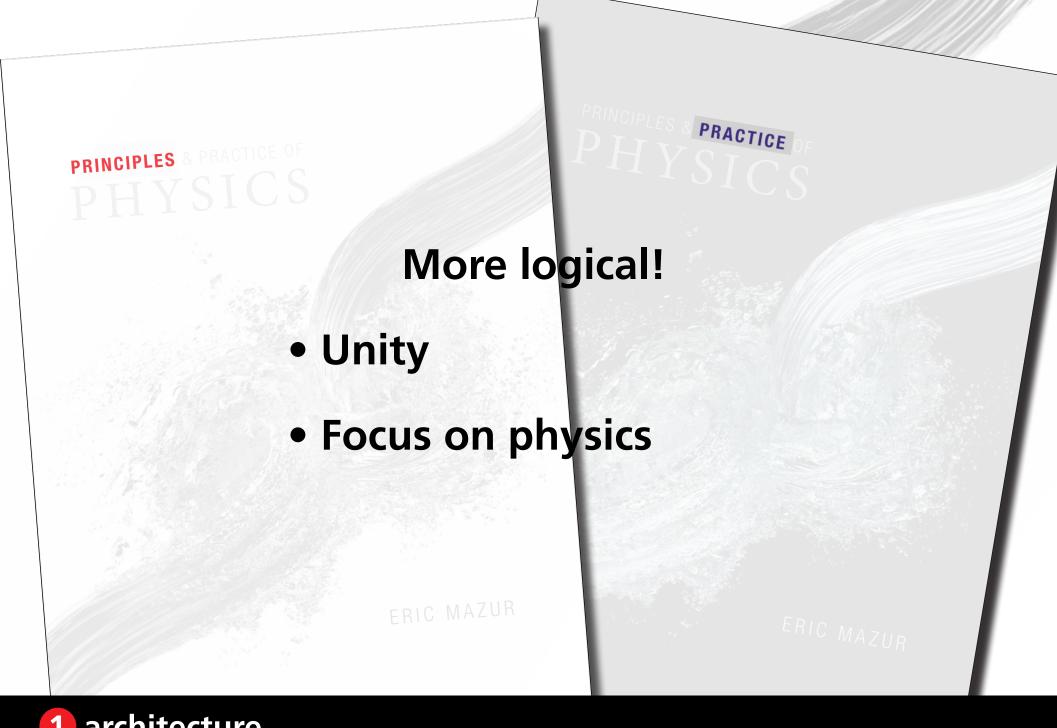
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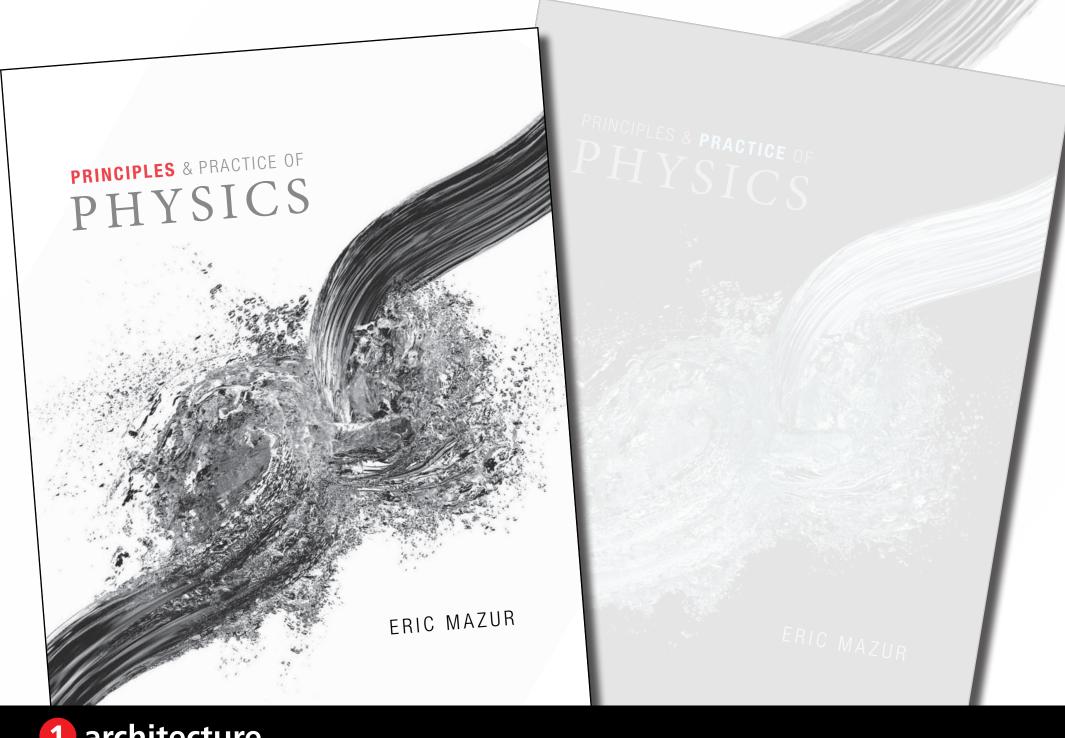
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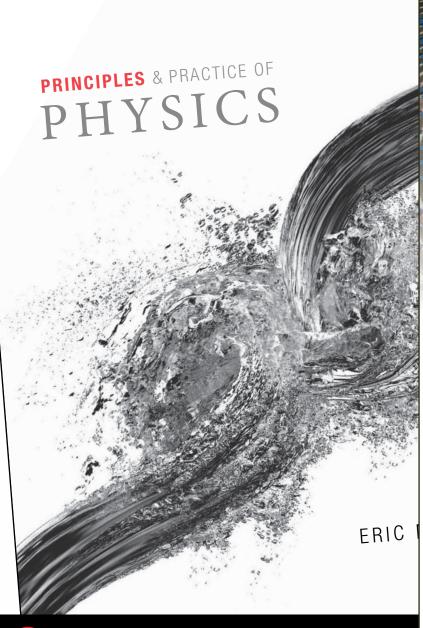
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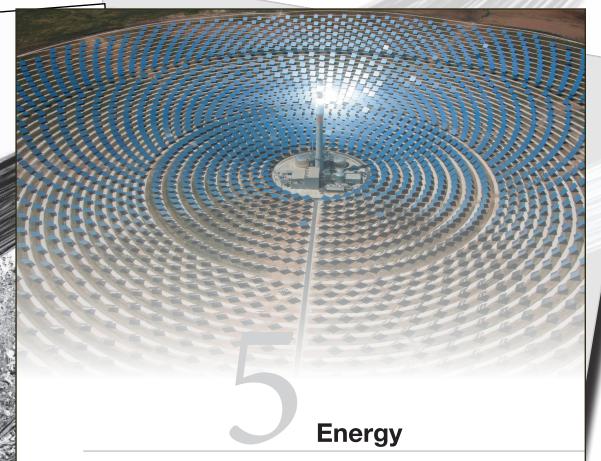
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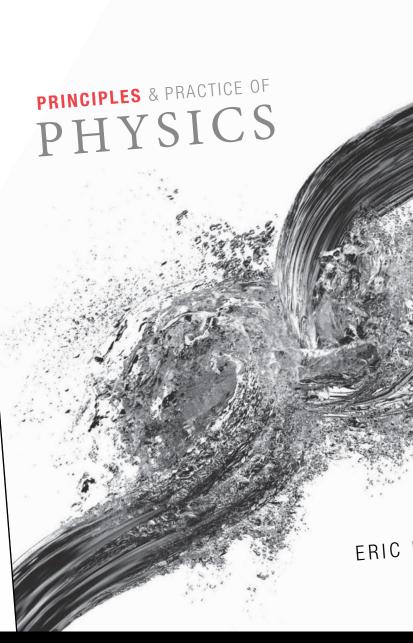


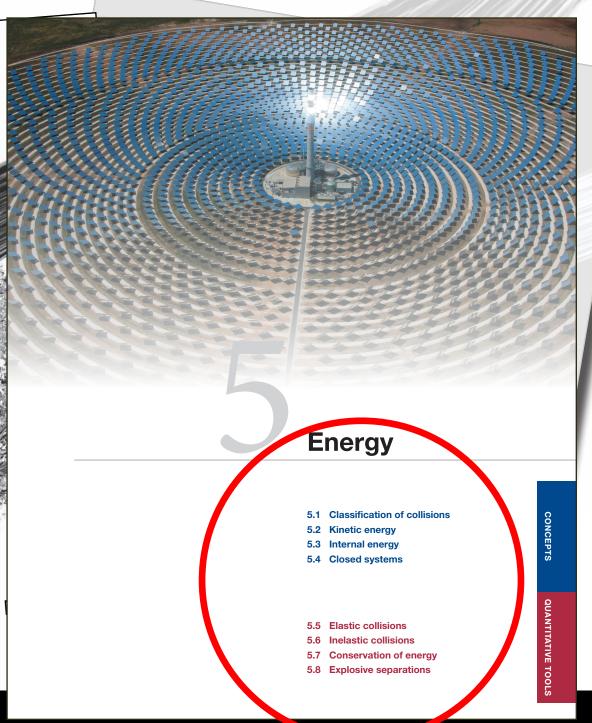


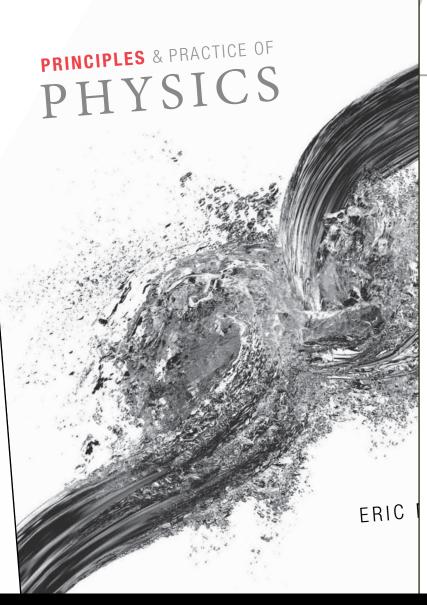




- 5.1 Classification of collisions
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems
- 5.5 Elastic collisions
- 5.6 Inelastic collisions
- 5.7 Conservation of energy
- 5.8 Explosive separations



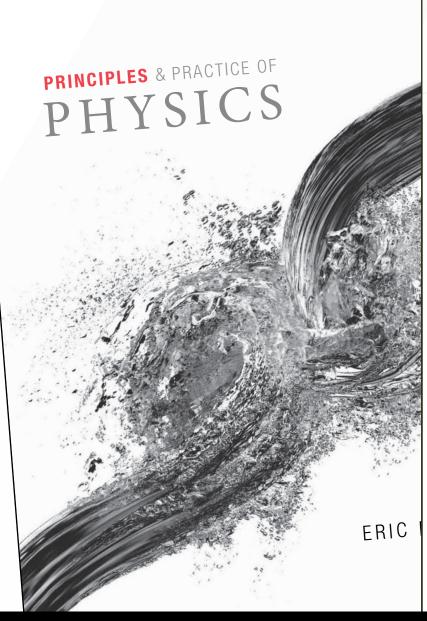




## **Energy**

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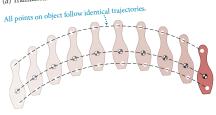
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The motion we have been dealing with so far in this text is called translational motion (Figure 11.1a). This type of motion involves no change in an object's orientation; in other words, all the particles in the object move along identical parallel trajectories. During rotational motion, which we begin to study in this chapter, the orientation of the object changes, and the particles in an object follow different circular paths centered on a straight line called the axis of rotation (Figure 11.1b). Generally, the motion of rigid objects is a combination of these two types of motion (Figure 11.1c), but as we shall see in Chapter 12 this combined motion can be broken down into translational and rotational parts that can be analyzed separately. Because we already know how to describe translational motion, knowing how to describe rotational motion will complete our description of the motion of rigid objects.

As Figure 11.1*b* shows, each particle in a rotating object traces out a circular path, moving in what we call circular

Figure 11.1 Translational and rotational motion of a rigid object.

(a) Translational motion

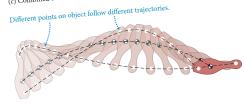


(b) Rotational motion

All points on object trace circles centered on axis of rotation.



(c) Combined translation and rotation

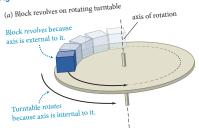


motion. We therefore begin our analysis of rotational motion by describing circular motion. Circular motion occurs all around us. A speck of dust stuck to a spinning CD, a stone being whirled around on a string, a person on a Ferris wheel—all travel along the perimeter of a circle, repeating their motion over and over. Circular motion takes place in a plane, and so in principle we have already developed all the tools required to describe it. To describe circular and rotational motion we shall follow an approach that is analogous to the one we followed for the description of translational motion. Exploiting this analogy, we can then use the same results and insights gained in earlier chapters to introduce a third conservation law.

## 11.1 Circular motion at constant speed

Figure 11.2 shows two examples of circular motion: a block dragged along a circle by a rotating turntable and a puck constrained by a string to move in a circle. The block and puck are said to revolve around the vertical axis through the center of each circular path. Note that the axis about which they revolve is external to the block and puck and perpendicular to the plane of rotation. This is the definition of revolve—to move in circular motion around an external center. Objects that turn about an internal axis, such as the turntable in Figure 11.2a, are said to rotate. These two types of motion are closely related because a rotating object can be considered as a system of an enormous number of particles, each revolving around the axis of rotation.

Figure 11.2 Examples of circular motion.



(b) Tethered puck revolves on air table



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CONCEPTS

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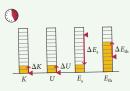
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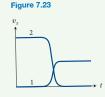
### Self-quiz

- 1. Two carts are about to collide head-on on a track. The inertia of cart 1 is greater than the inertia of cart 2, and the collision is elastic. The speed of cart 1 before the collision is higher than the speed of cart 2 before the collision. (a) Which cart experiences the greater acceleration during the collision? (b) Which cart has the greater change in momentum due to the collision? (c) Which cart has the greater change in kinetic energy during the collision?
- 2. Which of the following deformations are reversible and which are irreversible: (a) the deformation of a tennis ball against a racquet, (b) the deformation of a car fender during a traffic accident, (c) the deformation of a balloon as it is blown up, (d) the deformation of fresh snow as you walk through it?
- 3. Translate the kinetic energy graph in Figure 7.2 into three sets of energy bars: before the collision, during the collision, and after the collision. In each set, include a bar for K<sub>1</sub>, a bar for K<sub>2</sub>, and a bar for the internal energy of the system, and assume that the system is closed.
- 4. Describe a scenario to fit the energy bars shown in Figure 7.22. What happens during the interaction?

Figure 7.2

K U E<sub>s</sub> E<sub>th</sub>

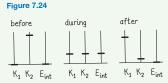




5. Describe a scenario to fit the velocity-versus-time curves for two colliding objects shown in Figure 7.23. What happens to the initial energy of the system of colliding objects during the interaction?

### **Answers**

- 1. (a) The cart with the smaller inertia experiences the greater acceleration (see Figure 7.2). (b) The magnitude of  $\Delta \vec{p}_1$  is the same as the magnitude of  $\Delta \vec{p}_2$ , but the changes are in opposite directions because the momentum of the system does not change during the collision. (c)  $|\Delta K_1| = |\Delta K_2|$ , but the changes are opposite in sign because the kinetic energy of the system before the elastic collision has to be the same as the kinetic energy of the system afterward.
- (a) Reversible. The ball returns to its original shape. (b) Irreversible. The fender remains crumpled. (c) Irreversible.
  The balloon does not completely return to its original shape after deflation. (d) Irreversible. Your footprints remain.
- 3. See Figure 7.24. Before the collision  $K_1=0$ ,  $K_2$  is maximal, and  $E_{\rm int}=0$ ; during the collision  $K_1$ ,  $K_2$ , and  $E_{\rm int}$  are all about one-third of the initial value of  $K_1$ ; after the collision  $K_1$  is about 7/8 of the initial value of  $K_1$ ,  $K_2$  is about 1/8 of the initial value of  $K_1$ , and  $E_{\rm int}=0$ . Because the system is closed, its energy is constant, which means the sum of the three bars is always the same.

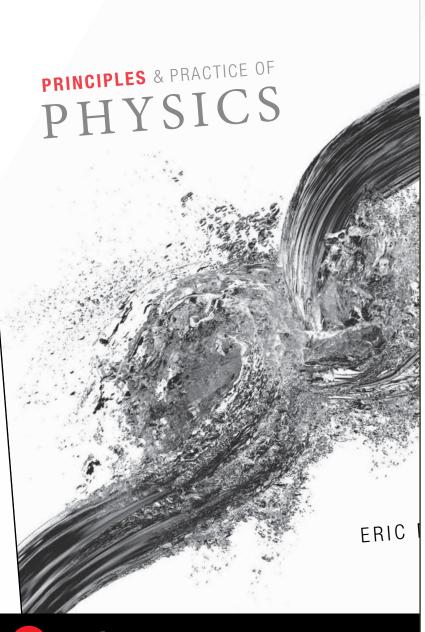


- 4. During the interaction, eight units of source energy is converted to two units of kinetic energy, two units of potential
- verted to two units of kinetic energy, two units of potential energy, and four units of thermal energy. One possible scenario is the vertical launching of a ball. Consider the system comprising you, the ball, and Earth from just before the ball is launched until after it has traveled some distance upward: The source energy goes down (you exert some effort), thermal energy goes up (in the process of exerting effort you heat up), kinetic energy goes up (the ball was at rest before the launch), and so does potential energy (the distance between the ground and the ball increases).
- 5. The graph represents an inelastic collision because the relative velocity of the two objects decreases to about half its initial value. In order for the momentum of the system to remain constant, the inertia of object 1 must be twice that of object 2. Possible scenario: Object 2, inertia *m*, collides inelastically with object 1, inertia 2*m*. The collision brings object 2 to rest and sets object 1 in motion. The interaction converts the initial kinetic energy of object 2 to kinetic energy of cart 1 and to thermal energy and/or incoherent configuration energy of both carts.

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QUANTITATIVE TOOLS

### 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 6.13b).\* Observer B sees the event at position  $\vec{r}_{\text{Be}}$  at clock reading  $t_{\text{Be}}$ . 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

$$t_{Ae} = t_{Be}. ag{6.1}$$

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

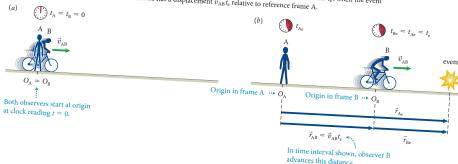
$$t_{\rm A} = t_{\rm B} = t. \tag{6.2}$$

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

$$\vec{r}_{Ae} = \vec{r}_{AB} + \vec{r}_{Be} = \vec{v}_{AB} t_e + \vec{r}_{Be}.$$
 (63)

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  $\vec{v}_{AB}t_{\rm e}$  relative to reference frame A.



<sup>\*</sup>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  $\underline{A}$ 's measurement of the position at which the event

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### 6.5 Galilean relativity

where—and if the two observers have synchronized their (identical) clocks, they both observe the event at the same clock readings, which means

# build to On Conceptual Because the clock readings of the two observers always agree, we can omit the

$$t_{A} = t_{B} = t. \tag{6.2}$$

From Figure 6 inderso pointings to  $\Delta t = t_r - 0 = t_r$ , and so  $r_{AR} = v_{AR} t_r$  because moves at constant velocity  $\sigma$ 

$$\vec{r}_{Ae} = \vec{r}_{AB} + \vec{r}_{Be} = \vec{v}_{AB} t_e + \vec{r}_{Be}.$$
 (63)

Equations 6.2 confirmed to data or Carlo de Cted play et a verse de Cted play equations so that they give the values of time and position in reference frame B

3 Two observers maying relative to each the state the same reconstruction of the least th



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(b) From Figure 10.18 I see that  $\tan \theta = |F_{\text{sp}x}^{\text{c}}|/|F_{\text{sp}y}^{\text{c}}|$ . For  $\theta < 45^{\circ}$ , tan  $\theta < 1$ , and so  $|F_{\rm sp}^{\rm c}| < |F_{\rm spy}^{\rm c}|$ . Because  $|F_{\rm spy}^{\rm c}| = F_{\rm Ep}^{\rm G}$ and  $|F_{\text{sp.x}}^{\text{c}}| = F_{\text{rp}}^{\text{c}}$ , I find that for  $\theta < 45^{\circ}$ ,  $F_{\text{rp}}^{\text{c}} < F_{\text{Ep}}^{G}$ . When  $\theta > 45^{\circ}$ , tan  $\theta > 1$ , and so  $|F_{\rm sp.x}^{\rm c}| > |F_{\rm sp.y}^{\rm c}|$  and  $F_{\rm rp}^{\rm c} > F_{\rm Ep}^{\rm G}$ .

(c)  $|\vec{F}_{\text{spy}}^{\text{c}}| = F_{\text{Ep}}^{G}$  and  $F_{\text{sp}}^{\text{c}} = \sqrt{(F_{\text{spx}}^{\text{c}})^{2} + (F_{\text{spy}}^{\text{c}})^{2}}$ . Therefore,  $F_{\text{sp}}^{\text{c}}$  must always be larger than  $F_{\text{Ep}}^{G}$  when  $\theta \neq 0$ . 4 EVALUATE RESULT I know from experience that you have to

pull harder to move a swing farther from its equilibrium position, and so my answer to part a makes sense. With regard to part b, when the swing is at rest at 45°, the forces  $\vec{F}_{rp}^c$  and  $\vec{F}_{Ep}^G$ on your friend make the same angle with the force  $F_{\rm sp}^{\rm rc}$ , and so  $\vec{F}_{\mathrm{rp}}^{\mathrm{c}}$  and  $\vec{F}_{\mathrm{Ep}}^{G}$  should be equal in magnitude. The force of gravity is independent of the angle, but the force exerted by the rope increases with increasing angle, and so it makes sense that for angles larger than 45°,  $\vec{F}_{\rm rp}^c$  is larger than  $\vec{F}_{\rm Ep}^G$ . In part c, because the vertical component of the force  $\vec{F}_{sp}^c$  exerted by the seat on your friend always has to be equal to the force of gravity, adding a horizontal component makes  $\vec{F}_{\rm sp}^{\rm c}$  larger than  $\vec{F}_{\rm Ep}^{\rm G}$ , as I found.

10.4 You decide to move a heavy file cabinet by sliding it across the floor. You push against the cabinet, but it doesn't budge. Draw a free-body diagram for it.

### 10.4 Friction

The force that opposes your push on the file cabinet in Checkpoint 10.4—the tangential component of the contact force exerted by the floor on the cabinet—has to do with friction. If the floor were very slick or if the cabinet had casters, there would be little friction and your push would easily move the cabinet. Instead, you have to lean against it with all your strength until, with a jerk, it suddenly begins to slide. Once you get the cabinet moving, you must keep pushing to keep it in motion. If you stop pushing, friction stops the motion.

**10.5** (a) Suppose you push the file cabinet just enough to keep it moving at constant speed. Draw a free-body diagram for the cabinet while it slides at constant speed. (b) Suddenly you stop pushing. Draw a free-body diagram for the file cabinet at

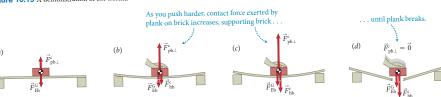
Don't skip Checkpoint 10.5! It will be harder to understand the rest of this section if you haven't thought about

Even though the normal and tangential components of the contact force exerted by the floor on the cabinet belong to the same interaction, they behave differently and are usually treated as two separate forces: the normal component being called the normal force and the tangential component being called the force of friction.

To understand the difference between normal and frictional forces, consider a brick on a horizontal wooden plank supported at both ends (Figure 10.19a). Because the brick is at rest, the normal force  $\vec{F}_{pb\perp}^c$  exerted by the plank on it is equal in magnitude to the gravitational force exerted on it. Now imagine using your hand to push down on the brick with a force  $\vec{F}_{hb}^c$ . Your downward push increases the total downward force exerted on the brick, and, like a spring under compression, the plank bends until the normal force it exerts on the brick balances the combined downward forces exerted by your hand and by Earth on the brick (Figure 10.19b). As you push down harder, the plank bends more, and the normal force continues to increase (Figure 10.19c) until you exceed the plank's capacity to provide support and it snaps, at which point the normal force suddenly disappears (Figure 10.19d). So, normal forces take on whatever value is required to prevent whatever is pushing down on a surface from moving through that surface up to the breaking point of the supporting material.

Next imagine that instead of pushing down on the brick of Figure 10.19a, you gently push it to the right, as in Figure 10.20. As long as you don't push hard, the brick remains at rest. This tells you that the horizontal forces exerted on the brick add to zero, and so the plank must be exerting on the brick a horizontal frictional force that is equal in magnitude to your push but in the opposite direction. This horizontal force is caused by microscopic bonds between the surfaces in contact. Whenever two objects are placed in contact, such bonds form at the extremities of microscopic bumps on the surfaces of the objects. When you try to slide the surfaces past each other, these tiny bonds prevent sideways motion. As you push the brick to the right, the bumps resist bending and, like microscopic springs, each bump exerts a force to the left. The net effect of all these microscopic forces is to hold the brick in place. As you increase the force of your push, the bumps resist bending more and the tangential component of the contact force grows. This friction exerted by surfaces that are not moving relative to each other is called static friction.

Figure 10.19 A demonstration of the normal force.



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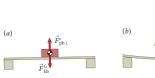
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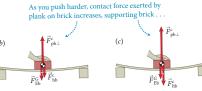
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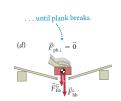
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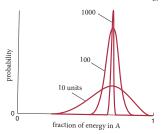
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Figure 19.14 Probability of finding a given fraction of the system's energy in compartment A of the box in Figure 19.13. As the number of energy units increases from 10 to 1000, the probability distribution becomes narrower but remains centered about the mean energy.



basic states available to the system is obtained by multiplying  $\Omega_A$  by  $\Omega_B$ :  $\Omega = \Omega_A \Omega_B$ .

The probability of each macrostate is obtained by dividing  $\Omega$ , the number of basic states associated with that macrostate, by  $\Omega_{\mathrm{tot}}$ , the number of basic states associated with all macrostates (2.00  $\times$  10<sup>7</sup>; see Table 19.2). The table shows you that this probability is greatest for the macrostate  $E_A = 7$ , as you would expect. Given that there are 14 particles in A and six in B, on average each particle has half an energy unit, and so the  $E_A = 7$  macrostate corresponds to an equipartitioning of the energy. The curve labeled 10 units in Figure 19.14 shows this probability as a function of the fraction of energy contained in A.

### **Example 19.6 Probability of macrostates**

In Figure 19.13, after a very large number of particle-partition collisions have occurred, what is the probability of finding the system in (a) the macrostate  $E_A = 1$  and (b) the macrostate  $E_{\Lambda} = 7$ ?

• GETTING STARTED Because all basic states are equally likely, the probability of finding the system in macrostate  $E_{\rm A}$  is equal to the fraction  $\Omega/\Omega_{\rm tot}$  where  $\Omega$  is the number of basic states of the system associated with the macrostate  $E_{\rm A}$  and  $\Omega_{\rm tot}$  is the total number of basic states associated with all macrostates  $(2.00 \times 10^7; Table 19.2).$ 

2 DEVISE PLAN To find the probability of a given macrostate  $E_{\rm A},$  I divide the value of  $\Omega$  for that macrostate given in Table 19.2 by  $\Omega_{\rm tot} = 2.00 \times 10^7$ .

**3 EXECUTE PLAN** (a) For  $E_A = 1$ , Table 19.2 tells me that  $\Omega = 2.80 \times 10^4$ . The probability of macrostate  $E_A = 1$  is thus  $(2.80 \times 10^4)/(2.00 \times 10^7) = 1.40 \times 10^{-3}$ 

(b) For the macrostate  $E_{\rm A}=7,\Omega=4.34\times10^6$ . So the probability of this macrostate occurring is  $(4.34 \times 10^6)/(2.00 \times 10^7) =$  $2.17 \times 10^{-1}$ .

4 EVALUATE RESULT My result shows that the macrostate  $E_{\scriptscriptstyle A}=7$  is more than 150 times more probable than the macrostate  $E_{\rm A}=1$ . This makes sense because, as we saw earlier, the macrostate  $E_A = 7$  is the equilibrium state for which there is an equipartition of energy.

If we increase the number of energy units in the box of Figure 19.13 to 100 or 1000, the number of basic states grows exponentially, and if we plot the probability of each macrostate as a function of the fraction of energy in A, we obtain the two curves labeled 100 and 1000 in Figure 19.14. Just as we saw in Figure 19.7, the most probable macrostate doesn't change, but the probability peaks much more narrowly around this state. In other words, the most probable macrostate—the equilibrium state—is now even more likely than any other macrostate.

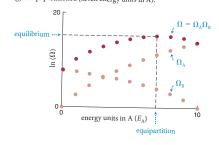
Note that the number of basic states is very large, even with just ten energy units and 20 particles. In a box of volume 1 m³ containing air at atmospheric pressure and room temperature, there are on the order of 1025 particles and 10<sup>20</sup> energy units per particle, and so the number of basic states becomes unimaginably large—on the order of ten raised to the power 10<sup>21</sup>! Because the number of basic states is so large, it is more convenient to work with the natural logarithm of that number. As you can see from the rightmost column in Table 19.2, the natural logarithm of the number of basic states is indeed much more manageable.

**Figure 19.15** shows how the natural logarithms of  $\Omega_A$ ,  $\Omega_B$ , and  $\Omega$  vary with the number of energy units in compartment A in Figure 19.13. As you can see, the natural logarithm of the number of basic states changes much less rapidly than the number of basic states. Note that as  $E_{\rm A}$  increases, the number of basic states  $\Omega_A$  increases. As  $E_A$  increases, however,  $E_B$ decreases and so  $\Omega_{\rm B}$  decreases. The number of basic states  $\Omega$  is maximum when  $E_A = 7$  and  $E_B = 3$ , representing an equipartition of energy. The most probable macrostate (equilibrium) is achieved when there is equipartition of energy.

19.15 What is the average energy per particle in compartments A and B in Figure 19.13 (a) when there is one energy unit in A and (b) when the system is at equilibrium?

As you can see from Table 19.2, with  $E_{\rm A}=1$  the number of basic states for the system (2.80 imes 10 $^4$ ) is more than 100 times smaller than it is at equilibrium ( $E_A = 7$ ,  $\Omega = 4.34 \times 10^6$ ). Collisions between the particles and the partition redistribute

Figure 19.15 Natural logarithm of the number of basic states for compartment A, for compartment B, and for the two compartments in Figure 19.13 combined. The number of basic states is maximal when the energy is equipartitioned (seven energy units in A).



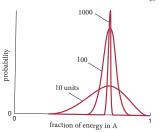
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### Example 19.6 Probability of macrostates

In Figure 19.13, after a very large number of particle-partion collisions have occurred, what is the probability of finding system in (a) the macrostate  $E_A = 1$  and (b) the macrostate  $E_A = 7$ ?

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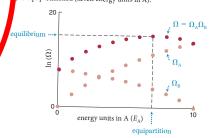
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### **Example 19.6 Probability of macrostates**

In Figure 19.13, after a very large number of particle-partition collisions have occurred, what is the probability of finding the system in (a) the macrostate  $E_A = 1$  and (b) the macrostate  $E_A = 7$ ?

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### **Example 19.6 Probability of macrostates**

In Figure 19.13, after a very large number of particle-partition collisions have occurred, what is the probability of finding the system in (a) the macrostate  $E_A = 1$  and (b) the macrostate  $E_A = 7$ ?

- **GETTING STARTED** Because all basic states are equally likely, the probability of finding the system in macrostate  $E_A$  is equal to the fraction  $\Omega/\Omega_{\rm tot}$ , where  $\Omega$  is the number of basic states of the system associated with the macrostate  $E_A$  and  $\Omega_{\rm tot}$  is the total number of basic states associated with all macrostates  $(2.00 \times 10^7; \text{ Table 19.2}).$
- **2 DEVISE PLAN** To find the probability of a given macrostate  $E_{\rm A}$ , I divide the value of  $\Omega$  for that macrostate given in Table 19.2 by  $\Omega_{\rm tot} = 2.00 \times 10^7$ .
- **3 EXECUTE PLAN** (a) For  $E_A = 1$ , Table 19.2 tells me that  $\Omega = 2.80 \times 10^4$ . The probability of macrostate  $E_A = 1$  is thus  $(2.80 \times 10^4)/(2.00 \times 10^7) = 1.40 \times 10^{-3}$ .
- (b) For the macrostate  $E_A = 7$ ,  $\Omega = 4.34 \times 10^6$ . So the probability of this macrostate occurring is  $(4.34 \times 10^6)/(2.00 \times 10^7) = 2.17 \times 10^{-1}$ .
- **EVALUATE RESULT** My result shows that the macrostate  $E_A = 7$  is more than 150 times more probable than the macrostate  $E_A = 1$ . This makes sense because, as we saw earlier, the macrostate  $E_A = 7$  is the equilibrium state for which there is an equipartition of energy.

**19y** 

fication of collisions

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al energy

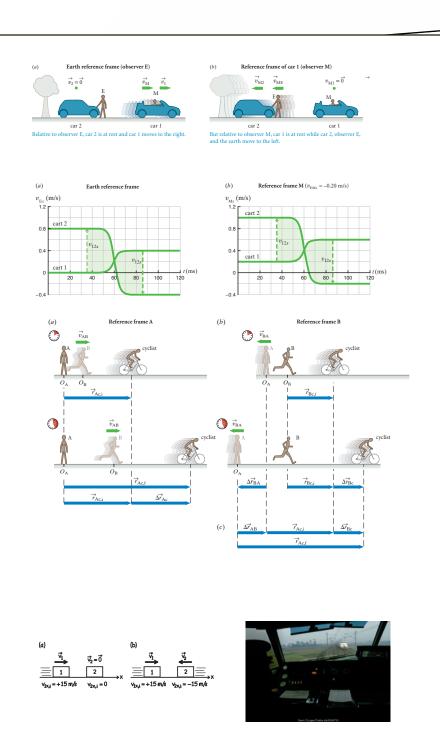
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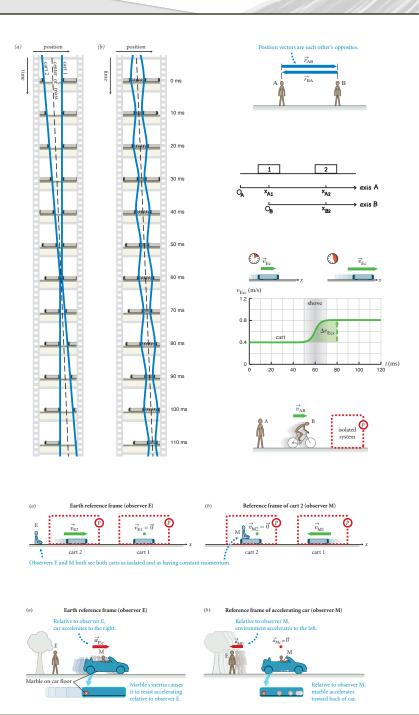
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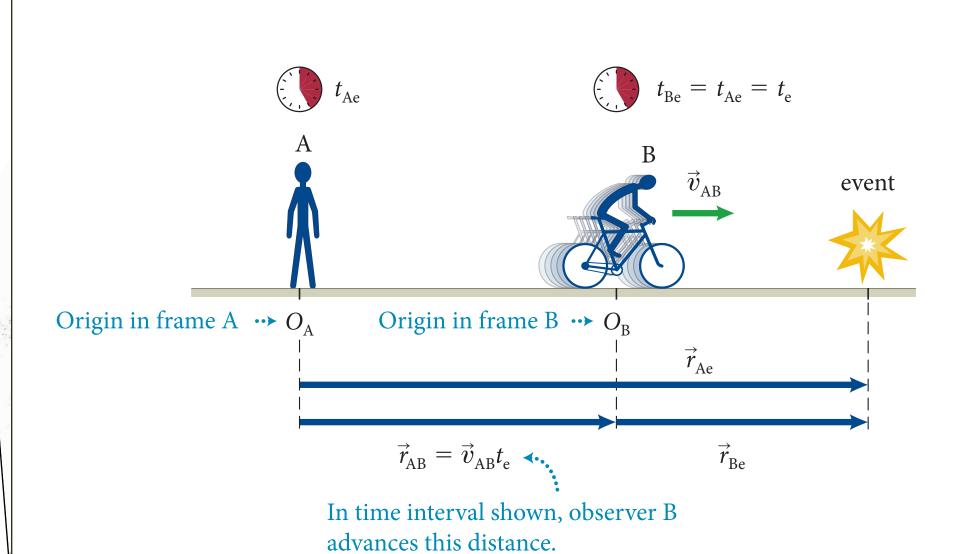
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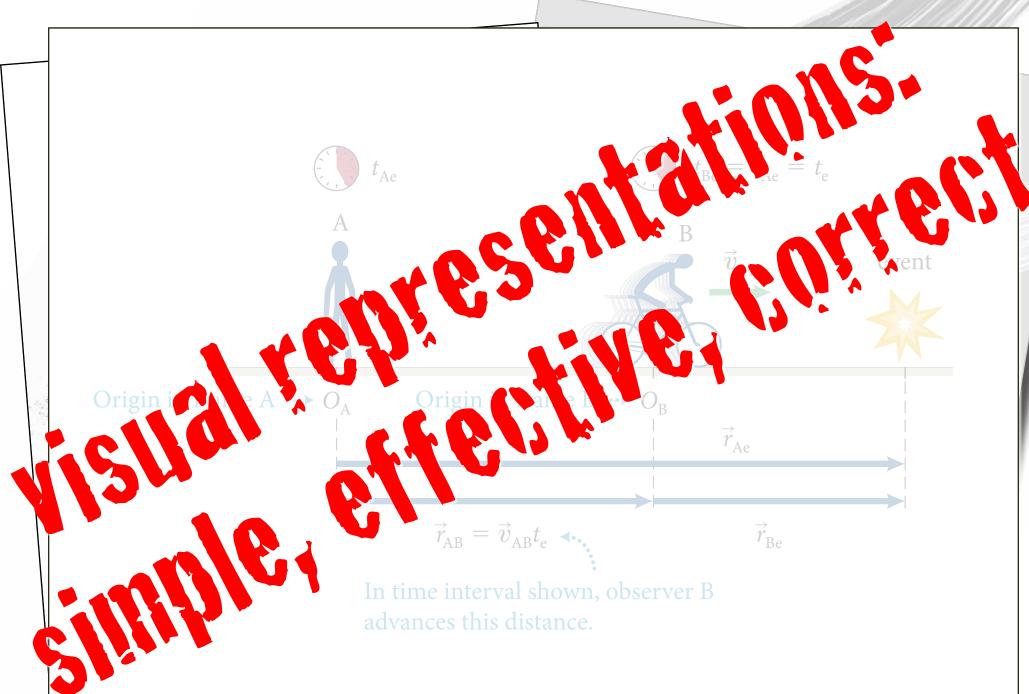
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sive separations









## **PRINCIPLES VOLUME**

respective reference frames and clocks (Figure 6.13). Let the origins of observers' reference frames coincide at t = 0 (Figure 6.13a). Observer A event as happening at position  $\vec{r}_{Ae}$  at clock reading  $t_{Ae}$  (Figure 6.13b).\* Observer the event at position  $\vec{r}_{Be}$  at clock reading  $t_{Be}$ . What is the relations tween these clock readings and positions?

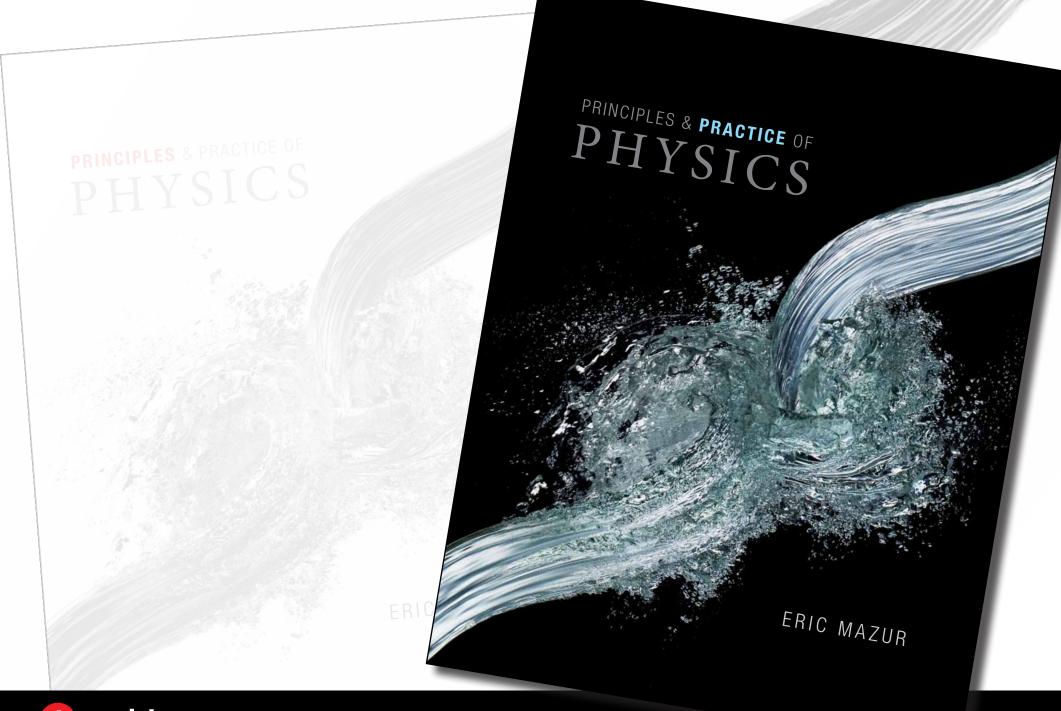
It, as we discussed in Chapter 1, we assume time is absolute—the same every where—and if the two observers have synchronized their (identical) clocks, the

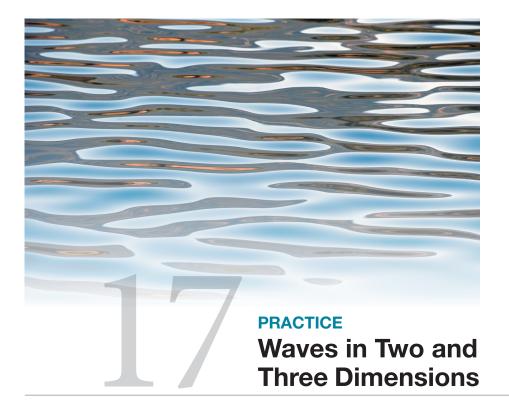
- concepts before quantitative tools
  - subscripts referring to the reference frames:
- checkpoints to thinking on  $\bar{r}_{AB}$  of observer B in reference frame A at instant  $t_s$  is equal to persplacement over the time interval  $\Delta t = t_s 0 = t_s$ , and so  $\bar{r}_{AB} = \bar{v}_{AB} t_s$  because B moves at constant velocity
- 4-step worked examples to collected in one reference frame to data on the same evaluation of these has to be at rest relative to Earth but their ordinine must coincide at t = 0). To this and we constant the
- research-based illustrations
- research-based pedagogy



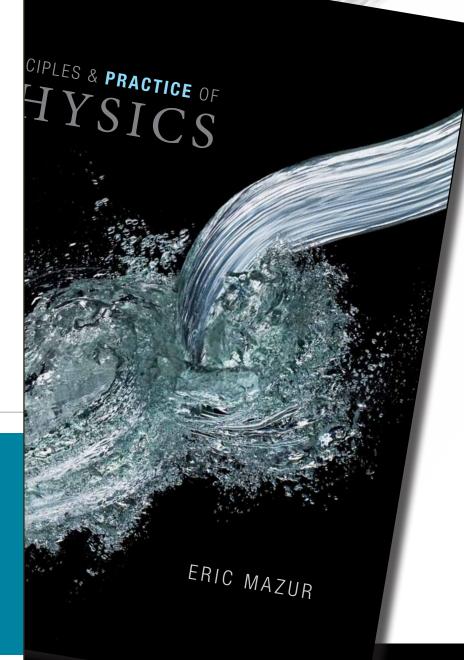
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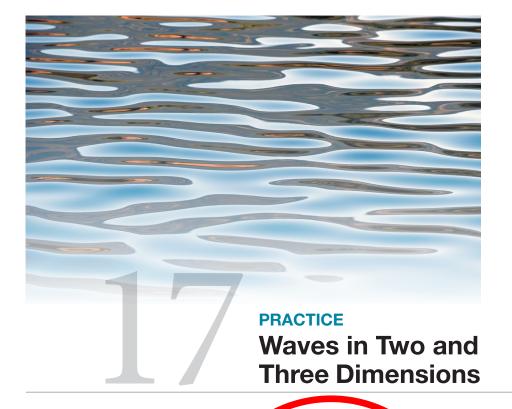
\*Remember our subscript form: The capital letter refers to the reference frame; the lowercase e is fe





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CIPLES & PRACTICE OF

HYSICS ERIC MAZUR

# Waves in Two and Three Dimensions

**Chapter Summary 304** 

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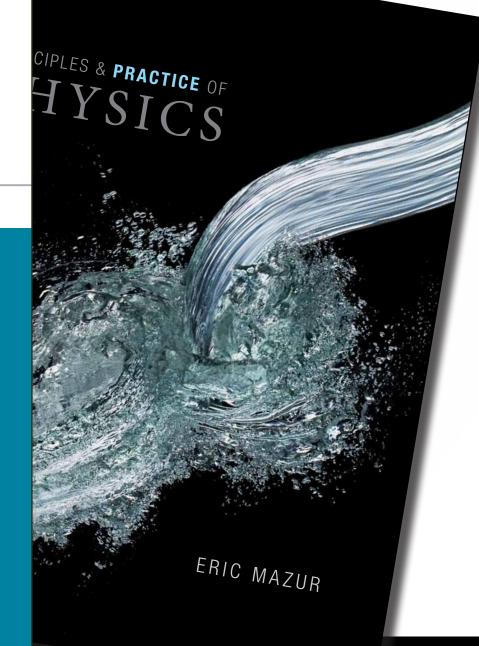
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# Waves in Two and Three Dimensions

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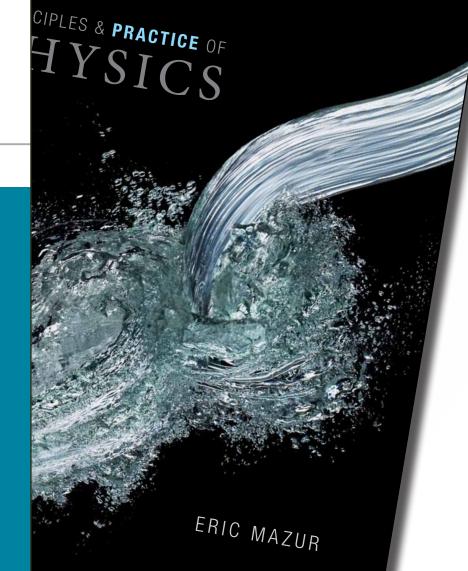
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PRACTICE

# **Waves in Two Three Dimens**

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192 CHAPTER 11 PRACTICE MOTION IN A CIRCLE

### 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 speed v of a point on the equator as Earth rotates (D, P)
- 2. The rotational inertia of a bowling ball about an axis tangent to
- 3. Your rotational inertia as you turn over in your sleep (V, C)
- 4. The angular momentum around the axle of a wheel/tire combination on your car as you cruise on the freeway (E, I, O, AA, S)
- 5. The angular momentum of a spinning ice skater with each arm held out to the side and parallel to the ice (G, X, N, U)
- 6. The speed you would need to orbit Earth in a low orbit (F,P)
- 7. The magnitude of the force exerted by the Sun on Earth to hold
- 8. The kinetic energy associated with Earth's rotation (Z, P, D)
- 9. The angular momentum, about a vertical axis through your house, of a large car driving down your street (H, Y, M)
- 10. The kinetic energy of a spinning yo-yo (K, W, J, Q)

If needed, see Key for answers to these guiding questions.

- A. What is the inertia of a bowling ball? B. How long a time interval is needed for Earth to make one revolu-
- C. What simple geometric shape is an appropriate model for a sleeping person?
- D. What is Earth's rotational speed?
- E. What is the combined inertia of the wheel and tire?
- F. What is the relationship between force and acceleration for this
- G. How can you model the skater's shape during her spin?
- H. What is the inertia of a midsize car?
- I. What is the radius of the tire? J. How many turns are needed to rewind the yo-yo?
- K. What is the yo-yo's rotational inertia?
- L. What is the radius of Earth's orbit?
- M. What is the perpendicular distance from the house to the car's
- N. What is the skater's rotational inertia with arms held out?
- O. How can you model the combined rotational inertia of the wheel
- P. What is Earth's radius?
- Q. What is the final rotational speed?
- R. What is the radius of a bowling ball?
- S. What is the rotational speed of the tire?
- T. What is the required centripetal acceleration?

- U. What is the skater's initial rotational speed?
- W. When thrown, how long a time interval does the yo-yo take to
- X. What is needed in addition to the formulas in Principles Table 11.3 in order to determine this quantity?
- Y. What is a typical speed for a car moving on a city street?
- Z. What is Earth's inertia?
- AA. What is a typical freeway cruising speed?

### Key (all values approximate)

A. 7 kg; B. 1 y =  $3 \times 10^7$  s; C. solid cylinder of radius 0.2 m; D. period = 24 h, so  $\omega = 7 \times 10^{-5} \text{ s}^{-1}$ ; E.  $10^1 \text{ kg}$ ; F. from Eqs. 8.6, 8.17, and 11.16,  $\Sigma \vec{F} = m\vec{a}$ , so  $mg = mv^2/r$ ; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H.  $2 \times 10^3$  kg; I. 0.3 m; J.  $2 \times 10^1$  turns; K.  $6 \times 10^{-5}$  kg·m² (with yo-yo modeled as solid cylinder);  $L.2 \times 10^{11}$  m;  $M.2 \times 10^{1}$  m; N.4 kg·m<sup>2</sup>; O. between  $MR^2$ (cylindrical shell representing tire) and  $MR^2/2$  (solid cylinder representing wheel)—say,  $3MR^2/4$ ; P.  $6 \times 10^6$  m; Q. about twice the average rotational speed, or  $\omega = 5 \times 10^2 \text{ s}^{-1}$ ; R. 0.1 m; S. no slipping, so  $\omega = v/r \approx 10^2 \, \text{s}^{-1}$ ; T. 8 × 10<sup>-3</sup> m/s<sup>2</sup>; U.  $\omega \approx 10~{\rm s}^{-1};~{\rm V.7}\times 10^1~{\rm kg};~{\rm W.0.5~s;}~{\rm X.~the~parallel-axis}$ theorem; Y. 3  $\times$  10  $^{1}$  mi/h; Z. 6  $\times$  10  $^{24}$  kg; AA. 3  $\times$  10  $^{1}$  m/s

# **Waves in Two Three Dimens**

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192 CHAPTER 11 PRACTICE MOTION IN A CIRCLE

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- 5. The angular momentum of a spinning ice skater with each arm held out to the side and parallel to the ice (G, X, N, U)
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# **Waves in Two Three Dimens**

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192 CHAPTER 11 PRACTICE MOTION IN A CIRCLE

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### What is Earth's radius?

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- AA. What is a typical freeway cruising speed?

### Key (all values approximate)

A. 7 kg; B. 1  $y = 3 \times 10^7$  s; C. solid cylinder of radius 0.2 m; D. period = 24 h, so  $\omega = 7 \times 10^{-5} \text{ s}^{-1}$ ; E.  $10^1 \text{ kg}$ ; F. from Eqs. 8.6, 8.17, and 11.16,  $\Sigma \vec{F} = m\vec{a}$ , so  $mg = mv^2/r$ ; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H.  $2 \times 10^3$  kg; I. 0.3 m; J.  $2 \times 10^1$  turns; K.  $6 \times 10^{-5}$  kg·m² (with yo-yo modeled as solid cylinder);  $L.2 \times 10^{11}$  m; M.  $2 \times 10^{1}$  m; N.  $4 \text{ kg} \cdot \text{m}^2$ ; O. between MR<sup>2</sup> (cylindrical shell representing tire) and  $MR^2/2$  (solid cylinder representing wheel)—say,  $3MR^2/4$ ; P.  $6 \times 10^6$  m; Q. about twice the average rotational speed, or  $\omega = 5 \times 10^2 \text{ s}^{-1}$ ; R. 0.1 m; S. no slipping, so  $\omega = v/r \approx 10^2 \, \text{s}^{-1}$ ; T. 8 ×  $10^{-3} \, \text{m/s}^2$ ; U.  $\omega \approx 10~{\rm s}^{-1};~V.7 \times 10^1$  kg; W. 0.5 s; X. the parallel-axis theorem; Y. 3  $\times$  10  $^{1}$  mi/h; Z. 6  $\times$  10  $^{24}$  kg; AA. 3  $\times$  10  $^{1}$  m/s

# **Waves in Two Three Dimens**

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192 CHAPTER 11 PRACTICE MOTION IN A CIRCLE

### 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 speed v of a point on the equator as Earth rotates (D, P)
- 2. The rotational inertia of a bowling ball about an axis tangent to
- 3. Your rotational inertia as you turn over in your sleep
- 4. The angular momentum around the axle of a wheel/ nation on your car as you cruise on the freeway (E, O, AA, S)
- 5. The angular momentum of a spinning ice skater, ith each arm held out to the side and parallel to the ice (G, )
- 6. The speed you would need to orbit Earth in a low orbit (F, P)  $\bar{}$
- 7. The magnitude of the force exerted by the Sun on Earth to hold
- 8. The kinetic energy associated with Earth's rotation (Z, P, D)
- 9. The angular momentum, about a vertical axis through your house, of a large car driving down your street (H, Y, M)
- 10. The kinetic energy of a spinning yo-yo (K, W, J, Q)

If needed, see Key for answers to these guiding questions.

- A. What is the inertia of a bowling by B. How long a time interval is needed for Earth to make one revolu-
- e is an appropriate model for a tion around the Sun? C. What simple geometric sha sleeping person?
- D. What is Earth's rotationa
- E. What is the combined inertia of the wheel and tire?
- F. What is the relations p between force and acceleration for this
- G. How can you model the skater's shape during her spin
- H. What is the ine ia of a midsize car?
- I. What is the radius of the tire? J. How many arns are needed to rewind the yo-yo?
- K. What is the yo-yo's rotational inertia?
- L. What is he radius of Earth's orbit? M. What the perpendicular distance from the house to the car's
- at is the skater's rotational inertia with arms held out?
- by can you model the combined rotational inertia of the wheel

- Q. What is the final rotational speed?
- R. What is the radius of a bowling ball?
- S. What is the rotational speed of the tire?
- T. What is the required centripetal acceleration?

- U. What is the skater's initial rotational speed?
- W. When thrown, how long a time interval does the yo-yo take to X. What is needed in addition to the formulas in Principles
- Table 11.3 in order to determine this quantity? Y. What is a typical speed for a car moving on a city street?
- Z. What is Earth's inertia?
- AA. What is a typical freeway cruising speed?

### Key (all values approximate)

A. 7 kg; B. 1  $y = 3 \times 10^7$  s; C. solid cylinder of radius 0.2 m; D. period = 24 h, so  $\omega = 7 \times 10^{-5} \text{ s}^{-1}$ ; E.  $10^1 \text{ kg}$ ; F. from Eqs. 8.6, 8.17, and 11.16,  $\Sigma \vec{F} = m\vec{a}$ , so  $mg = mv^2/r$ ; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H.  $2 \times 10^3$  kg; I. 0.3 m; J.  $2 \times 10^1$  turns; K.  $6 \times 10^{-5}$  kg·m² (with yo-yo modeled as solid cylinder); L.  $2 \times 10^{11}$  m; M.  $2 \times 10^{1}$  m; N.  $4 \text{ kg} \cdot \text{m}^2$ ; O. between MR<sup>2</sup> (cylindrical shell representing tire) and  $MR^2/2$  (solid cylinder the average rotational speed, or  $\omega = 5 \times 10^2 \text{ s}^{-1}$ ; R. 0.1 m; S. no slipping, so  $\omega = v/r \approx 10^2 \, \text{s}^{-1}$ ; T. 8 ×  $10^{-3} \, \text{m/s}^2$ ; U.  $\omega \approx 10~\text{s}^{-1};~V.7 \times 10^1$  kg; W. 0.5 s; X. the parallel-axis theorem; Y. 3  $\times$  10  $^{1}$  mi/h; Z. 6  $\times$  10  $^{24}$  kg; AA. 3  $\times$  10  $^{1}$  m/s

# **Waves in Two Three Dimens**

**Chapter Summary** 304 **Review Questions 305** 

**Developing a Feel** 

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### 192 CHAPTER 11 PRACTICE MOTION IN A CIRCLE

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- 2. The rotational inertia of a bowling ball about an axis tangent to
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- 5. The angular momentum of a spinning ice skater ith each arm held out to the side and parallel to the ice (G,
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- 7. The magnitude of the force exerted by the Sun on E Earth in orbit (B, L, T, Z)
- 8. The kinetic energy associated with Earth's rotation (
- 9. The angular momentum, about a vertical axis thr house, of a large car dri
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- Q. What is the final rotational speed?
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- S. What is the rotational speed of the tire?
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- Z. What is Earth's inertia? AA. What is a typical freeway cruising speed?

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# Waves in Two and Three Dimensions

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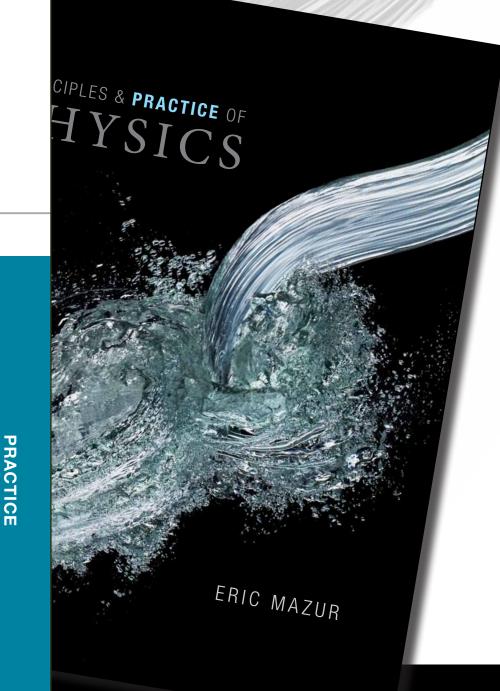
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# Waves in Two a **Three Dimension**

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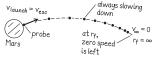
**Answers to Guided Problems 316** 

238 CHAPTER 13 PRACTICE GRAVITY

## Worked Problem 13.3 Escape at last

The Mars Colony wants to launch a deep-space probe, but they have no rocket engines. They decide to launch a probe with an electromagnetic cannon, which means they must launch at escape speed.

**1 GETTING STARTED** Let us do a quick sketch to help our thinking (Figure WG13.3). We select the Mars-probe system for analysis. In order to reach "deep space," the probe must attain a very great distance from Mars. This will require a significant amount of initial kinetic energy, which the probe must acquire during launch. After launch, the kinetic energy immediately begins to decrease, and the potential energy of the Mars-probe system increases as the separation distance increases. We assume a reference frame where Mars is fixed and only the probe moves. When the probe is far enough away (infinity, really, but practically it doesn't need to go quite this far), the kinetic energy has its minimum value, which we can take to be zero because the colonists presumably do not want to supply any more energy than needed to get the probe out there. The gravitational potential energy has its maximum value, which is also zero. (Remember that universal gravitational potential energy is negative.) We also assume that the Sun and other planets have a negligible influence on our system, and we ignore the rotation of Mars.



2 DEVISE PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted to gravitational potential energy of the Mars-probe system. We want to know the initial speed of the probe acquired at launch. The initial potential energy is the value when the probe is still near the Martian surface. The final state of the probe is zero speed at an infinite distance from Mars. The Principles volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this version of an energy conservation equation for  $v_{\rm i}=v_{\rm esc}$  in terms of Guided Problem 13.4 Spring to the stars

Suppose that, instead of using chemical rockets, NASA decided to use a compressed spring to launch a spacecraft. If the spring constant is 100,000 N/m and the mass of the spacecraft is 10,000 kg, how far must the spring be compressed in order to launch the craft to a position outside Earth's gravitational influence?

## 1 GETTING STARTED

- Describe the problem in your own words. Are there similarities
- 2. Draw a diagram showing the initial and final states. What is the spacecraft's situation in the final state? 3. How does the spacecraft gain the necessary escape speed?

## 2 DEVISE PLAN

4. What law of physics should you invoke?

**3 EXECUTE PLAN** Let us use  $r_i$  for the initial Mars-probe radial center-to-center separation distance,  $r_1 = \infty$  for the final separation distance,  $R_{\rm M}$  for the radius of Mars, and  $m_{\rm M}$  and  $m_{\rm p}$  for the two masses. We begin with Eq. 13.23:

$$\begin{split} E_{\rm mech} &= \tfrac{1}{2} m_{\rm p} v_{\rm esc}^2 - G \frac{m_{\rm M} m_{\rm p}}{R_{\rm M}} = 0 \\ & \tfrac{1}{2} v_{\rm esc}^2 - G \frac{m_{\rm M}}{R_{\rm M}} = 0 \\ & \tfrac{1}{2} v_{\rm esc}^2 - G \frac{m_{\rm M}}{R_{\rm M}} \\ & v_{\rm esc} = \sqrt{2 G \frac{m_{\rm M}}{R_{\rm M}}} \\ & v_{\rm esc} = \sqrt{2 (6.67 \times 10^{-11} \, \mathrm{N} \cdot \mathrm{m}^2/\mathrm{kg}^2) \frac{6.42 \times 10^{23} \, \mathrm{kg}}{3.40 \times 10^6 \, \mathrm{m}}} \\ & = 5.02 \times 10^3 \, \mathrm{m/s} = 5 \, \mathrm{km/s}. \end{split}$$

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars's gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars's radius), and G. We expect  $v_{\rm esc}$  to increase with  $m_{\rm M}$  because the gravitational pull increases with increasing mass. We also expect  $v_{\rm esc}$  to decrease as the distance between the launch position and Mars's center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

An escape speed of 18,000 km/h is smaller than (but on the order of) the escape speed from Earth, and so the answer is not unreasonable.

We assumed that the initial Mars-probe separation distance is equal to the planet's radius. Of course, the length of the cannon may be tens of meters, but this tiny difference would have no impact on the numerical answer. We ignored the rotation of Mars, which could supply a small amount of the needed kinetic energy. We also ignored the effect of the Sun, which is fine for getting away from the surface of Mars, but we would need to account for it if the destina-

5. As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you

6. What equation allows you to relate the initial and final states?

#### **3** EXECUTE PLAN

- 7. What is your target unknown quantity? Algebraically isolate it on one side of your equation.
- 8. Substitute the numerical values you know to get a numerical

## **4** EVALUATE RESULT

- 9. Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth's mass and radius change?
- 10. If you were the head of a design team, would you recommend pursuing this launch method?

# Waves in Two a **Three Dimension**

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238 CHAPTER 13 PRACTICE GRAVITY

## Worked Problem 13.3 Escape at last

The Mars Colony wants to launch a deep-space probe, but they have no rocket engines. They decide to launch a probe with an electromagnetic cannon, which means they must launch at escape speed.

• GETTING STARTED Let us do a quick sketch to help our thinking (Figure WG13.3). We select the Mars-probe system for analysis. In order to reach "deep space," the probe must attain a very great distance from Mars. This will require a significant amount of initial kinetic energy, which the probe must acquire during launch. After launch, the kinetic energy immediately begins to decrease, and the potential energy of the Mars-probe system increases as the separation distance increases. We assume a reference frame where Mars is fixed and only the probe moves. When the probe is far enough away (infinity, really, but practically it doesn't need to go quite this far), the kinetic energy has its minimum value, which we can take to be zero because the colonists presumably do not want to supply any more energy than needed to get the probe out there. The gravitational potential energy has its maximum value, which is also zero. (Remember that universal gravitational potential energy is negative.) We also assume that the Sun and other planets have a negligible influence on our system, and we ignore the rotation of Mars.



**Q** DEVISE PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted to gravitational potential energy of the Mars-probe system. We want to know the initial speed of the probe acquired at launch. The initial potential energy is the value when the probe is still near the Martian surface. The final state of the probe is zero speed at an infinite distance from Mars. The Principles volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this version of an energy conservation equation for  $v_{\rm i}=v_{\rm esc}$  in terms of

## Guided Problem 13.4 Spring to the stars

Suppose that, instead of using chemical rockets, NASA decided to use a compressed spring to launch a spacecraft. If the spring constant is 100,000 N/m and the mass of the spacecraft is 10,000 kg, how far must the spring be compressed in order to launch the craft to a position outside Earth's gravitational influence?

## 1 GETTING STARTED

- Describe the problem in your own words. Are there similarities
- 2. Draw a diagram showing the initial and final states. What is the spacecraft's situation in the final state? 3. How does the spacecraft gain the necessary escape speed?

## 2 DEVISE PLAN

4. What law of physics should you invoke?

**3 EXECUTE PLAN** Let us use  $r_i$  for the initial Mars-probe radial center-to-center separation distance,  $r_l = \infty$  for the final separation distance,  $R_{\rm M}$  for the radius of Mars, and  $m_{\rm M}$  and  $m_{\rm p}$  for the two masses. We begin with Eq. 13.23:

$$\begin{split} E_{\rm mech} &= \tfrac{1}{2} m_{\rm p} v_{\rm esc}^2 - G \frac{m_{\rm M} m_{\rm p}}{R_{\rm M}} = 0 \\ & \tfrac{1}{2} v_{\rm esc}^2 - G \frac{m_{\rm M}}{R_{\rm M}} = 0 \\ & \tfrac{1}{2} v_{\rm esc}^2 - G \frac{m_{\rm M}}{R_{\rm M}} \\ & v_{\rm esc} = \sqrt{2 G \frac{m_{\rm M}}{R_{\rm M}}} \\ & v_{\rm esc} = \sqrt{2 (6.67 \times 10^{-11} \, \mathrm{N} \cdot \mathrm{m}^2/\mathrm{kg}) \frac{6.42 \times 10^{23} \, \mathrm{kg}}{3.40 \times 10^6 \, \mathrm{m}}} \\ & = 5.02 \times 10^3 \, \mathrm{m/s} = 5 \, \mathrm{km/s}. \end{split}$$

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars's gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars's radius), and G. We expect  $v_{\rm esc}$  to increase with  $m_{\rm M}$  because the gravitational pull increases with increasing mass. We also expect  $v_{\rm esc}$  to decrease as the distance between the launch position and Mars's center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

An escape speed of 18,000 km/h is smaller than (but on the order of) the escape speed from Earth, and so the answer is not unreasonable.

We assumed that the initial Mars-probe separation distance is equal to the planet's radius. Of course, the length of the cannon may be tens of meters, but this tiny difference would have no impact on the numerical answer. We ignored the rotation of Mars, which could supply a small amount of the needed kinetic energy. We also ignored the effect of the Sun, which is fine for getting away from the surface of Mars, but we would need to account for it if the destina-

- 5. As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you
- 6. What equation allows you to relate the initial and final states?

#### **3** EXECUTE PLAN

- 7. What is your target unknown quantity? Algebraically isolate it on one side of your equation.
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## **4** EVALUATE RESULT

- 9. Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth's mass and radius change?
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**Worked and Guided Problems** 

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## Worked Problem 13.3 Escape at last

The Mars Colony wants to launch a deep-space probe, but they have no rocket engines. They decide to launch a probe with an electromagnetic cannon, which means they must launch at escape speed.

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DEVISE PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted to gravitational potential energy of the Mars-probe system. We want to know the initial speed of the probe acquired at launch. The initial potential energy is the value when the probe is still near the Martian surface. The final state of the probe is zero speed at an infinite distance from Mars. The Principles volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this version of an energy conservation equation for  $v_{\rm i}=v_{\rm esc}$  in terms of

## Guided Problem 13.4 Spring to the stars

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## **1** GETTING STARTED

- Describe the problem in your own words. Are there similarities
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- 3. How does the spacecraft gain the necessary escape speed?

## 2 DEVISE PLAN

4. What law of physics should you invoke?

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$$\frac{1}{2}v_{\rm esc}^2 - G\frac{m_{\rm M}}{R_{\rm M}} = 0$$

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# Waves in Two a **Three Dimension**

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238 CHAPTER 13 PRACTICE GRAVITY

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4. What law of physics should you invoke?

**3 EXECUTE PLAN** Let us use  $r_i$  for the initial Mars-probe radial center-to-center separation distance,  $r_1 = \infty$  for the final separation distance,  $R_{\rm M}$  for the radius of Mars, and  $m_{\rm M}$  and  $m_{\rm p}$  for the two masses. We begin with Eq. 13.23:

$$\begin{split} E_{\rm mech} &= \tfrac{1}{2} m_{\rm p} v_{\rm esc}^2 - G \frac{m_{\rm M} m_{\rm p}}{R_{\rm M}} = 0 \\ & \tfrac{1}{2} v_{\rm esc}^2 - G \frac{m_{\rm M}}{R_{\rm M}} = 0 \\ & \tfrac{1}{2} v_{\rm esc}^2 = G \frac{m_{\rm M}}{R_{\rm M}} \\ & v_{\rm esc} = \sqrt{2G \frac{m_{\rm M}}{R_{\rm M}}} \\ v_{\rm esc} &= \sqrt{2(6.67 \times 10^{-11} \, \mathrm{N} \cdot \mathrm{m}^2/\mathrm{kg}^2) \frac{6.42 \times 10^{23} \, \mathrm{kg}}{3.40 \times 10^6 \mathrm{m}}} \\ &= 5.02 \times 10^3 \, \mathrm{m/s} = 5 \, \mathrm{km/s}. \end{split}$$

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars's gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars's radius), and G. We expect  $v_{\rm esc}$  to increase with  $m_{\rm M}$  because the gravitational pull increases with increasing mass. We also expect  $v_{\rm esc}$  to decrease as the distance between the launch position and Mars's center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

An escape speed of 18,000 km/h is smaller than (but on the order of) the escape speed from Earth, and so the answer is not unreasonable.

We assumed that the initial Mars-probe separation distance is equal to the planet's radius. Of course, the length of the cannon may be tens of meters, but this tiny difference would have no impact on the numerical answer. We ignored the rotation of Mars, which could supply a small amount of the needed kinetic energy. We also ignored the effect of the Sun, which is fine for getting away from the surface of Mars, but we would need to account for it if the destina-

- 5. As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you
- 6. What equation allows you to relate the initial and final states?

#### **3** EXECUTE PLAN

- 7. What is your target unknown quantity? Algebraically isolate it on one side of your equation.
- 8. Substitute the numerical values you know to get a numerical

## **4** EVALUATE RESULT

- 9. Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth's mass and radius change?
- 10. If you were the head of a design team, would you recommend pursuing this launch method?

# Waves in Two a **Three Dimension**

**Chapter Sum** 

**Guided Problems** 

Questions and Problems 311

**Answers to Review Questions** 

**Answers to Guided Problems 316** 

238 CHAPTER 13 PRACTICE GRAVITY

## Worked Problem 13.3 Escape at last

The Mars Colony wants to launch a deep-space probe, but they have no rocket engines. They decide to launch a probe with an electromagnetic cannon, which means they must launch at escape speed.

• GETTING STARTED Let us do a quick sketch to help our thinking (Figure WG13.3). We select the Mars-probe system In order to reach "deep space," the probe must attal distance from Mars. This will require a sig kinetic energy, which the probe must acqu launch, the kinetic energy immediately begin potential energy of the Mars-probe system is tion distance increases. We assum is fixed and only the probe move away (infinity, really, but far), the kinetic ener to be zero because nal potential energy is negand other planets have a neglind we ignore the rotation of Mars.



2 DEVISE PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted to gravitational potential energy of the Mars-probe system. We want to know the initial speed of the probe acquired at launch. The initial potential energy is the value when the probe is still near the Martian surface. The final state of the probe is zero speed at an infinite distance from Mars. The Principles volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this version of an energy conservation equation for  $v_{\rm i}=v_{\rm esc}$  in terms of

## Guided Problem 13.4 Spring to the stars

Suppose that, instead of using chemical rockets, NASA decided to use a compressed spring to launch a spacecraft. If the spring constant is 100,000 N/m and the mass of the spacecraft is 10,000 kg, how far must the spring be compressed in order to launch the craft to a position outside Earth's gravitational influence?

## 1 GETTING STARTED

- Describe the problem in your own words. Are there similarities
- 2. Draw a diagram showing the initial and final states. What is the spacecraft's situation in the final state? 3. How does the spacecraft gain the necessary escape speed?

## 2 DEVISE PLAN

4. What law of physics should you invoke?

tion distance, R<sub>M</sub> for

$$E_{\rm m} = \frac{1}{2} m_{\rm b} = G$$

$$v_{\text{esc}} = \sqrt{\frac{2(6.67 \times 10^{-11} \,\text{N} \cdot \text{m}^2/\text{kg}^2)}{3.40 \times 10^6 \,\text{m}}} = 0$$

$$\frac{\frac{1}{2}v_{\text{esc}}^2 = G \frac{m_{\text{M}}}{R_{\text{M}}}}{v_{\text{esc}}}$$

$$v_{\text{esc}} = \sqrt{\frac{2(6.67 \times 10^{-11} \,\text{N} \cdot \text{m}^2/\text{kg}^2)}{3.40 \times 10^6 \,\text{m}}} = 5.02 \times 10^3 \,\text{m/s} = 5.1 \,\text{m/s}$$

 $= 5.02 \times 10^3 \,\mathrm{m/s} = 5 \,\mathrm{km/s}$ 

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars's gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars's radius), and G. We expect  $v_{\rm esc}$  to increase with  $m_{\rm M}$  because the gravitational pull increases with increasing mass. We also expect  $v_{\rm esc}$  to decrease as the distance between the launch position and Mars's center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

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- 7. What is your target unknown quantity? Algebraically isolate it on one side of your equation.
- 8. Substitute the numerical values you know to get a numerical

- 9. Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth's mass and radius change?
- 10. If you were the head of a design team, would you recommend pursuing this launch method?

not just end-of-chapter material

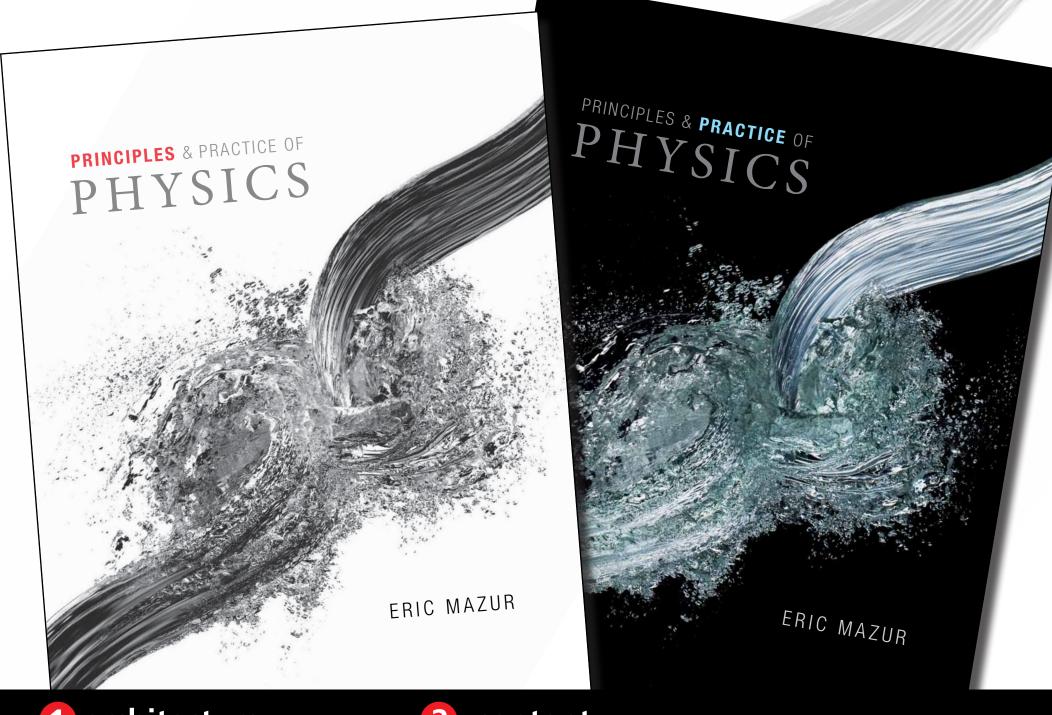
$$E_{\text{mech}} = \frac{1}{2} m_{\text{p}} v_{\text{esc}}^2 - G \frac{m_{\text{M}} m_{\text{p}}}{R_{\text{M}}} = 0$$

$$\frac{\frac{1}{2} v_{\text{esc}}^2 - G \frac{m_{\text{M}}}{R_{\text{M}}} = 0$$

$$\frac{\frac{1}{2} v_{\text{esc}}^2 - G \frac{m_{\text{M}}}{R_{\text{M}}}$$

many innovative features

teaches authentic problem solving



1 architecture

2 content

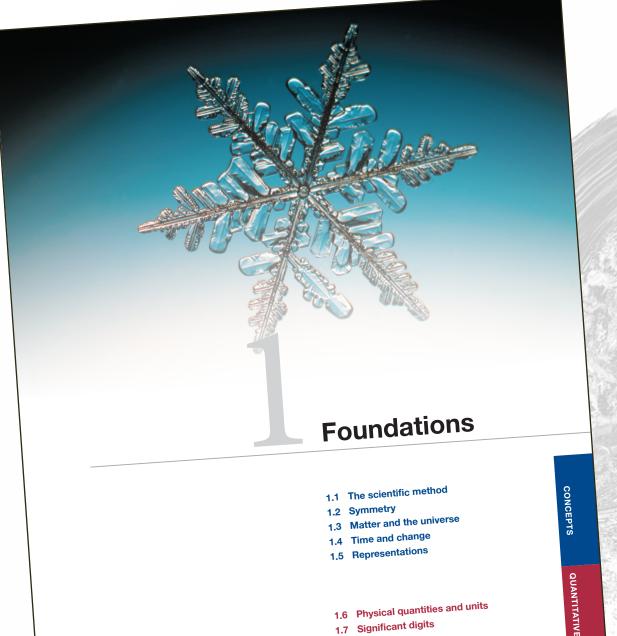
PRINCIPLES & PRACTICE OF PRINCIPLES & PRACTICE OF

PHYSICS & PRACTICE OF

# conservation principles before force laws?

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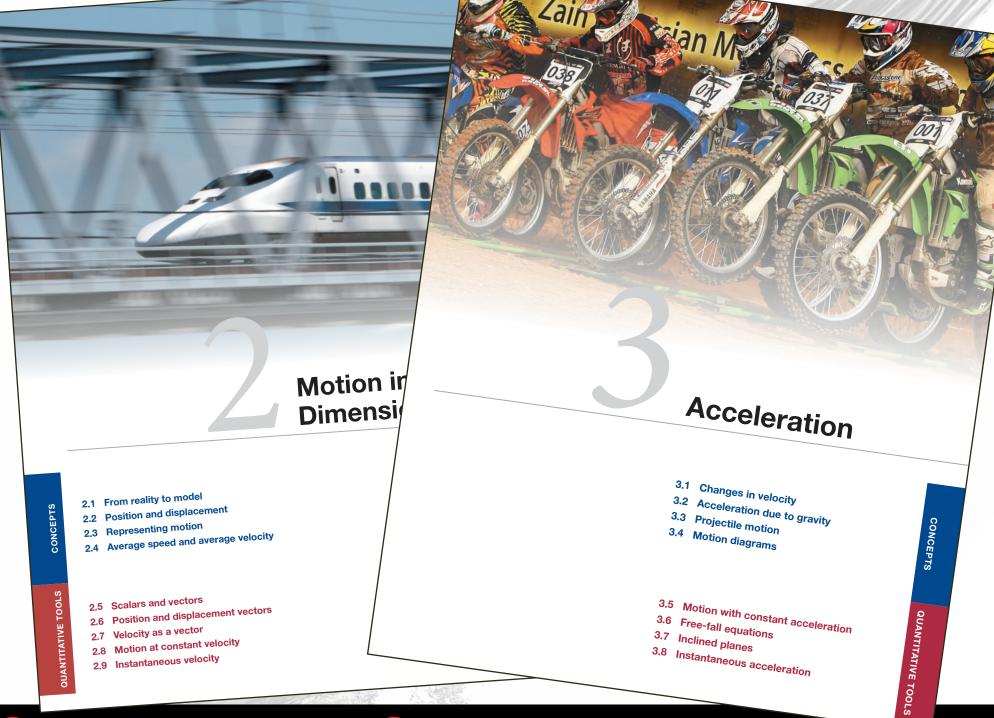


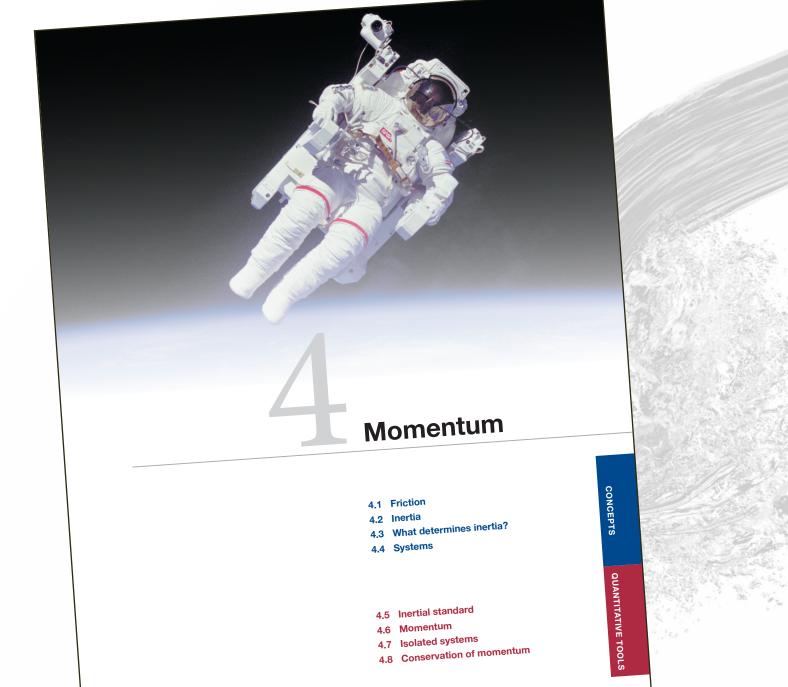
- 1.8 Solving problems
- 1.9 Developing a feel



- 1.1 The scientific method
- 1.2 Symmetry
- 1.3 Matter and the universe
- 1.4 Time and change
- 1.5 Representations

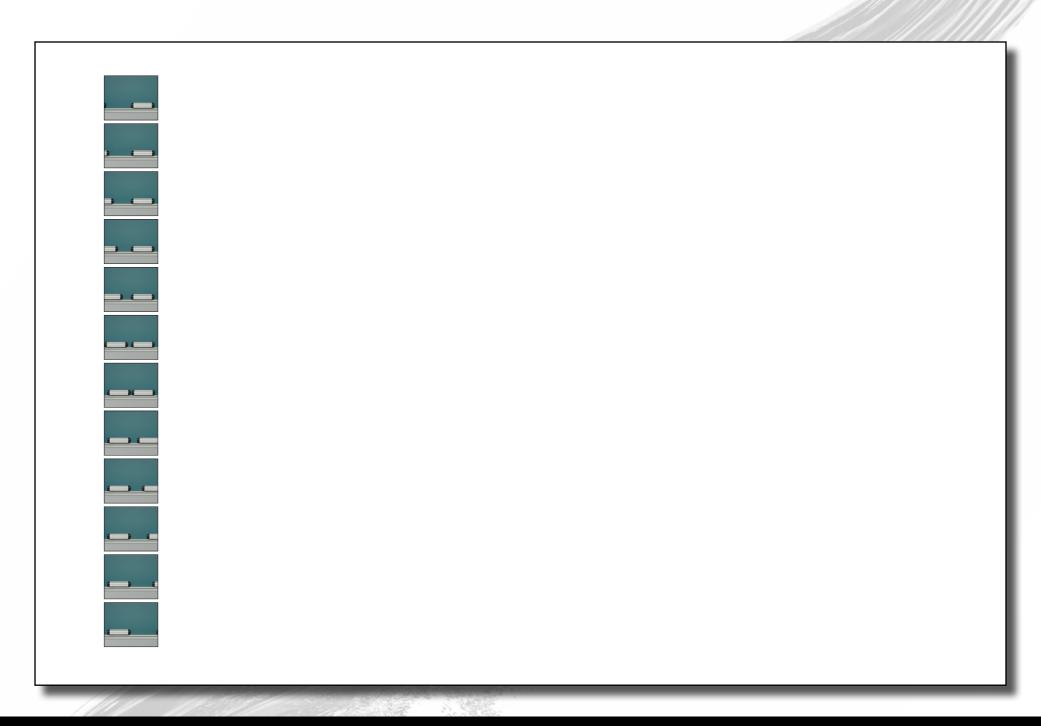
- 1.6 Physical quantities and units
- 1.7 Significant digits
- 1.8 Solving problems
- 1.9 Developing a feel

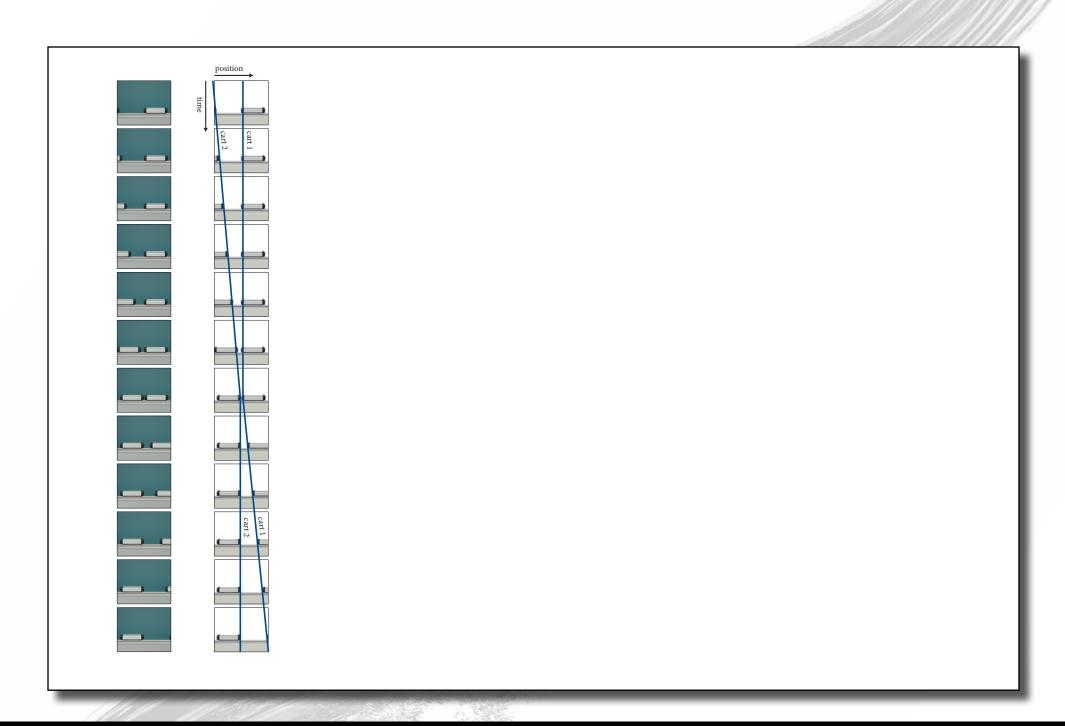


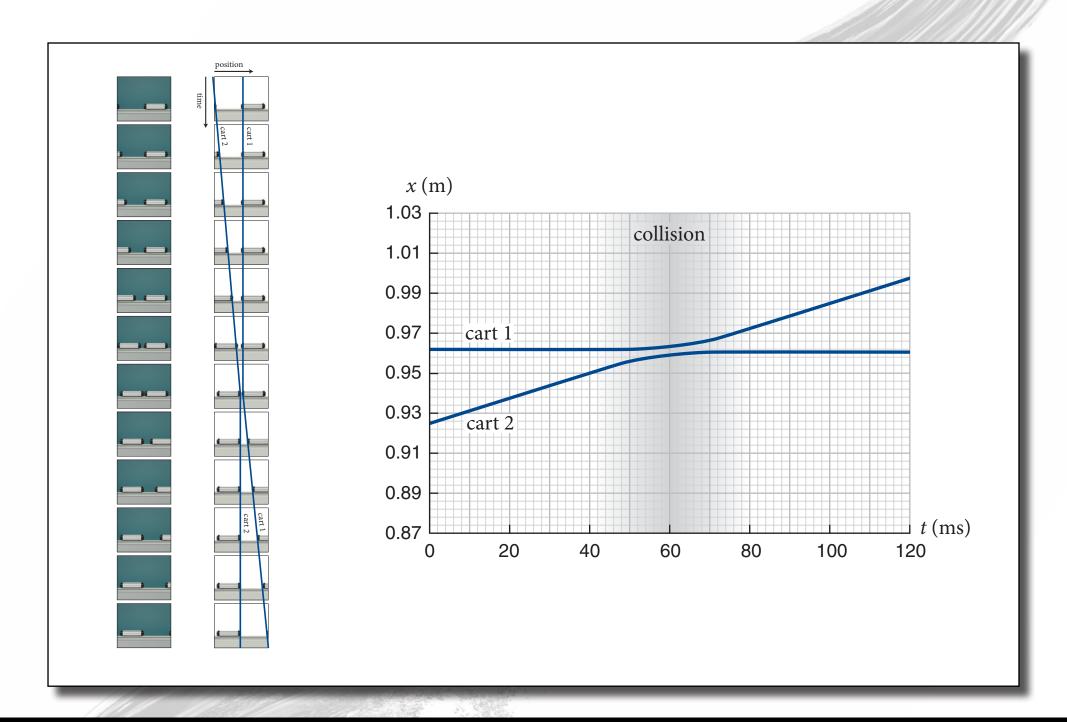


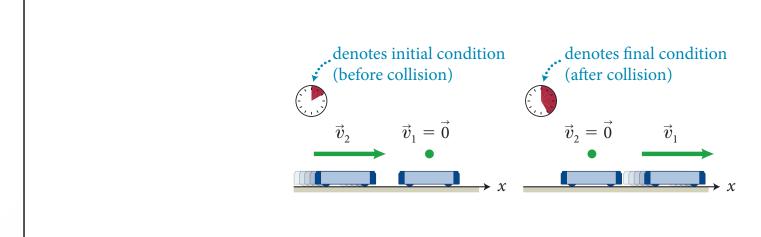
- 4.1 Friction
- 4.2 Inertia
- 4.3 What determines inertia?
- 4.4 Systems

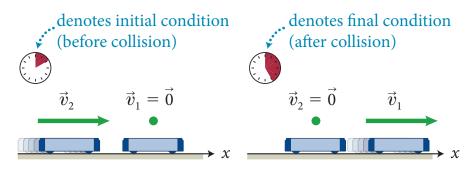
- 4.5 Inertial standard
- 4.6 Momentum
- 4.7 Isolated systems
- 4.8 Conservation of momentum

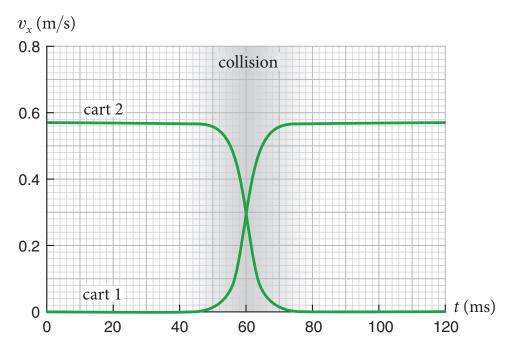


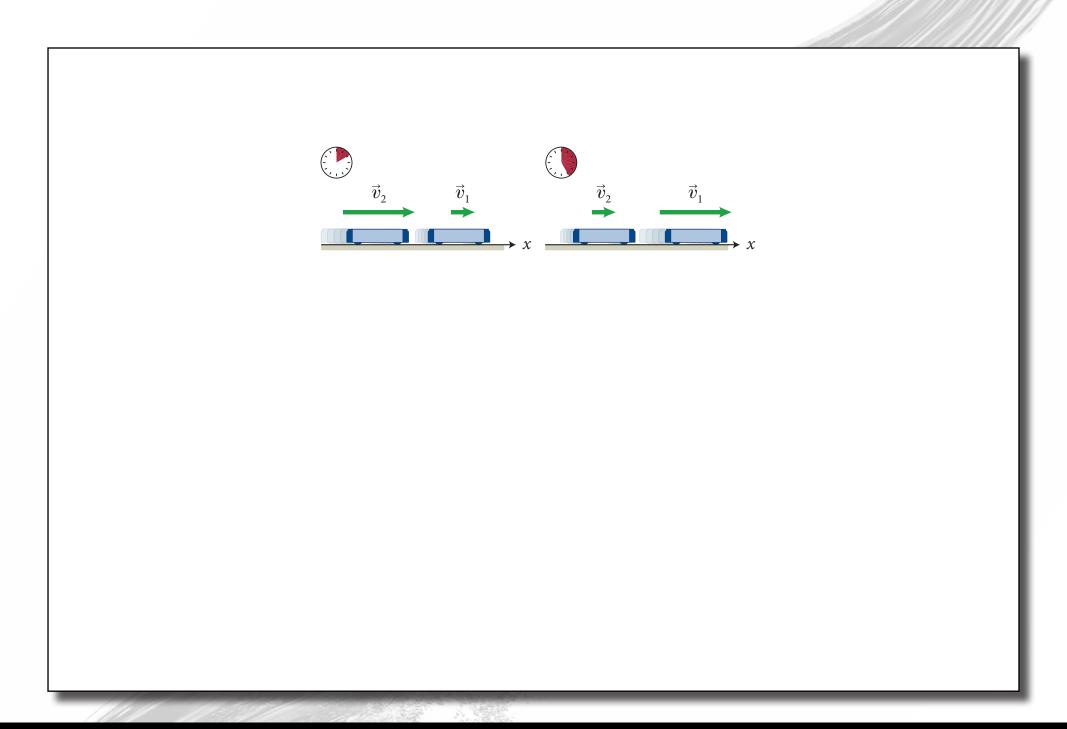


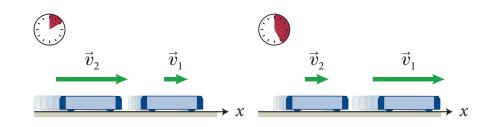


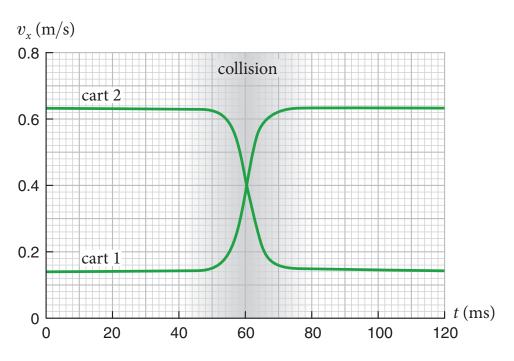


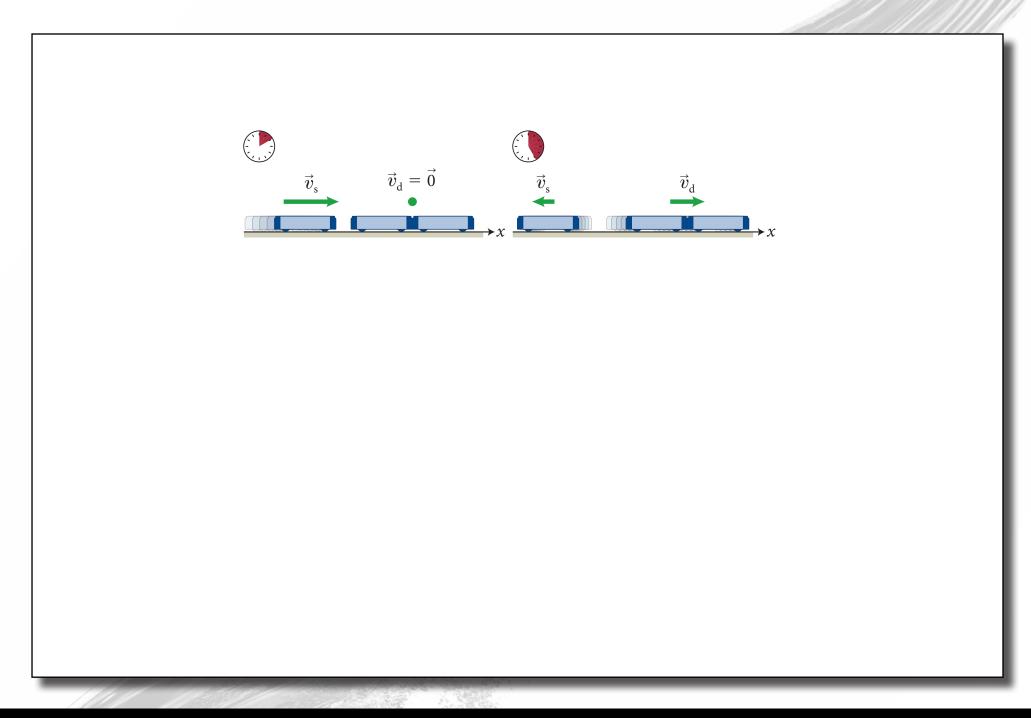


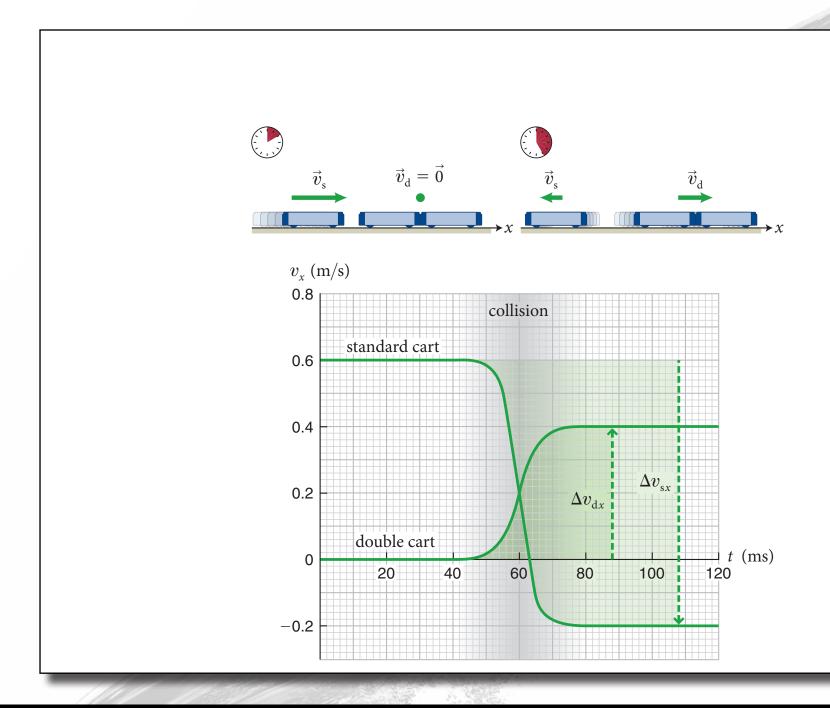


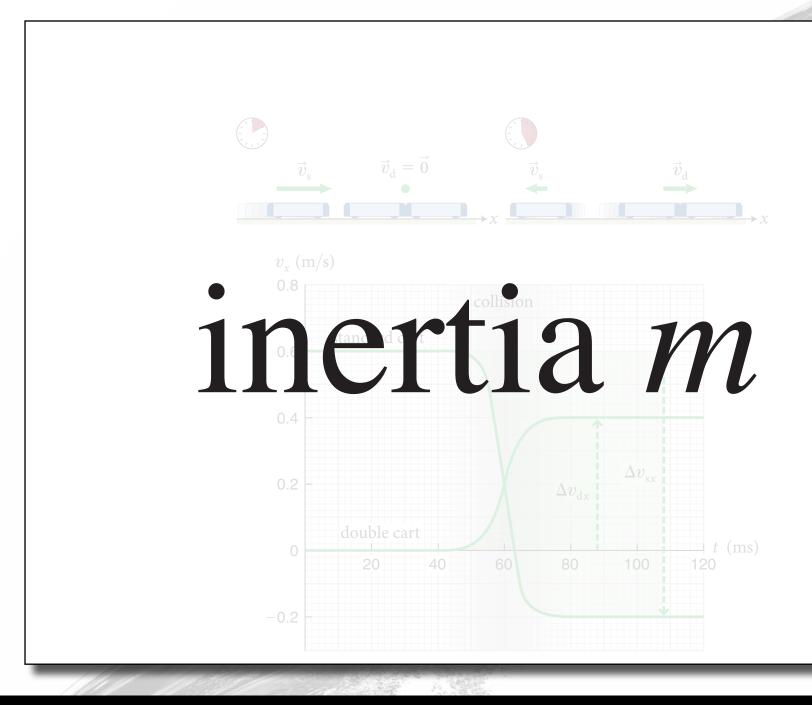


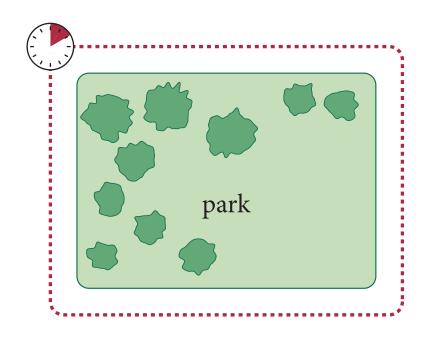


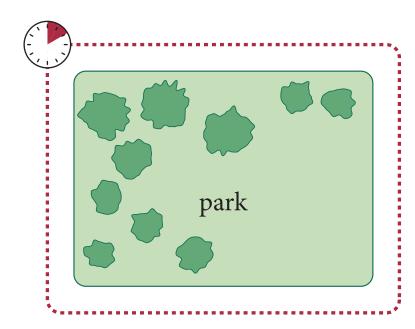


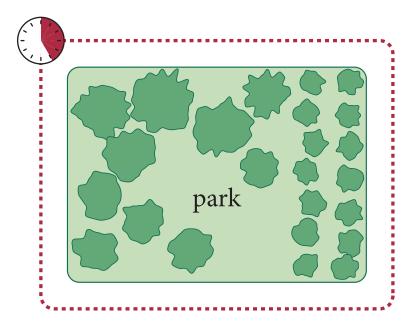
















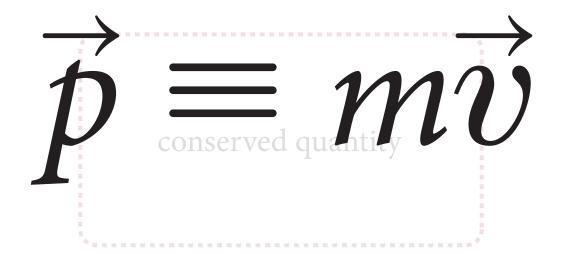


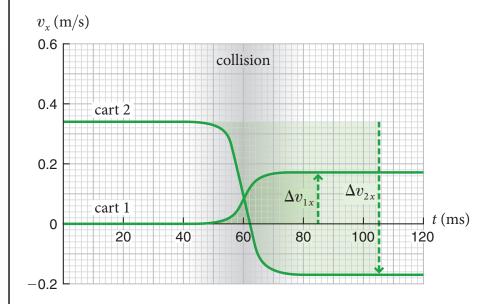


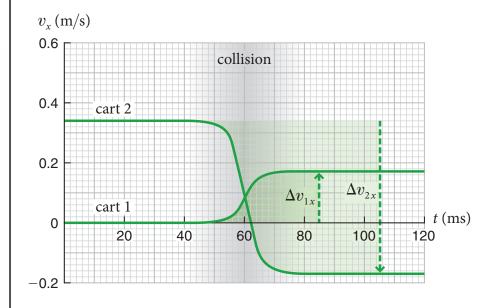
conserved quantity

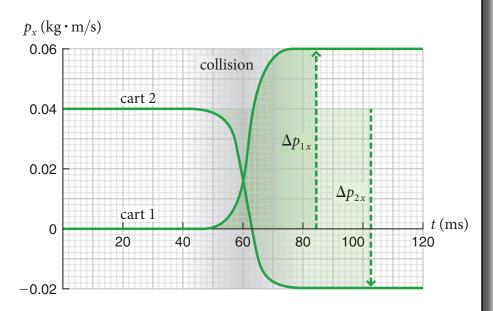
conserved quantity in isolated system

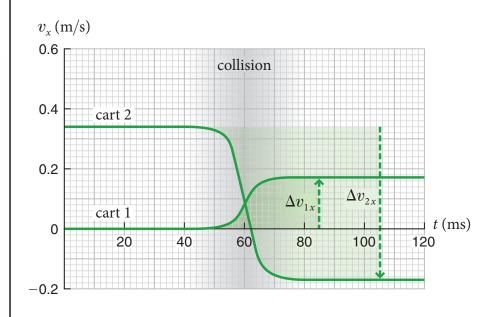
can't change (constant)

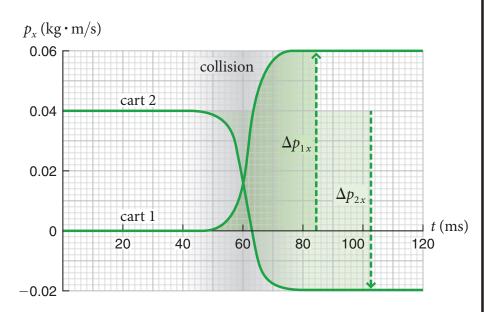




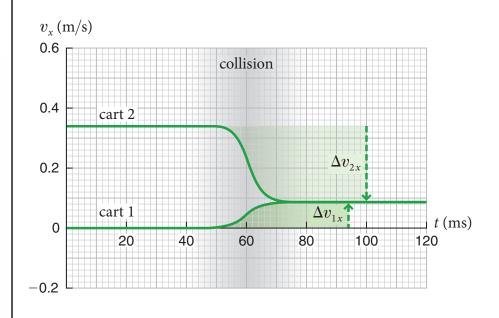


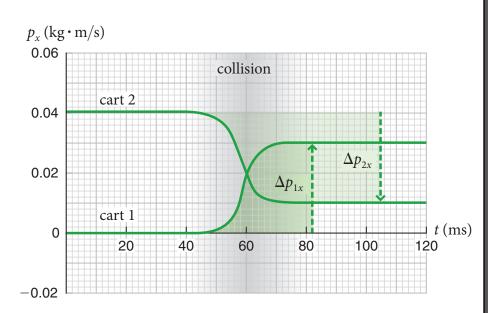




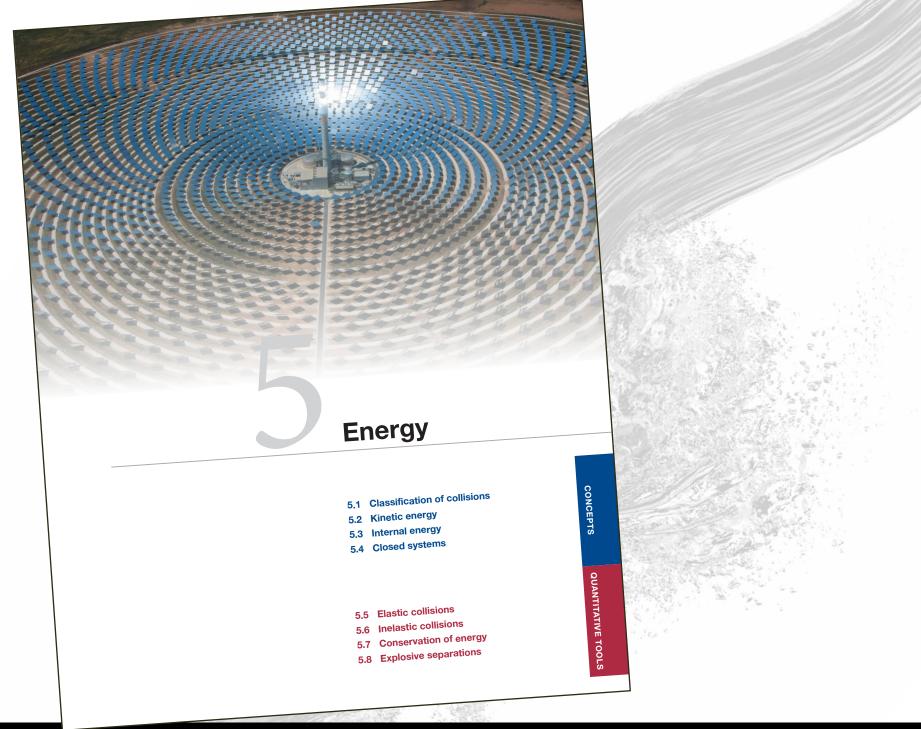


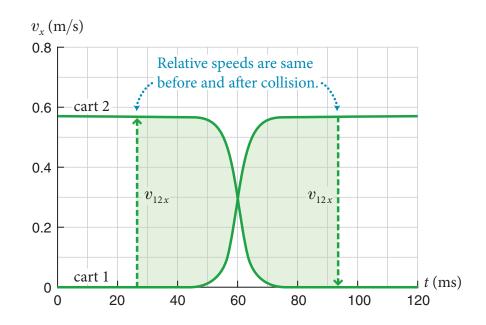
$$\Delta \vec{p} \equiv \Delta \vec{p}_1 + \Delta \vec{p}_2 = \vec{0}.$$

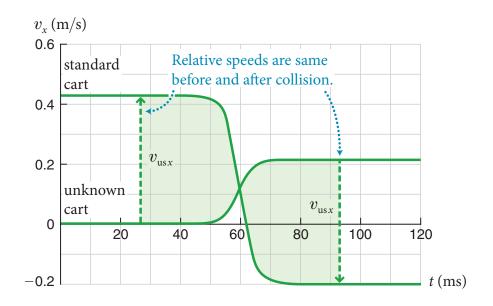




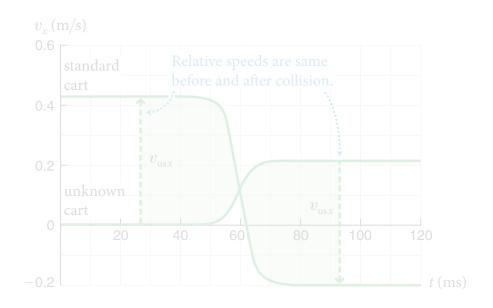
$$\Delta \vec{p} = \Delta \vec{p}_1 + \Delta \vec{p}_2 = \vec{0}.$$



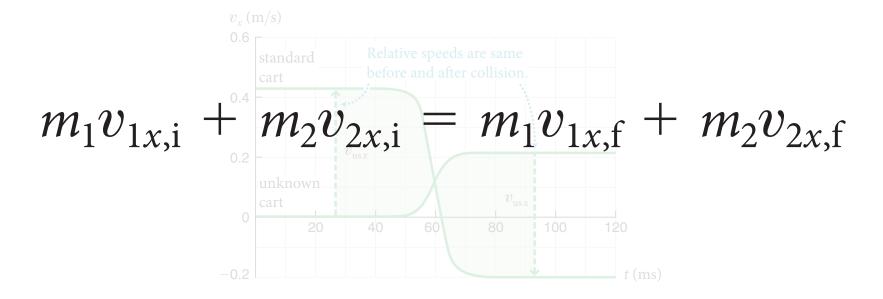




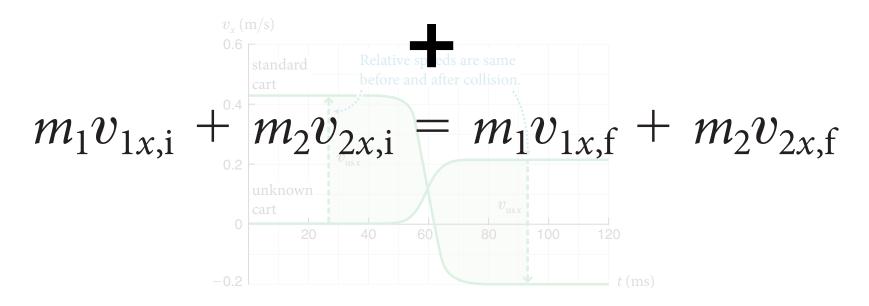
$$v_{12i} = v_{12f}$$



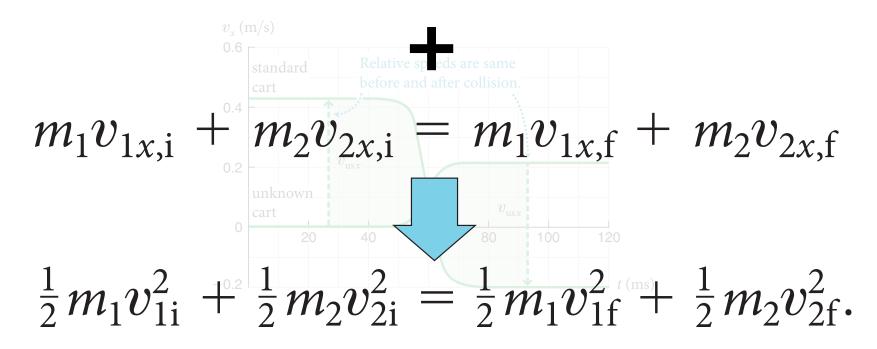
$$v_{12i} = v_{12f}$$



$$v_{12i} = v_{12f}$$



$$v_{12i} = v_{12f}$$









elastic: reversible

inelastic: irreversible

type	relative speed	state	
elastic	unchanged	unchanged	
inelastic	changed	changed	

type	relative speed	state	
elastic	unchanged	unchanged	
inelastic	changed	changed	
	$\Delta K$		

type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed
	$\Delta K$	$\Delta E_{int}$

## conservation of energy

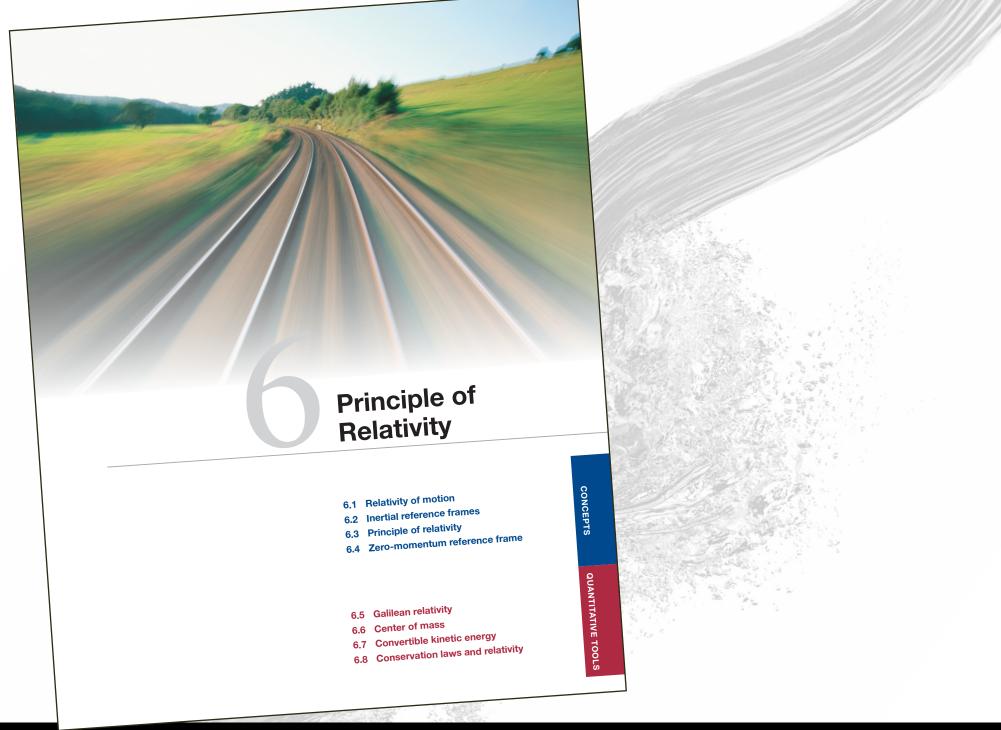
$$E = K + E_{\text{int}}$$

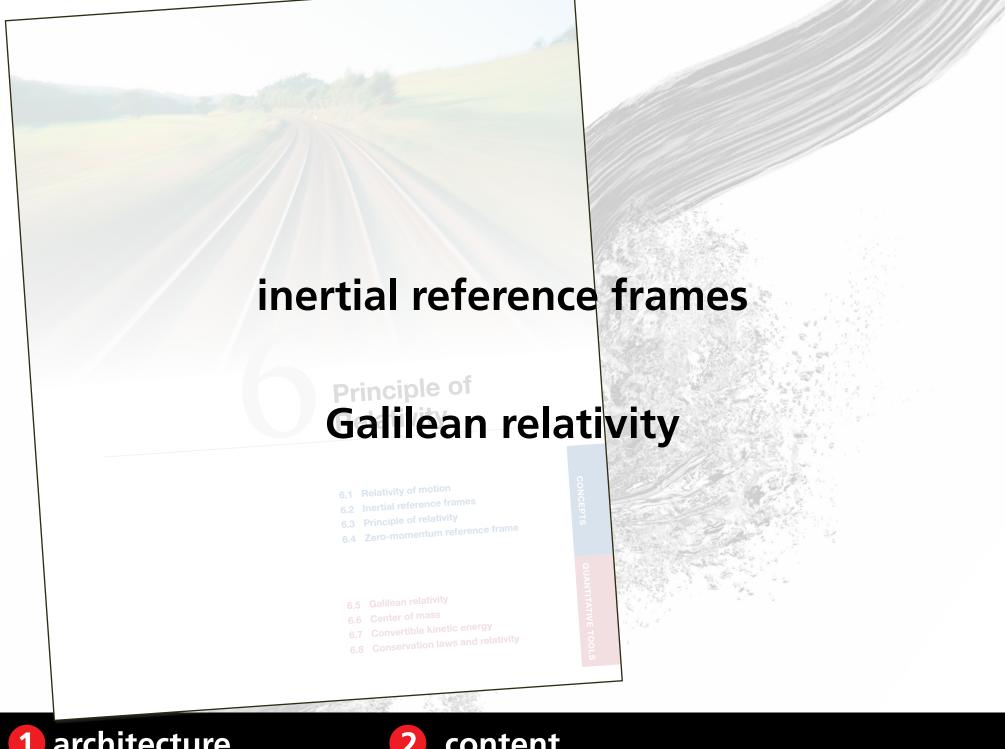
## conservation of energy

$$E = K + E_{\text{int}}$$

closed system:

$$\Delta E = 0$$





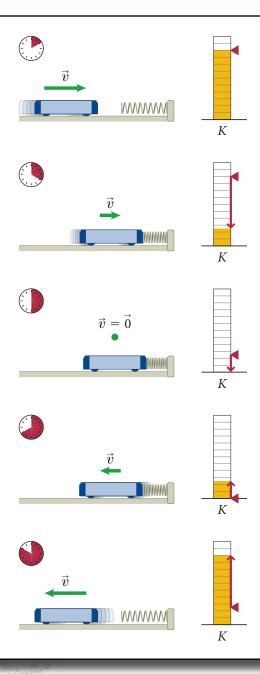
- 7.8 Nondissipative interactions
- 7.9 Potential energy near Earth's surface
- 7.10 Dissipative interactions

- 7.1 The effects of interactions
- 7.2 Potential energy
- **7.3 Energy dissipation**
- Source energy
- **7.5** Interaction range
- 7.6 Fundamental interactions

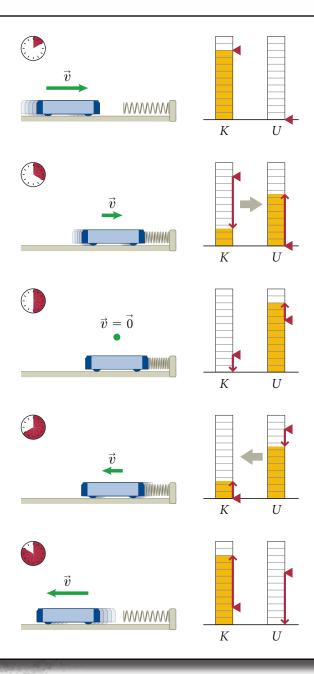
- 7.4 Source energy
- 7.5 Interaction range
- 7.6 Fundamental interactions
- 7.7 Interactions and accelera
- 7.8 Nondissipative interaction
- 7.9 Potential energy near Ea
- 7.10 Dissipative interactions

- 7.7 Interactions and accelerations
- 7.8 **Nondissipative interactions**
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- 7.10 Dissipative interactions

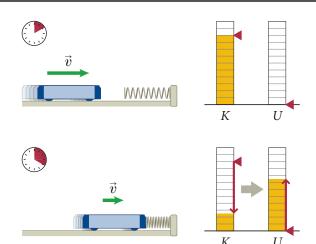
# potential energy



# potential energy

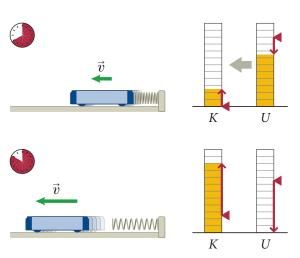


# potential energy



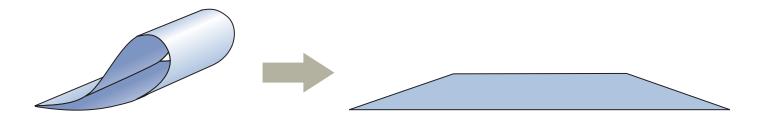
 $\vec{v} = \vec{0}$ 

reversible state change



# reversible and irreversible state changes

(a) Coherent deformation: reversible

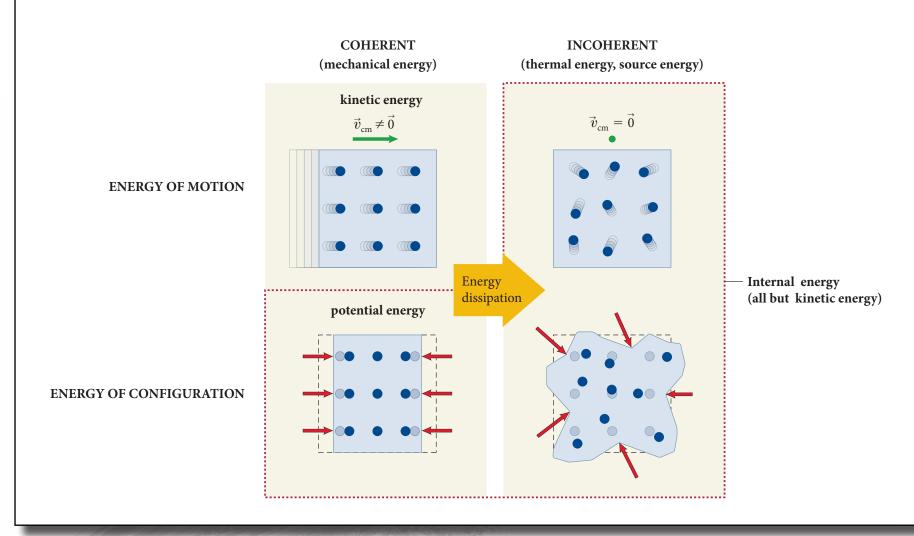


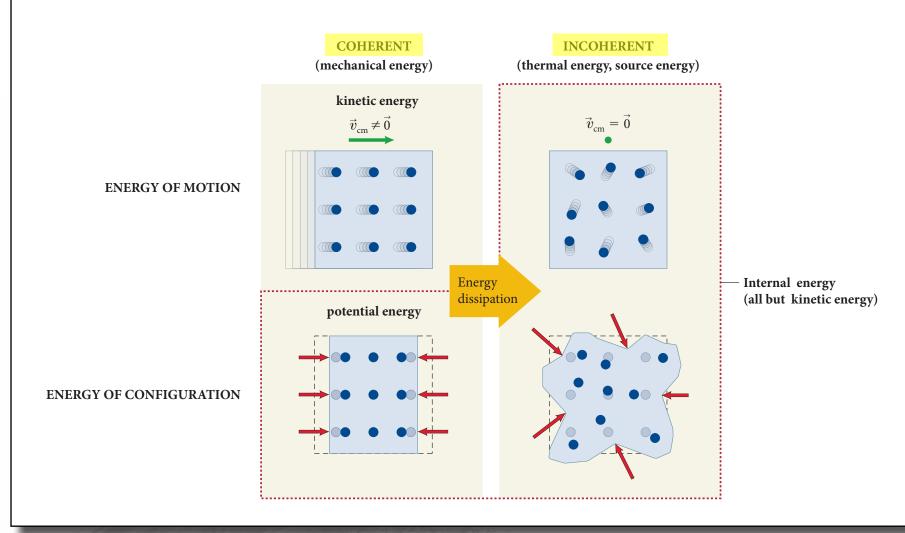
(b) Incoherent deformation: irreversible

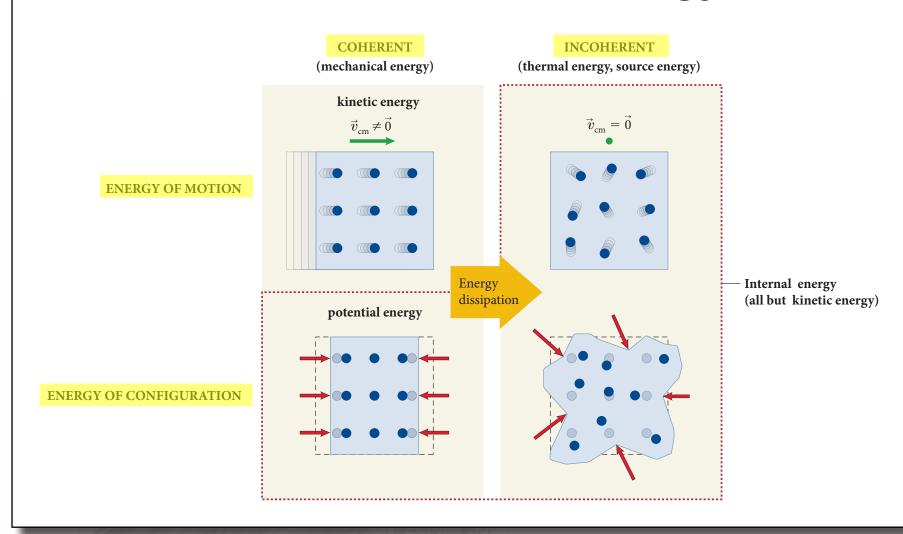


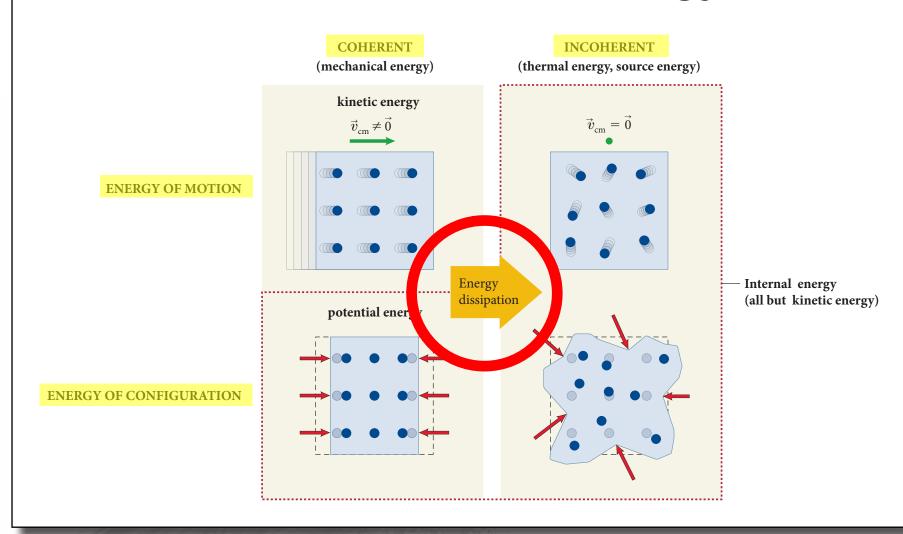




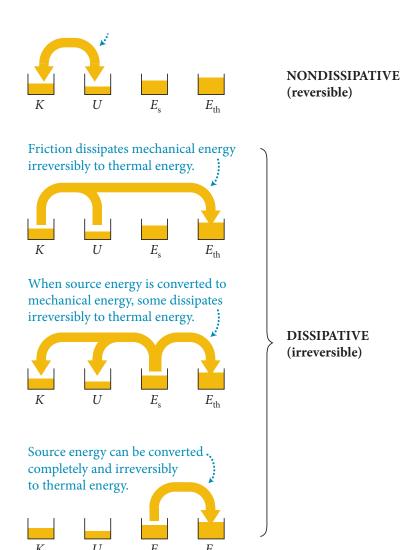




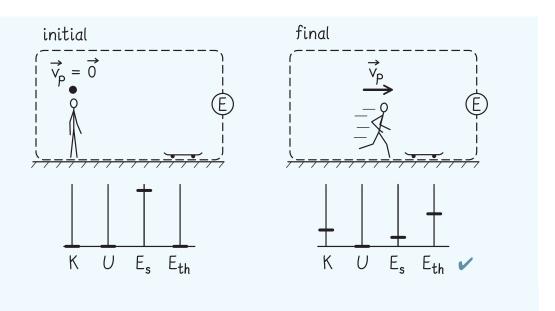




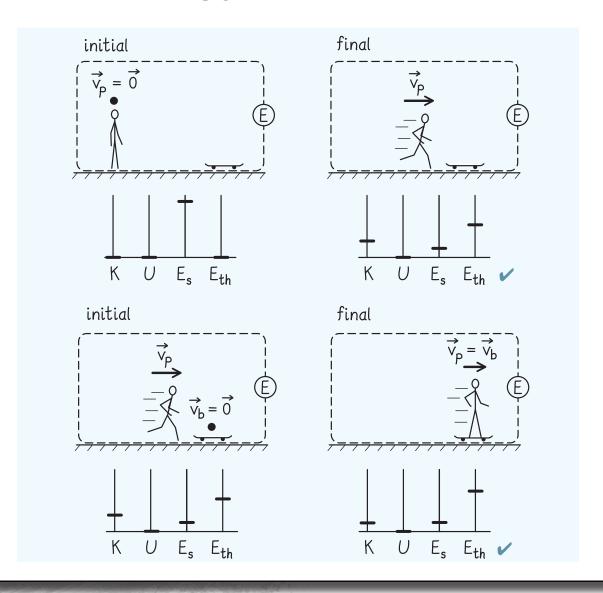
## energy conversions

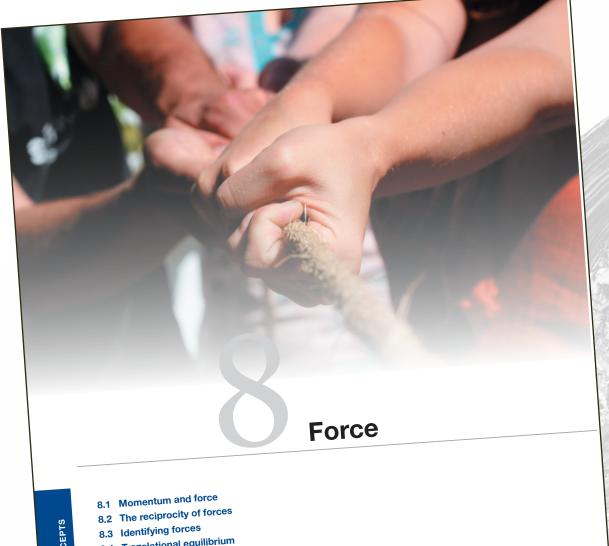


# energy conversions

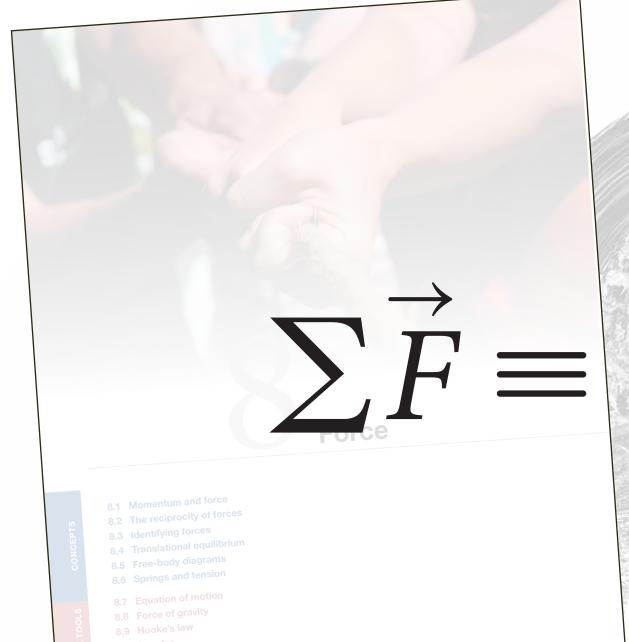


# energy conversions





- 8.4 Translational equilibrium
- 8.5 Free-body diagrams
- 8.6 Springs and tension
- 8.7 Equation of motion
- 8.8 Force of gravity
- 8.9 Hooke's law
- 8.10 Impulse
- 8.11 Systems of two interacting objects
- 8.12 Systems of many interacting objects



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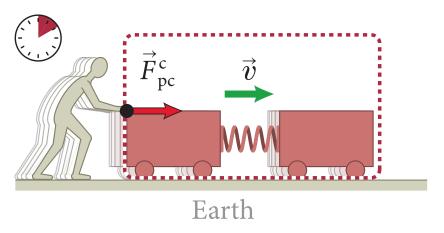
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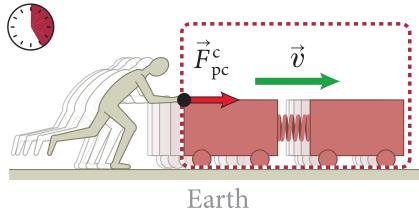
8 1	Momentum	and	force
0			

- 8.2 The reciprocity of forces
- 8.3 Identifying forces
- 8.4 Translational equilibrium
- 8.5 Free-body diagrams
- 8.6 Springs and tension
- 8.7 Equation of motion
- 8.8 Force of gravity
- 8.9 Hooke's law
- 8.11 Systems of two interac
- 8.12 Systems of many intera

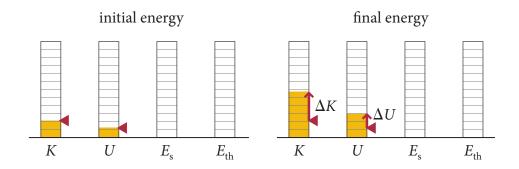
- **Momentum and force**
- 8.2 The reciprocity of forces
- **Identifying forces**
- Translational equilibrium
- Free-body diagrams
- Springs and tension 8.6
- **Equation of motion**
- Force of gravity 8.8
- 8.9 Hooke's law
- 8.10 **Impulse**
- Systems of two interacting objects 8.11
- **Systems of many interacting objects**

- 9.4 Choice of system
- 9.5 Work done on a single particle
- 9.6 Work done on a many-particle system
- 9.7 Variable and distributed forces
- 9.8 Power

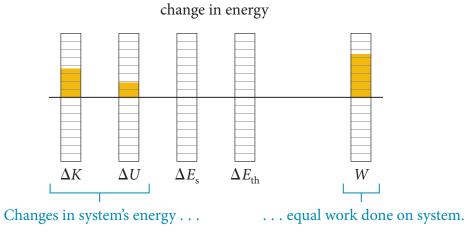


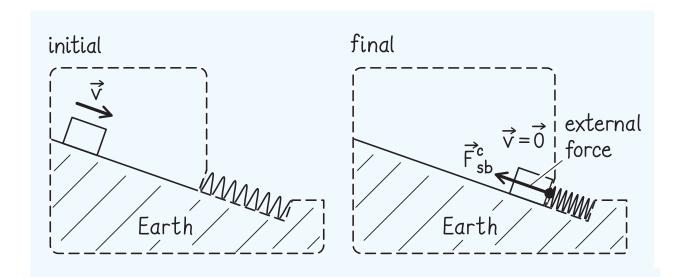


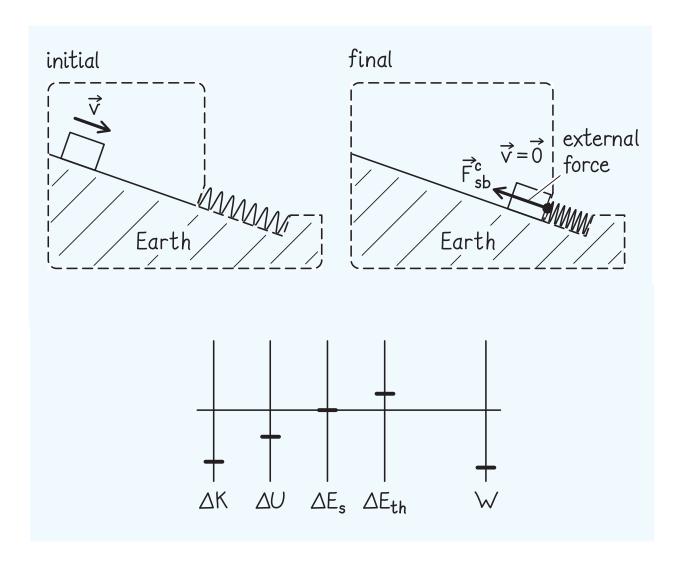
We can represent the changes in energy by initial and final bar diagrams . . .



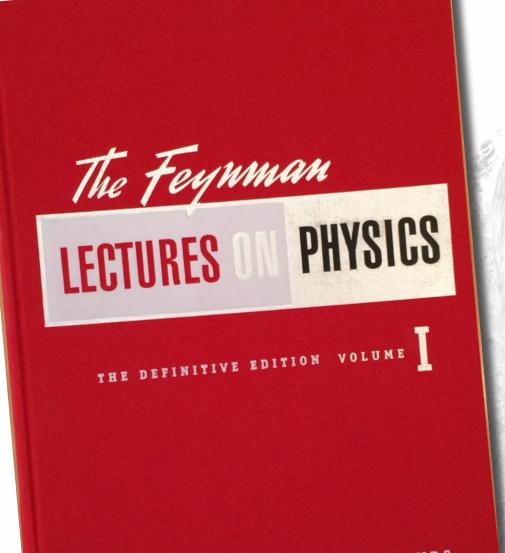
(c) . . . or by a single **energy diagram**.



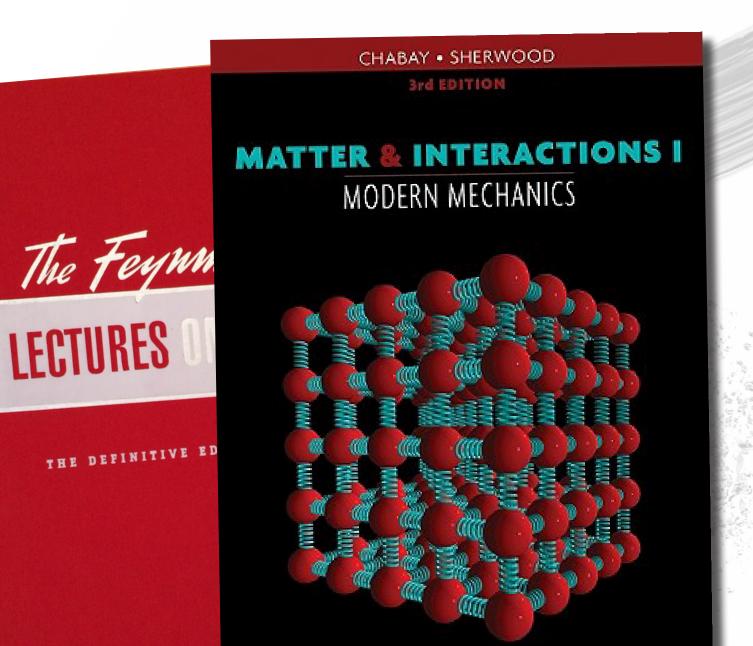




# how much work is it to switch?



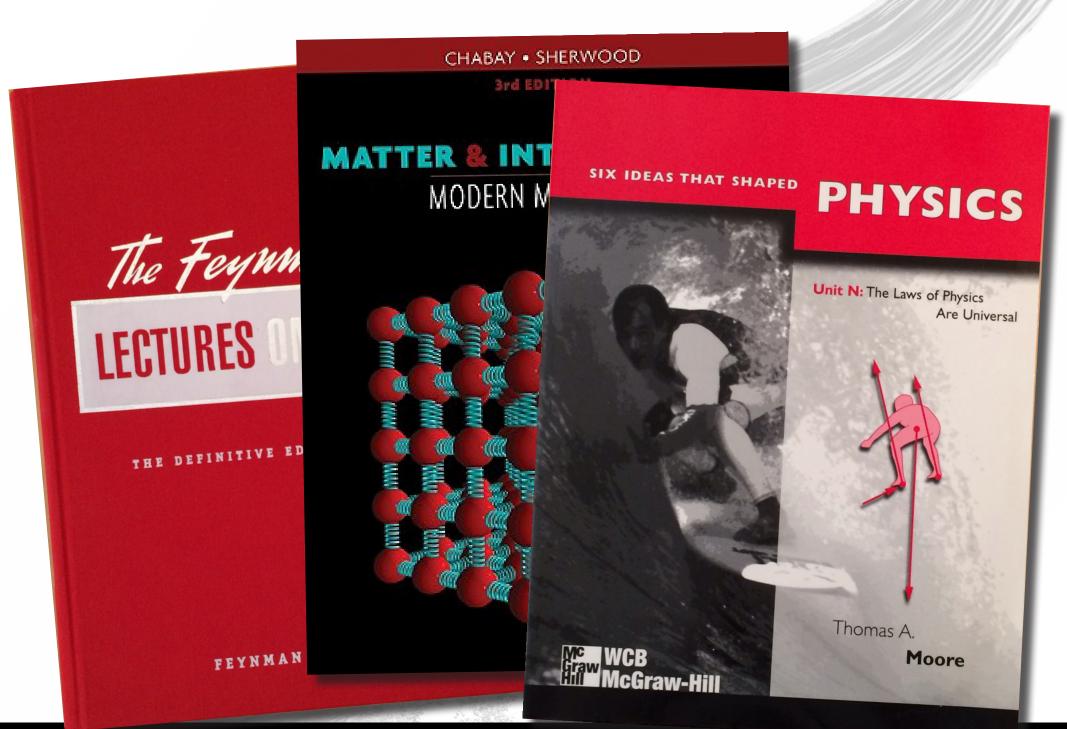
FEYNMAN · LEIGHTON · SANDS



FEYNMAN

1 architecture

2 content



1 architecture

2 content

#### **Principles and Practice**

- 1. Physics and measurement
- 2. Motion in one dimension
- 3. Vectors
- 4. Motion in two dimensions
- 5. The laws of motion
- 6. Circular motion
- 7. Work and kinetic energy
- 8. Potential energy and CoE
- 9. Momentum and collisions
- 10. Rotation about a fixed axis
- 11. Rolling motion and angular momentum
- 12. Static equilibrium and elasticity
- 13. Oscillatory motion
- 14. The law of gravity
- 15. Fluid mechanics
- 16. Wave motion
- 17. Sound waves
- 18. Superposition and standing waves

- 1. Foundations
- 2. Motion in one dimension
- 3. Acceleration
- 4. Momentum
- 5. Energy
- 6. Principle of relativity
- 7. Interactions
- 8. Force
- 9. Work
- 10. Motion in a plane
- 11. Motion in a circle
- 12. Torque
- 13. Gravity
- 14. Special Relativity
- 15. Periodic Motion
- 16. Waves in one dimension
- 17. Waves in 2 and 3 dimensions
- 18. Fluids

#### **Principles and Practice**

1. Physics and measurement	1. Foundations
2. Motion in one dimension	2. Motion in one dimension
3. Vectors	3. Acceleration
4. Motion in two dimensions	4. Momentum
5. The laws of motion	5. Energy 1D
6. Circular motion	6. Principle of relativity
7. Work and kinetic energy	7. Interactions
8. Potential energy and CoE	8. Force
9. Momentum and collisions	9. Work
10. Rotation about a fixed axis	10. Motion in a plane
11. Rolling motion and angular momentum	11. Motion in a circle
12. Static equilibrium and elasticity	12. Torque
13. Oscillatory motion	13. Gravity
14. The law of gravity	14. Special Relativity
15. Fluid mechanics	15. Periodic Motion
16. Wave motion	16. Waves in one dimension
17. Sound waves	17. Waves in 2 and 3 dimensions

18. Superposition and standing waves

18. Fluids

#### **Principles and Practice**

1D

**3D** 

1. Physics and measurement

2. Motion in one dimension

3. Vectors

4. Motion in two dimensions

5. The laws of motion

6. Circular motion

7. Work and kinetic energy

8. Potential energy and CoE

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**3D** 

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14. Special Relativity

15. Periodic Motion

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18. Fluids

#### **Principles and Practice**

1. Foundations 1. Physics and measurement 2. Motion in one dimension 2. Motion in one dimension 3. Acceleration 3. Vectors 4. Motion in two dimensions 4. Momentum 5. The laws of motion 5. Energy 1D 6. Circular motion 6. Principle of relativity 7. Work and kinetic energy 7. Interactions 8. Potential energy and CoE 8. Force 9. Momentum and collisions 9. Work 10. Rotation about a fixed axis 10. Motion in a plane 11. Rolling motion and angular momentum 11. Motion in a circle **3D** 12. Static equilibrium and elasticity 12. Torque 13. Oscillatory motion 13. Gravity 14. The law of gravity 14. Special Relativity 15. Periodic Motion 15. Fluid mechanics 16. Wave motion 16. Waves in one dimension 17. Sound waves 17. Waves in 2 and 3 dimensions 18. Superposition and standing waves 18. Fluids

#### **Principles and Practice**

1. Physics and measurement	1. Foundations	
2. Motion in one dimension	2. Motion in one dimension	
3. Vectors	3. Acceleration	
4. Motion in two dimensions	4. Momentum	
5. The laws of motion	5. Energy	conservation
6. Circular motion	6. Principle of relativity	
7. Work and kinetic energy	7. Interactions	
8. Potential energy and CoE	8. Force	dynamics
9. Momentum and collisions	9. Work	uymannics
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12. Static equilibrium and elasticity	12. Torque	
13. Oscillatory motion	13. Gravity	
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#### **Principles and Practice**

1.	Phy	/sics	and	measu	ırement

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- 13. Gravity
- 14. Special Relativity
- 15. Periodic Motion
- 16. Waves in one dimension
- 17. Waves in 2 and 3 dimensions
- 18. Fluids

#### periodic





# mostly minor rearrangements!

# easily custom tailored

TO THE INSTRUCTOR

VII

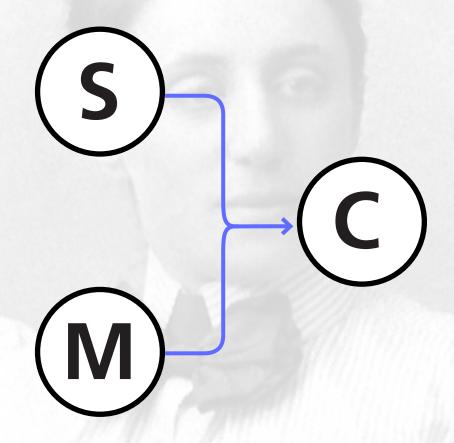
**Table 1** Scheduling matrix

Topic	Chapters	Can be inserted after chapter	Chapters that can be omitted without affecting continuity
Mechanics	1-14		6, 13–14
Waves	15–17	12	16–17
Fluids	18	9	
Thermal Physics	19-21	10	21
Electricity & Magnetism	22-30	12 (but 17 is needed for 29–30)	29-30
Circuits	31–32	26 (but 30 is needed for 32)	32
Optics	33-34	17	34

# **Emmy Noether**



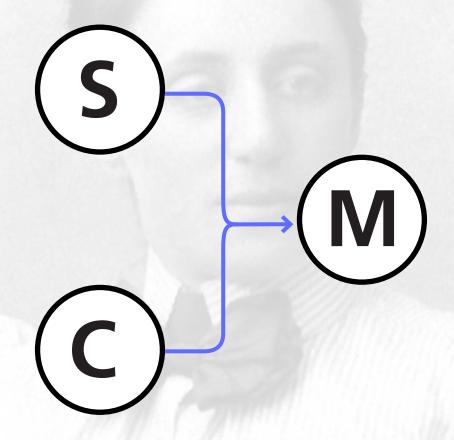
# **Emmy Noether**



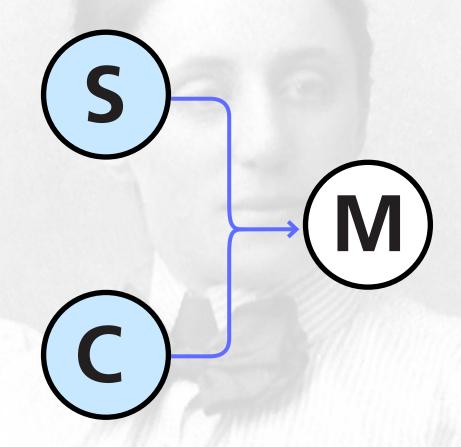
# **Emmy Noether**



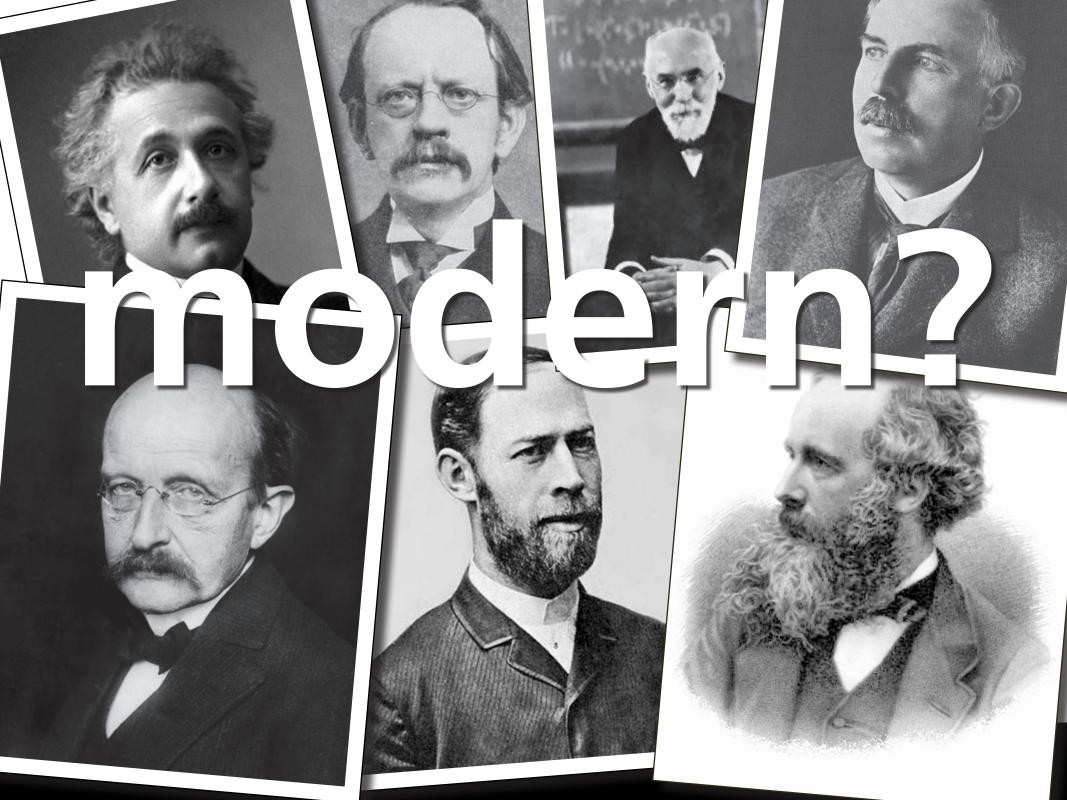
### **Noether inverted**

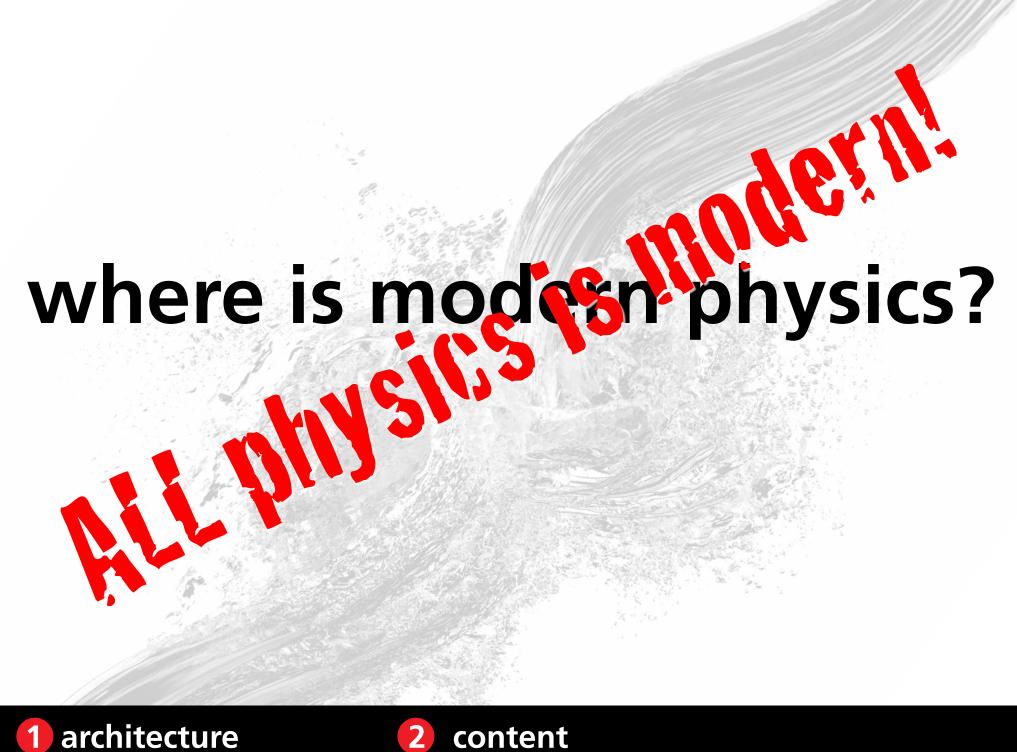


# aesthetically more appealing









# conservation as modern foundation

- 1. Foundation
- 2. Motion in one
- 3. Acceleration
- 4. Momentum
- 5. Energy
- 6. Principle of relativity
- 7. Interactions
- 8. Force
- 9. Work
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- 25. Work and energy in electrostatics
- 26. Charge separation and storage
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- 29. Changing magnetic fields
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- 31. Electric circuits
- 32. Electronics
- 33. Ray optics
- 34. Wave and particle optics

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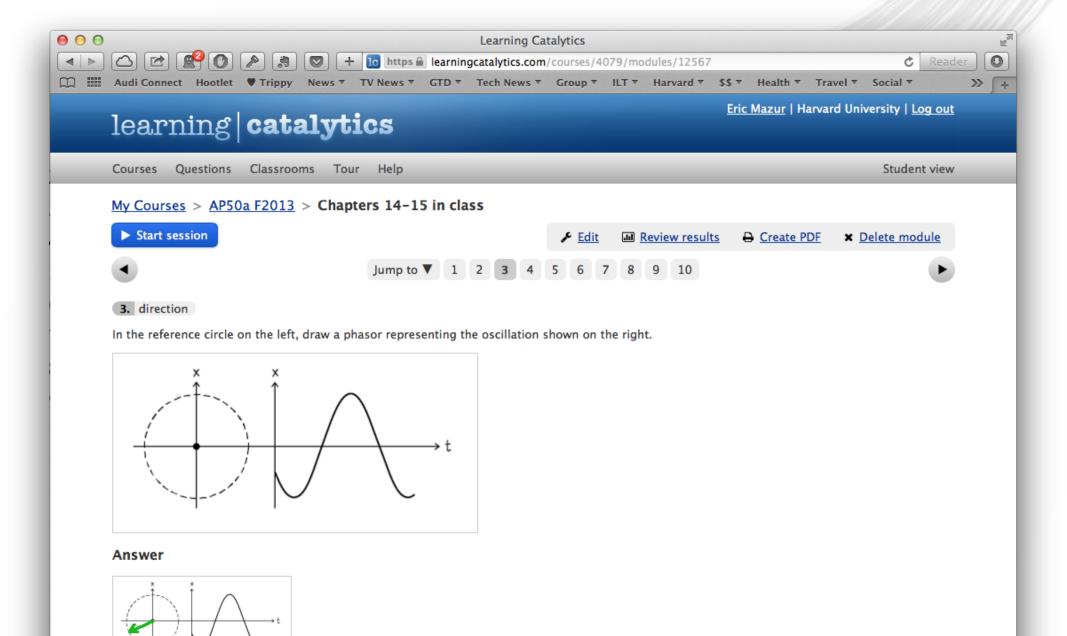
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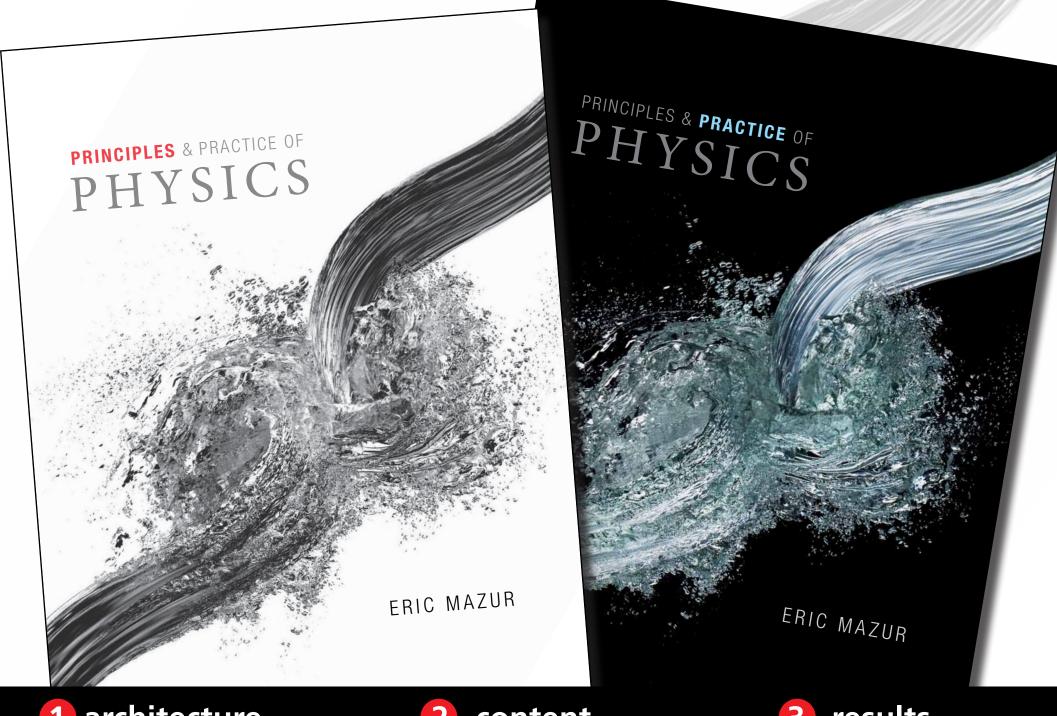
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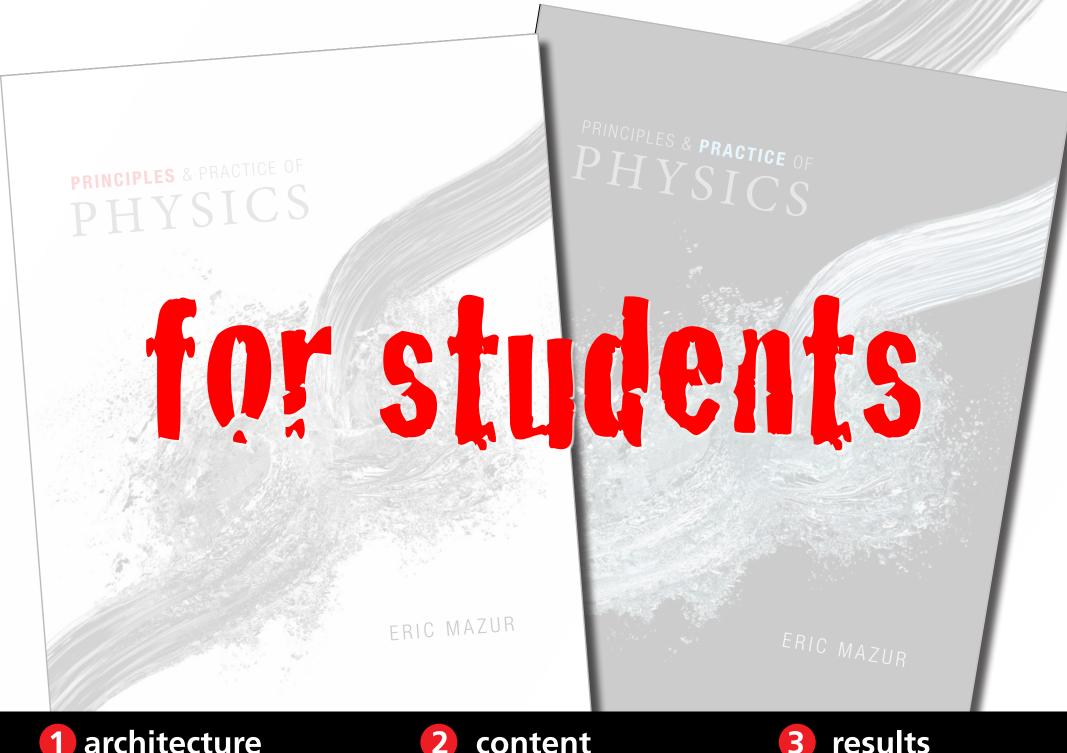




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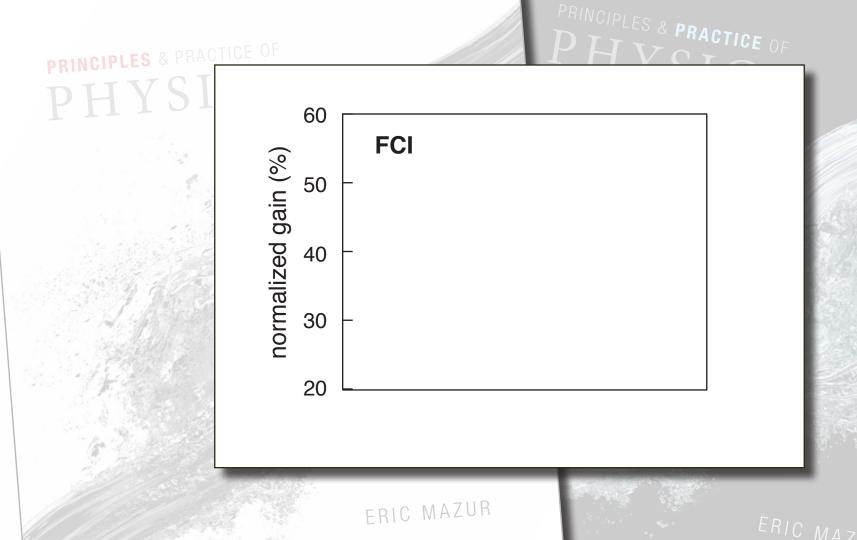
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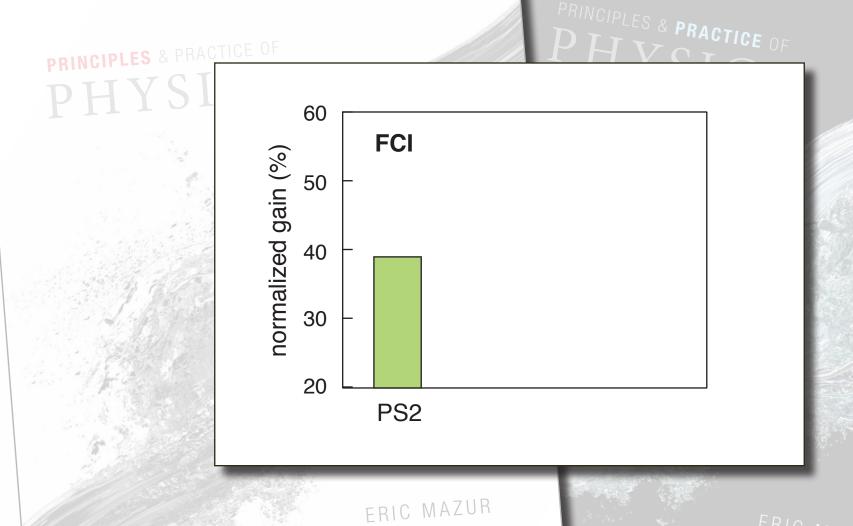
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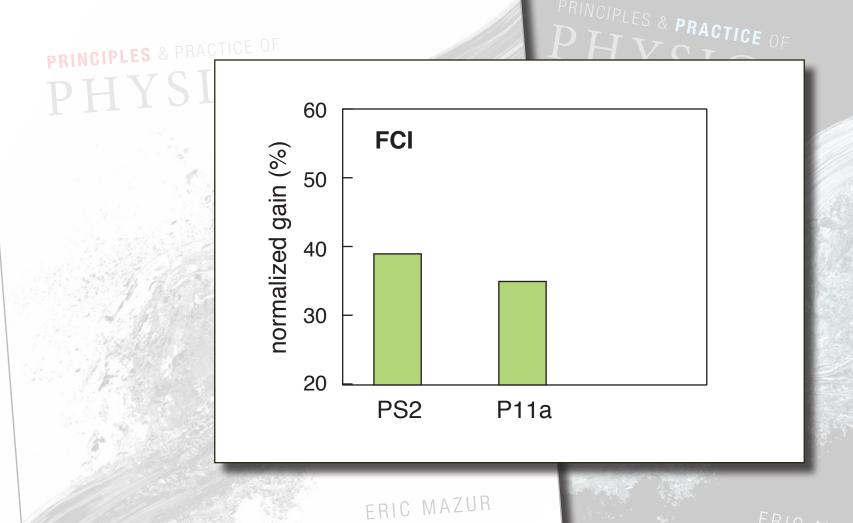






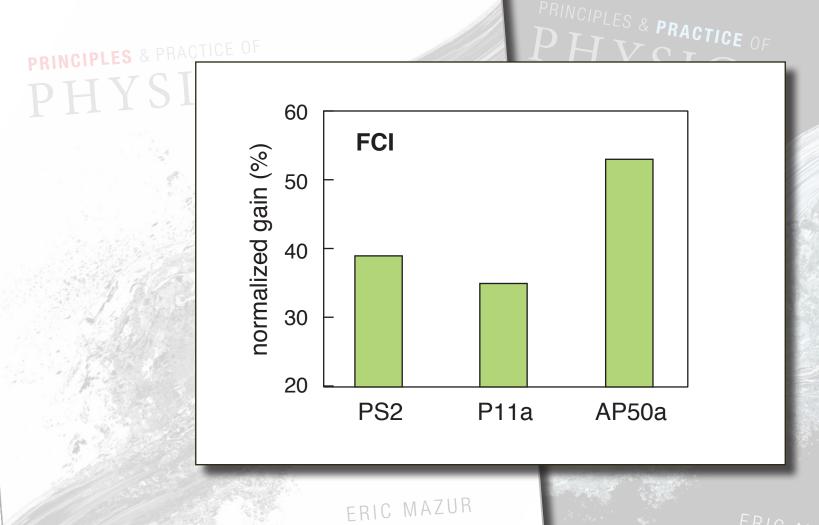












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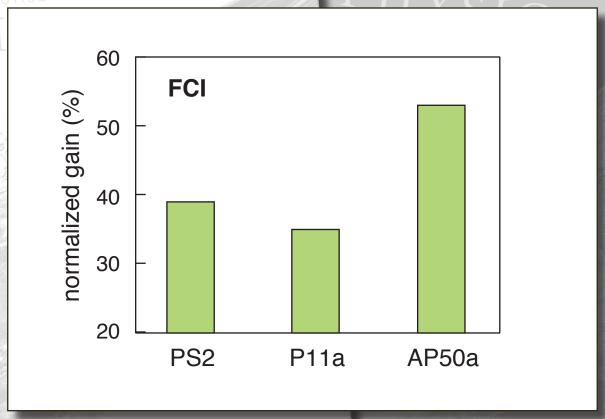






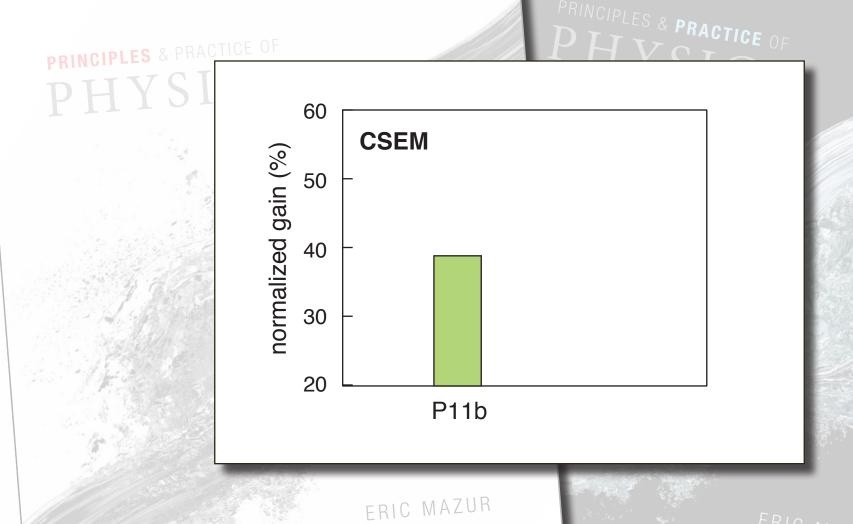






largest conceptual gain in any course past 6 yrs!



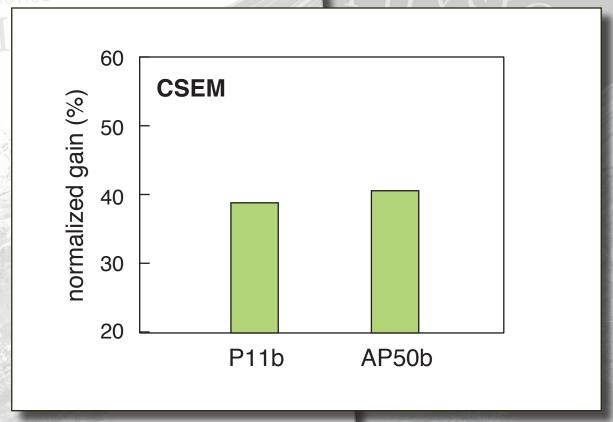


1 architecture

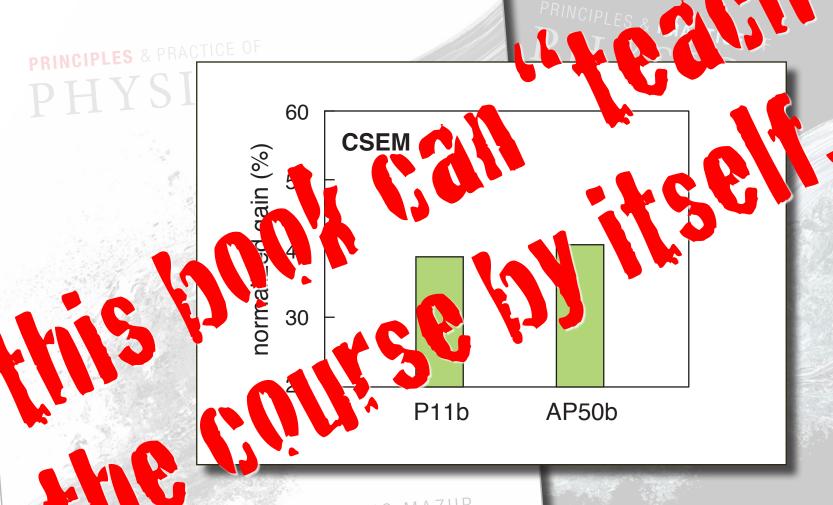
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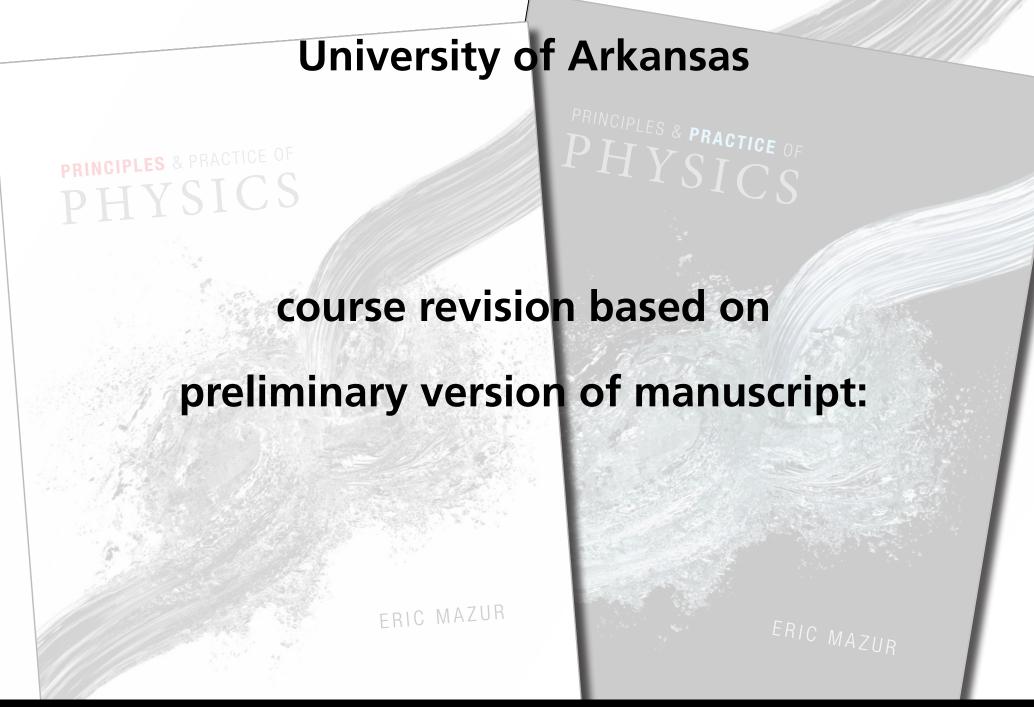
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# **University of Arkansas**

PRINCIPLES & PRACTICE OF PHYSICS

PHYSICS & PRACTICE OF

course revision based on preliminary version of manuscript: normalized FCI gain DOUBLED

ERIC MAZUR

ERIC MAZIL





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