

Brigham oung University Prove, UT, 4 March 2015







$$\begin{aligned} F_{d} = -bv & x(\theta) = x_{n}e^{-\frac{b^{2}}{2n}} \cos(\omega^{2} + + \theta) & w^{2} \sqrt{\frac{b^{2}}{n}} - \frac{b^{2}}{4n^{2}} & E(\theta) = \frac{1}{2}kx_{n}^{2}e^{-\frac{b^{2}}{n}} & (e^{1})(e^{1}) = \frac{1}{2}kx \\ F_{d} = -bv & x(\theta) = x_{n}e^{-\frac{b^{2}}{2n}} \cos(\omega^{2} + \theta) & w^{2} \sqrt{\frac{b^{2}}{n}} - \frac{b^{2}}{4n^{2}} & E(\theta) = \frac{1}{2}kx_{n}^{2}e^{-\frac{b^{2}}{n}} & (e^{1})(e^{1}) = \frac{1}{2}kx \\ F_{1} = 2\pi\sqrt{\frac{b^{2}}{n}} - \frac{1}{2n\sqrt{\frac{b^{2}}{n}}} + \frac{b^{2}}{n} \cos(\omega^{2} + \theta) & w^{2} \sqrt{\frac{b^{2}}{n}} - \frac{b^{2}}{n} \sin^{2}} & (e^{1})(e^{1}) + \frac{b^{2}}{n} \sin^{2}} & (e^{1})(e^{1}$$



Enematics Reciperation of the second sec

Matics Calculus.

Adiabatic QEO AFE-W RVEART QUALT SATAN & Pale = 0

Matics Control S $F = m\vec{a}$

kinematics Control States $F = m \vec{a}$ momentum

Ginematics esp. $F = m\vec{a}$ momentum collisions







energy **nomentum**

conservation of energy

conservation of momentum

conservation of energy

Just algebra!

conservation of momentum

conservation of energy Why not START the easy way? conservation momentum

The historical approach

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

er A. Freedman odd G. Ruskell tilip R. Kesten David L. Tauck

E PHYSICS E > EIGHTH EDITION

Ernst Mach (1838–1916)

Collisions

COLLEGE PHYSICS

- Conservation of momentum
- Newton's laws
- Work and energy
- Conservation of energy

er A. Freedman odd G. Ruskell uilip R. Kesten David L. Tauck

E PHYSICS E > EIGHTH EDITION

Ernst Mach (1838–1916)

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

er A. Freedman odd G. Ruskell ilip R. Kesten David L. Tauck

E PHYSICS E > EIGHTH EDITION

Halliday / Resnick / Walker

RWAY/FAUC

COLLEGE PHYSICS

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

SERWAY

PHYSICS FOR SCIENTIST AND ENGINEERS

Eighth Edition

Volume 1

er A. Freedman odd G. Ruskell hilip R. Kesten David L. Tauck

we can!



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

ERIC MAZUR

RIC MAZUR

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

ERIC MAZUR

RIC MAZUR

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

What about

engineers?

• Work

ERIC MAZUR

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



ERIC MAZUR

RIC MAZUR

Principles and Pract

ysics



ConservationPrinciplesand theStructure ofStructure ofEngineeringEngineering



Charles J. Glover Kevin M. Lunsford John A. Fleming



erimental)

ntal)









ERIC MAZUR









 $PHYSICS & {\sf PRACTICE} \ {\sf OF}$

why 2 books?

ERIC MAZUR

ERIC MAZUR



PRINCIPLES & **PRACTICE** OF **PHYSICS**

RIC MAZUR

More logical!

CIPLES & PRACTICE

• Unity

Focus on physics

ERIC MAZUR

ERIC MAZUR


More practical!

ES & PRACTICE

Contexts different

• Lighter

ERIC MAZUR







RIC MAZUR

architecture

1

ERIC

Energy

- 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

CONCEPTS

QUANTITATIVE TOOLS

architecture

1

ERIC



- 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

QUANTITATIVE TOOLS

CONCEPTS

Energy

- **5.1 Classification of collisions**
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems

5.5 Elastic collisions

ERIC

- 5.6 Inelastic collisions
- 5.7 Conservation of energy
- 5.8 Explosive separations



Energy

- **5.1 Classification of collisions**
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems

5.5 Elastic collisions

ERIC

- 5.6 Inelastic collisions
- 5.7 Conservation of energy
- 5.8 Explosive separations



11.1 CIRCULAR MOTION AT CONSTANT SPEED 255

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 rota-

tional 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

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 defini-

tion 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.

third conservation law.

of rotation.

motion. We therefore begin our analysis of rotational motion by describing circular motion. Circular motion occurs

≺he 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 11.1b 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 All points on object follow identical trajectories

(b) Rotational motion

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

axis of rotatio



(c) Combined translation and rotation

anchitecture





Different points on object follow different trajectories













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 vstems

CONCEPTS

nergy

energy

ation of collisions

CONCEPTS

≺he motion we have been dealing with so far in this text is called translational motion (Figure 11.1a). ject's orientation; in other words, all the particles in the object move along identical parallel trajectories. During

arcintecture



representations

vect rollow identical trajectories. Verbal and center. Objects that turn about an *interest of the strengthere* object can be sufficiented as a system of particles, each revolving around the axis

ation of collisions nergy energy vstems

SELF-QUIZ 163

Self-quiz

- 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 K₁, a bar for K₂, 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?



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

- (a) The cart with the smaller inertia experiences the greater acceleration (see Figure 7.2). (b) The magnitude of Δp

 ¹/_p is the same as the magnitude of Δp

 ²/_p, but the changes are in opposite directions because the momentum of the system does not change during the collision. (c) |ΔK₁| = |ΔK₂|, 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.
- 2. (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 $E_{int} = 0$; during the collision K_1 , K_2 , and E_{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 $E_{int} = 0$. Because the system is closed, its energy is constant, which means the sum of the three bars is always the same.



During the interaction, eight units of source energy is converted 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.

cation of collisions energy energy systems

collisions collisions ration of energy re separations

Energy

- 5.1 Classification of collisions
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems

5.5 Elastic collisions

ERIC

- 5.6 Inelastic collisions
- 5.7 Conservation of energy
- 5.8 Explosive separations



6.5 GALILEAN RELATIVITY 133

6.5 Galilean relativity

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

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

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

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

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

(6.1)

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

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

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

architecture

1

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





c collisions tic collisions ervation of energy sive separations

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

From Figure A under pinnings to ence frame A under pinnings to $\Delta t = t_r - 0 = t_r$, and so $\tau_{AB} = \overline{v}_{AB} t_r$ becaule B moves at constant velocity.

Equations 6.2 Experience of the first one (neither of these has to be a strengthed and the strengthed to the first one (neither of these has to be a strengthed and the strengthed and t

equations so that they give the values of time and position in reference frame B

The abservers moving relative to each the same of the

collisions tic collisions ervation of energy sive separations



(b) From Figure 10.18 I see that $\tan \theta = |F_{\text{spx}}^c| / |F_{\text{spy}}^c|$. For $\theta < 45^\circ$, $\tan \theta < 1$, $\operatorname{and} \operatorname{so} |F_{\text{spx}}^c| < |F_{\text{spy}}^c|$. Because $|F_{\text{spy}}^c| = F_{\text{Ep}}^c$ and $|F_{\text{spx}}^c| = F_{\text{rp}}^c$. I find that for $\theta < 45^\circ$, $F_{\text{rp}}^c < F_{\text{Ep}}^c$. When $\theta > 45^\circ$, $\tan \theta > 1$, $\operatorname{and} \operatorname{so} |F_{\text{spx}}^c| > |F_{\text{spy}}^c|$ and $F_{\text{rp}}^c > F_{\text{Ep}}^c$. \checkmark (c) $|F_{\text{spy}}^c| = F_{\text{Ep}}^c$ and $F_{\text{sp}}^c = \sqrt{(F_{\text{spy}}^c)^2 + (F_{\text{spy}}^c)^2}$. Therefore, F_{sp}^c must always be larger than F_{Ep}^c when $\theta \neq 0$.

● 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}_{Ep}^{c} and \vec{F}_{Ep}^{c} on your friend make the same angle with the force \vec{F}_{Ep} , and \vec{F}_{Ep}^{c} 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}_{Fp}^{c} is larger than \vec{F}_{Ep}^{c} . In part *c*, because the vertical component of the force \vec{F}_{sp}^{c} are the vertex of your friend always has to be equal to the force of gravity, adding a horizontal component makes \vec{F}_{sp}^{c} larger than \vec{F}_{Ep}^{c} , 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

CONCEPTS

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 this instant.

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

architecture

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 fric-

Even though the normal and tangential components of

tional 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 surfaceup 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.



cation of collisions energy energy systems

ollisions collisions ation of energy e separations

Figure 10.19 A demonstration of the normal force.

(b) From Figure 10.18 I see that $\tan \theta = |F_{spx}^c| / |F_{spy}^c|$. For $\theta < 45^{\circ}$, tan $\theta < 1$, and so $|F_{spx}^{c}| < |F_{spy}^{c}|$. Because $|F_{spy}^{c}| = F_{Ep}^{G}$ and $|F_{spx}^c| = F_{rp}^c$, I find that for $\theta < 45^\circ$, $F_{rp}^c < F_{Ep}^G$. When $\theta > 45^{\circ}$, tan $\theta > 1$, and so $|F_{spx}^c| > |F_{spy}^c|$ and $F_{rp}^c > F_{Ep}^G$. (c) $|\vec{F}_{spy}^c| = F_{Ep}^G$ and $F_{sp}^c = \sqrt{(F_{spx}^c)^2 + (F_{spy}^c)^2}$. Therefore, F_{sp}^c must always be larger than F_{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 \vec{F}_{sp}^{c} , and so $\vec{F}_{\rm rp}^{\rm c}$ and $\vec{F}_{\rm Ep}^{\rm G}$ 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}_{rp}^{c} is larger than \vec{F}_{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}_{sp}^{c} larger than \vec{F}_{Ep}^{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

CONC

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 ing, friction pushing to hop it in motion. If you stop p s 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 this instant.

it skip Checkpoint 10.5! It will be harder to mought about stand the r these situations.

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 surfaceup 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 ands prevent sideways motion. As you push the brick to right, the bumps resist bending and, like microscopic rings, each bump exerts a force to the left. The net effect 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.



der-

cation of collisions energy energy systems

Figure 10.19 A demonstration of the normal force.

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 cation of collisions 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 this instant.

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

Figure 10.19 A demonstration of the normal force.

As you push harder, con plank on brick increases

energy energy systems

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 cation of collisions 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 this instant.

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

Figure 10.19 A demonstration of the normal force.

As you push harder, con plank on brick increases

energy energy systems

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 Ω_A by Ω_B : $\Omega = \Omega_A \Omega_B$.

The probability of each macrostate is obtained by dividing Ω , the number of basic states associated with that macrostate, by Ω_{tov} the number of basic states associated with all macrostates (2.00×10^7 ; 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 $E_A = 7$?

O GETTING STARTED Because all basic states are equally likely, the probability of finding the system in macrostate E_A is equal to the fraction $\Omega / \Omega_{\text{torb}}$ where Ω is the number of basic states of the system associated with the macrostate E_A and Ω_{tor} 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 $E_{A^{3}}$ I divide the value of Ω for that macrostate given in Table 19.2 by $\Omega_{\text{tot}} = 2.00 \times 10^{7}$.

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 $(4.34\times10^6)/(2.00\times10^7)=2.17\times10^{-1}$. \checkmark

C 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.

architecture

1

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 10^{25} particles and 10^{20} energy units per particle, and so the number of basic states becomes unimaginably large—on the order of ten raised to the power 10^{21} ! 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 Ω_A , Ω_B , and Ω 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_A increases, the number of basic states Ω_A increases. As E_A increases, however, E_B decreases and so Ω_B decreases. The number of basic states Ω 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 $E_A = 1$ the number of basic states for the system (2.80×10^4) 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).



fication of collisions c energy al energy d systems

c collisions tic collisions ervation of energy sive separations

CONCEPTS

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 Ω_A by Ω_B : $\Omega = \Omega_A \Omega_B$.

The probability of each macrostate is obtained by dividing Ω , the number of basic states associated with that macrostate, by Ω_{tov} the number of basic states associated with all macrostates (2.00×10^7 ; 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.

g) tomanica in fi.

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 $E_A = 7$?

0 GETTING STARTED Because all basic states are equally likely, the probability of finding the system in macrostate E_A is equal to the fraction $\Omega / \Omega_{\text{tot}}$ where Ω is the number of basic states of the system associated with the macrostate E_A and Ω_{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 $E_{A^{3}}$ I divide the value of Ω for that macrostate given in Table 19.2 by $\Omega_{\text{tot}} = 2.00 \times 10^{7}$.

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

O 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 meacrostate $E_A = 7$ is the equilibrium state for which the is an equivartition of energy.

architecture

1

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 10^{25} particles and 10^{20} energy units per particle, and so the number of basic states becomes unimaginably large—on the order of ten raised to the power 10^{21} ! 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 Ω_A , Ω_B , and Ω 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_A increases, the number of basic states Ω_A increases. As E_A increases, however, E_B decreases and so Ω_B decreases. The number of basic states Ω 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 $E_A = 1$ the number of sic states for the system (2.80 × 10⁴) is more than 100 times aller than it is at equilibrium ($E_A = 7$, $\Omega = 4.34 \times 10^6$). Isions between the particles and the partition redistribute

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



fication of collisions c energy al energy d systems

c collisions tic collisions ervation of energy sive separations

CONCEPTS

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 $E_A = 7$?

1 GETTING STARTED Because all basic states are equally likely, the probability of finding the system in macrostate E_A is equal to the fraction $\Omega/\Omega_{\text{tot}}$, where Ω is the number of basic states of the system associated with the macrostate E_A and Ω_{tot} is the total number of basic states associated with all macrostates (2.00 × 10⁷; Table 19.2).

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

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 $(4.34 \times 10^6)/(2.00 \times 10^7) = 2.17 \times 10^{-1}$.

4 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.

fication of collisions c energy al energy d systems

collisions ic collisions vation of energy ive separations

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 $E_A = 7$?

O GETTING STARTED Because all basic states are equally likely, the probability of finding the system in macrostate E_A is equal to the fraction $\Omega/\Omega_{\text{tot}}$, where Ω is the number of basic states of the system associated with the macrostate E_A and Ω_{tot} is the total number of basic states associated with all macrostates (2.00 × 10⁷; Table 19.2).

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

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 $(4.34 \times 10^6)/(2.00 \times 10^7) = 2.17 \times 10^{-1}$.

4 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.

fication of collisions c energy al energy d systems

collisions c collisions vation of energy ve separations

















Position vectors are each other's opposites.

 \overrightarrow{r}_{AB}





(a) Earth reference frame (observer E) Relative to observer E, elerates to the righ car ac Marble on car floor Marble's inertia causes it to resist accelerating relative to observer E.















6.5 GALILEAN RELATIVITY 133

PRINCIPLES VOLUME

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

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

concepts before quantitative tools

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

- checkpoints to thinking
 - **Construction** \vec{r}_{AB} of observer B in reference frame A at instant t_e is equal to the displacement over the time interval $\Delta t = t_e 0 = t_e$, and so $\vec{r}_{AB} = \vec{v}_{AB} t_e$ because B moves at constant velocity \vec{v}_{AB} . Therefore
- 4-step worked examples

Frame to data on the same events 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

- research-based illustrations
- research-based pedagogy











Chapter Summary304Review Questions305Developing a Feel306Worked and Guided Problems307Questions and Problems311Answers to Review Questions316Answers to Guided Problems316

PRACTICE

ciples & **practice** of HYSICS

ERIC MAZUR

Chapter Summary 304 Review Questions 305 Developing a Feel 306 Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 Answers to Guided Problems 316

PRACTICE

ciples & **practice** of HYSICS

ERIC MAZUR

Chapter Summary 304 **Review Questions** 305 **Developing a Feel 306** Worked and Guided Problems 307 **Questions and Problems** 311 Answers to Review Questions 316 Answers to Guided Problems 316

PRACTICE

CIPLES & **PRACTICE** OF

HYSICS

ERIC MAZUR

Chapter Summary 304 **Review Questions** 305 **Developing a Feel 306** Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 Answers to Guided Problems 316

PRACTICE

CIPLES & **PRACTICE** OF

AYSICS

ERIC MAZUR

Chapter Summary 304 **Review Questions** 305

Developing a Feel 306

Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 Answers to Guided Problems 316

RACTICE

192 CHAPTER 11 PRACTICE MOTION IN A CIRCLE

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)

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

A. What is the inertia of a bowling ball?

H. What is the inertia of a midsize car?

K. What is the yo-yo's rotational inertia?

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?

L. What is the radius of Earth's orbit?

I. What is the radius of the tire?

sleeping person? D. What is Earth's rotational speed?

and tire? P. What is Earth's radius?

4. The angular momentum around the axle of a wheel/tire combi-

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)

nation on your car as you cruise on the freeway (E, I, O, AA, S)

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

F. What is the relationship between force and acceleration for this G. How can you model the skater's shape during her spin?

M. What is the perpendicular distance from the house to the car's

O. How can you model the combined rotational inertia of the wheel

N. What is the skater's rotational inertia with arms held out?

E. What is the combined inertia of the wheel and tire?

J. How many turns are needed to rewind the yo-yo?

- **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:

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)

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

A. 7 kg; B. 1 y = 3×10^7 s; C. solid cylinder of radius 0.2 m;

Eqs. 8.6, 8.17, and 11.16, $\sum \vec{F} = m\vec{a}$, so $mg = mv^2/r$; G. a solid

cylinder with two thin-rod arms of inertia 4 kg held out perpen-

(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 m/s²;

U. $\omega \approx 10 \text{ s}^{-1}$; V. 7 × 10¹ kg; W. 0.5 s; X. the parallel-axis

theorem; Y. 3 \times 10¹ mi/h; Z. 6 \times 10²⁴ kg; AA. 3 \times 10¹ m/s

representing wheel)—say, $3MR^2/4$; P. 6 × 10⁶ m; Q. about twice

K. 6 \times 10⁻⁵ kg · m² (with yo-yo modeled as solid cylinder); L. 2×10^{11} m; M. 2×10^{1} m; N. 4 kg * m²; O. between MR^2

D. period = 24 h, so $\omega = 7 \times 10^{-5} \text{ s}^{-1}$; E. 10¹ kg; F. from

dicularly; H. 2 \times 10³ kg; I. 0.3 m; J. 2 \times 10¹ turns;

Table 11.3 in order to determine this quantity? Y. What is a typical speed for a car moving on a city street?

AA. What is a typical freeway cruising speed?

10. The kinetic energy of a spinning yo-yo (K, W, J, Q)

U. What is the skater's initial rotational speed?

Z. What is Earth's inertia?

Key (all values approximate)

Chapter Summary 304 **Review Questions** 305

Developing a Feel 306

Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 Answers to Guided Problems 316

RACTICE

192 CHAPTER 11 PRACTICE MOTION IN A CIRCLE

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)

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

A. What is the inertia of a bowling ball?

H. What is the inertia of a midsize car?

K. What is the yo-yo's rotational inertia?

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?

L. What is the radius of Earth's orbit?

I. What is the radius of the tire?

sleeping person? D. What is Earth's rotational speed?

and tire? P. What is Earth's radius?

4. The angular momentum around the axle of a wheel/tire combi-

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)

nation on your car as you cruise on the freeway (E, I, O, AA, S)

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

F. What is the relationship between force and acceleration for this G. How can you model the skater's shape during her spin?

M. What is the perpendicular distance from the house to the car's

O. How can you model the combined rotational inertia of the wheel

N. What is the skater's rotational inertia with arms held out?

E. What is the combined inertia of the wheel and tire?

J. How many turns are needed to rewind the yo-yo?

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:

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)

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?

U. What is the skater's initial rotational speed?

AA. What is a typical freeway cruising speed?

Key (all values approximate)

A. 7 kg; B. 1 y = 3×10^7 s; C. solid cylinder of radius 0.2 m; D. period = 24 h, so $\omega = 7 \times 10^{-5} \text{ s}^{-1}$; E. 10¹ kg; F. from Eqs. 8.6, 8.17, and 11.16, $\sum \vec{F} = m\vec{a}$, so $mg = mv^2/r$; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H. 2 \times 10³ kg; I. 0.3 m; J. 2 \times 10¹ turns; K. 6 \times 10⁻⁵ kg · m² (with yo-yo modeled as solid cylinder); L. 2×10^{11} m; M. 2×10^{1} m; N. 4 kg * m²; O. between MR^2 (cylindrical shell representing tire) and $MR^2/2$ (solid cylinder representing wheel)—say, $3MR^2/4$; P. 6 × 10⁶ 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 m/s²; U. $\omega \approx 10 \text{ s}^{-1}$; V. 7 × 10¹ kg; W. 0.5 s; X. the parallel-axis theorem; Y. 3 \times 10¹ mi/h; Z. 6 \times 10²⁴ kg; AA. 3 \times 10¹ m/s

Chapter Summary 304 Review Questions 305 Developing a Feel 306 Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 Answers to Guided Problems 316



Chapter Summary 304 Review Questions 305 Developing a Feel 306 Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 Answers to Guided Problems 316



Chapter Summary 304 Review Questions 305 Developing a Feel 306 Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 Answers to Guided Problems 316



Chapter Summary 304 Review Questions 305 Developing a Feel 306 Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 Answers to Guided Problems 316



Chapter Summary 304 **Review Questions** 305 **Developing a Feel** Worked and Ausled Modelens

d Problems 311 uesti to Review Questions 316 s to Guided Problems 316

307

RACTICE

192 CHAPTER 11 PRACTICE MOTION IN A CIRCLE Make an order-of-magnitude estimate of each of the following quantities. Letters in parentheses refer to **Developing a Feel** 6. The speed you would need to orbit Earth in a low orbit (F, P) hints below. Use them as needed to guide your thinking: 7. The magnitude of the force exerted by the Sun on E 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 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 3. Your rotational inertia as you turn over in your sleep its surface (A, R, X) (C) 4. The angular momentum around the axle of a wheel/ e combihouse, of a large car dri nation on your car as you cruise on the freeway (E, , O, AA, S) 10. The kinetic energy of a 5. The angular momentum of a spinning ice skater, ith each arm held out to the side and parallel to the ice (G, If needed, see Key for answers to these guiding questions initial rota ong a time interval does the yo-yo take to A. What is the inertia of a bowling b B. How long a time interval is need is needed in addition to the formulas in Principles tion around the Sun? 11.3 in order to determine this quantity? C. What simple geometric What is a typical speed for a car moving on a city street? sleeping person? 2. What is Earth's inertia? What is Ear AA. What is a typical freeway cruising speed? during her spin Key (all values approximate) D. period = 24 h, so $\omega = 7 \times 10^{-5} s^{-1}$; E. 10^{1} kg; F. from rns are needed to rewind the yo-yo? s the yo-yo's rotational inertia? dicularly; H. 2 \times 10³ kg; I. 0.3 m; J. 2 \times 10¹ turns; radius of Earth's orbit? What, the perpendicular distance from the house to the car's What is the skater's rotational inertia with arms held out? w can you model the combined rotational inertia of the wheel 0 nd tire? What is Earth's radius? U. $\omega \approx 10 \text{ s}^{-1}$; V. 7 × 10¹ kg; W. 0.5 s; X. the parallel-axis Q. What is the final rotational speed? theorem; Y. 3 \times 10¹ mi/h; Z. 6 \times 10²⁴ kg; AA. 3 \times 10¹ m/s 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?

A. 7 kg; B. 1 y = 3×10^7 s; C. solid cylinder of radius 0.2 m; 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 perpen-K. 6 \times 10⁻⁵ kg · m² (with yo-yo modeled as solid cylinder); L. 2×10^{11} m; M. 2×10^{1} m; N. 4 kg · m²; O. between MR^2 (cylindrical shell representing tire) and MR²/2 (solid cylinder $\frac{1}{2}$ $\frac{1}$ 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 m/s²;
PRACTICE Waves in Two and **Three Dimensions**

Chapter Summary 304 **Review Questions** 305 **Developing a Feel 306** Worked and Guided Problems 307 **Questions and Problems** 311 Answers to Review Questions 316 Answers to Guided Problems 316

PRACTICE

CIPLES & **PRACTICE** OF

HYSICS

ERIC MAZUR

PRACTICE Waves in Two a **Three Dimensi**

Chapter Summary 304 **Review Questions** 305 **Developing a Feel 306** Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 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 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.

Figure WG13.3



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 $v_i = v_{esc}$ 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

- 1. 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

PRACTICE

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, $r_f = \infty$ 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:



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.

G 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
- 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?

PRACTICE Waves in Two a **Three Dimensi**

Chapter Summary 304 **Review Questions** 305 **Developing a Feel 306** Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 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.

O 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 $v_i = v_{esc}$ 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

- 1. 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

PRACTICE

4. What law of physics should you invoke?

SEXECUTE PLAN Let us use r_i for the initial Mars-probe radial center-to-center separation distance, $r_f = \infty$ 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:



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.

O 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
- 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?

PRACTICE Waves in Two a **Three Dimensid**

Chapter Sommar **Review Q** tions Developin eel Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 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 electro-**3** EXECUTE PLAN Let u magnetic cannon, which means they must launch at escape speed.

O GETTING STARTED Let us do a quick sketch to help a ing (Figure WG13.3). We select the Mars-probe system for In order to reach "deep space," the probe must attain a ve distance from Mars. This will require a significant amount kinetic energy, which the probe must acquire during lat launch, the kinetic energy immediately begin potential energy of the Mars-probe system tion distance increases. We assume a refe is fixed and only the probe away (infinity, really, but pr far), the kinetic en to be zero bec ene out there. The graviwhich is also zero. ntial energy is nega-Sun and other planets have a negliem, and we ignore the rotation of Mars. always slowing down at r_f, Zero speed is left

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 $v_i = v_{esc}$ 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?

GETTING STARTED

- 1. 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

PRACTICE

4. What law of physics should you invoke?



supply

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.

O 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
- 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?

PRACTICE Waves in Two a **Three Dimensi**

Chapter Summary 304 **Review Questions** 305 **Developing a Feel 306** Worked and Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316

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 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.

Figure WG13.3



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 $v_i = v_{esc}$ 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

- 1. 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

PRACTICE

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, $r_f = \infty$ 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:



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.

G 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
- 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?

PRACTICE Waves in Two a **Three Dimensi**

Chapter Sum Guided Problems 307 Questions and Problems 311 Answers to Review Questions 316 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 electro-**3** EXECUTE P magnetic cannon, which means they must launch at escape speed.

r analys

e gravi

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 atta. distance from Mars. This will require a sig very o kinetic energy, which the probe must acqu nt amount launch, the kinetic energy immediately begin potential energy of the Mars-probe system in tion distance increases. We assum as th is fixed and only the probe move away (infinity, really, but far), the kinetic ener doesn't need to be zero because any more ener hich is also zero. nal potential energy is negand other planets have a negliad we ignore the rotation of Mars. always slowing down Zero speed is left

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 $v_i = v_{esc}$ 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

- 1. 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

PRACTICE

4. What law of physics should you invoke?



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.

G 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
- 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?

PRACTICE VOLUME Waves in ¹ **Three Dimensi**

not just end-of-chapter material

many innovative features

teaches authentic problem solving



PRINCIPLES & **PRACTICE** OF **PHYSICS**

ERIC MAZUR





PRINCIPLES & PRACTICE OF PHYSICS

 $HYSICS & {\sf practice} \ {\sf of} \\ HYSICS$

conservation principles before force laws?

ERIC MAZUR







Foundations

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

content

CONCEPTS

QUANTITATIVE TOOLS

- 1.7 Significant digits
- 1.8 Solving problems
- 1.9 Developing a feel

2



- **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**





Momentum

4.1 Friction 4.2 Inertia

4.3 What determines inertia?

CONCEPTS

QUANTITATIVE TOOLS

4.4 Systems

4.5 Inertial standard

- 4.6 Momentum
- 4.7 Isolated systems
- 4.8 Conservation of momentum

2

content



















1







































systems & extensive quantities







































2 content




























elastic: relative speed unchanged





elastic: relative speed unchanged







elastic: relative speed unchanged

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









2 content









elastic vs. inelastic









































Principle of Relativity

6.1 Relativity of motion

- 6.2 Inertial reference frames
- 6.3 Principle of relativity
- 6.4 Zero-momentum reference frame

6.5 Galilean relativity

- 6.6 Center of mass
- 6.7 Convertible kinetic energy
- 6.8 Conservation laws and relativity

1 architecture

2 content

CONCEPTS

QUANTITATIVE TOOLS

inertial reference frames

Galilean relativity

content

e 1 Relativity of motion

e o Inertial reference frames

0.2 mercials of relativity

6.3 Principle of the reference frame

6.4 Zero-moment

6.5 Galilean relativity

6.6 Center of mas

6.7 Convertible kinetic energy

2

a Conservation laws and relativity

Interactions

MANAN

- 7.1 The effects of interactions
- 7.2 Potential energy
- 7.3 Energy dissipation
- 7.4 Source energy

CONCEPTS

QUANTITATIVE TOOLS

- 7.5 Interaction range
- 7.6 Fundamental interactions

7.7 Interactions and accelerations

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

1 architecture

2 content



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

- 7.7 Interactions and accelerations
- 7.8 Nondissipative interactions
- 7.9 Potential energy near Earth's surface
- 7.10 Dissipative interactions

content

2















reversible and irreversible state changes

(*a*) Coherent deformation: reversible



(*b*) Incoherent deformation: irreversible



























energy conversions



Friction dissipates mechanical energy irreversibly to thermal energy.



When source energy is converted to mechanical energy, some dissipates irreversibly to thermal energy.



Source energy can be converted . completely and irreversibly to thermal energy. K U E_s E_{th} NONDISSIPATIVE (reversible)

DISSIPATIVE (irreversible)





energy conversions







energy conversions





1 architecture

2 content







- 8.1 Momentum and force
- 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

content

- 8.8 Force of gravity
- 8.9 Hooke's law
- 8.10 Impulse

2

- 8.11 Systems of two interacting objects
- 8.12 Systems of many interacting objects










energy diagram

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?











Bed SDITION

MATTER & INTERACTIONS I MODERN MECHANICS





THE DEFINITIVE ED

FEYNMAN





1 architecture

2 content

- 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

Principles and Practice

- 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

architecture

content

2

- 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

Principles and Practice

- 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

architecture

content 2

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
- 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

architecture

- 15. Fluid mechanics
- 16. Wave motion
- 17. Sound waves
- 18. Superposition and standing waves

- 1. Foundations
- 2. Motion in one dimension

Principles and Practice

- 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

2

content

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
- 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

Principles and Practice

- 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

and the second of the

1 architecture

2 content

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
- 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



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 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

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



- 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

Principles and Practice

- 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

periodic

17. Waves in 2 and 3 dimensions



18. Fluids



mostly minor rearrangements!





easily custom tailored

			TO THE INSTRUCTOR
Table 1 Scheduling matrix			
Торіс	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







where is modern physics?







where is modern physics?





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
- 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
- 19. Entropy
- 20. Energy transferred thermally
- 21. Degradation of energy
- 22. Electric interactions
- 23. The electric field
- 24. Gauss's law
- 25. Work and energy in electrostatics
- 26. Charge separation and storage
- 27. Magnetic interactions
- 28. Magnetic fields of charged particles in motion
- 29. Changing magnetic fields
- 30. Changing electric fields
- **31. Electric circuits**
- 32. Electronics
- 33. Ray optics
- 34. Wave and particle optics

1 architecture

content

- 1. Foundation
- 2. Motion i
- 3. Accelera
- 4. Momentum, interactions

universality;

particle

- 5. Energy
- 6. Principle of relation
- 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
- 19. Entropy
- 20. Energy transferred thermally
- 21. Degradation of energy
- 22. Electric interactions
- 23. The electric field
- 24. Gauss's law
- 25. Work and energy in electrostatics
- 26. Charge separation and storage
- 27. Magnetic interactions
- 28. Magnetic fields of charged particles in motion
- 29. Changing magnetic fields
- 30. Changing electric fields
- **31. Electric circuits**
- 32. Electronics
- 33. Ray optics
- 34. Wave and particle optics

1 architecture

content

- **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

concepts of general relativity

- 18. Fluids
- 19. Entropy
- 20. Energy transferred thermally
- 21. Degradation of energy
- 22. Electric interactions
- 23. The electric field
- 24. Gauss's law
 - Work and energy in electrostatics
 - Charge separation and storage
- 27. Magnetic interactions
- 28. Magnetic fields of charged particles in motion
- 29. Changing magnetic fields
- 30. Changing electric fields
- **31. Electric circuits**
- **32. Electronics**
- 33. Ray optics
- 34. Wave and particle optics



- **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

S.R. as part of mechanics

- 18. Fluids
- 19. Entropy
- 20. Energy transferred thermally
- 21. Degradation of energy
- 22. Electric interactions
- 23. The electric field
- 24. Gauss's law
- 25. Work and energy in electrostatics
 - Charge separation and storage
 - . Magnetic interactions
- 28. Magnetic fields of charged particles in motion
- 29. Changing magnetic fields
- 30. Changing electric fields
- **31. Electric circuits**
- 32. Electronics
- 33. Ray optics
- 34. Wave and particle optics



- 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 **19. Entropy** d thermally 20. Energy transfer 21. Degradation of 22. Electric inter statistical 23. The electr foundation 24. Gauss's la for thermo 25. Work and 26. Charge separate 27. Magnetic interactions 28. Magnetic fields of charged particles in motion 29. Changing magnetic fields **30. Changing electric fields** 31. Electric circuits 32. Electronics 33. Ray optics 34. Wave and particle optics





- **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 **19. Entropy** 20. Energy transferr relativistic 21. Degradatic 22. Electric in E&M 23. The elect connection 24. Gauss's law 25. Work and ener 26. Charge separate and storage 27. Magnetic interactions 28. Magnetic fields of charged particles in motion 29. Changing magnetic fields **30. Changing electric fields** 31. Electric circuits
 - 32. Electronics
 - 33. Ray optics
 - 34. Wave and particle optics



- **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
- **19. Entropy**
- 20. Energy transferred thermally
- 21. Degradation of energy
- 22. Electric interactions
- 23. The electric field
- 24. Gauss's law
- 25. Work and energy
- 26. Charge sep semiconductors

transistors

otion

- 27. Magnetic
- 28. Magnetic
 - 29. Changing in logic gates
 - 30. Changing elect
 - 31. Electric circuits
 - 32. Electronics
 - 33. Ray optics
 - 34. Wave and particle optics





- **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
- **19. Entropy**
- 20. Energy transferred thermally
- 21. Degradation of energy
- 22. Electric interactions
- 23. The electric field
- 24. Gauss's law
- 25. Work and energy in electrostatics

photons &

particle

interference

motion

- 26. Charge separation and storage
- 27. Magnetic intera
- 28. Magnetic fi
- 29. Changing
- 30. Changing
- 31. Electric circu
- 32. Electronics
- 33. Ray optics
- 34. Wave and particle optics









Strategy

Overview

- Topics that are not covered
- Terminology

Notation and visual representations

Cautionary notes

Common student difficulties and concerns

Sample recommendations from Practice Vol


















1 architecture











University of Arkansas

PRINCIPLES & PRACTICE OF PHYSICS $PHYSICS & { extsf{PRACTICE}} \ { extsf{of}} \ { extsf{of}}$

course revision based on

preliminary version of manuscript:

ERIC MAZUR

ERIC MAZUR







University of Arkansas

PRINCIPLES & PRACTICE OF PHYSICS $PHYSICS & {\sf PRACTICE} \ {\sf OF} \\ OF & {\sf OF} \ {\sf OF}$

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

ERIC MAZUR

ERIC MAZUR











For a copy of these slides: mazur.harvard.edu

Textbook info/copies: pearsonhighered.com/mazur1e

