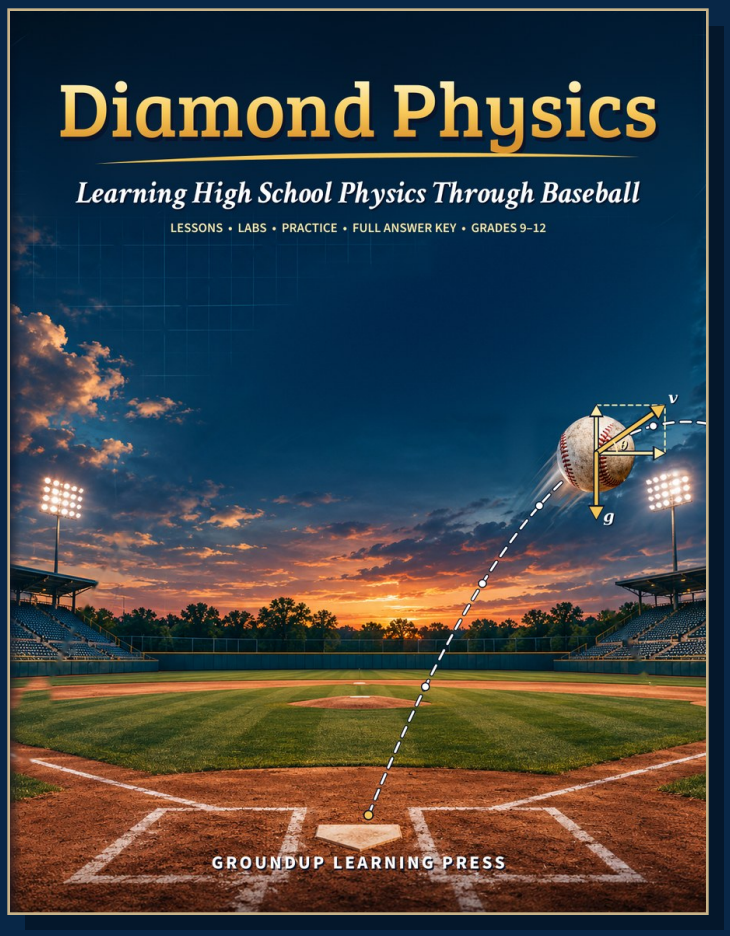
Diamond Physics

FULL STUDY GUIDE

Free companion to the Diamond Physics workbook

All 12 chapters · key ideas · vocabulary · formulas · worked examples · self-checks



High school physics through baseball · Grades 9–12

GROUNDUP LEARNING PRESS

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How to Use This Guide

A free companion to Diamond Physics: Learning High School Physics Through Baseball.

WHAT THIS GUIDE IS

This guide follows the 12 chapters of the **Diamond Physics** workbook. For each chapter you get the chapter's big question, the key ideas in short bullets, the vocabulary, every formula and constant exactly as the book states it, one new worked example, and a few self-check questions with answers at the back.

It is a review tool, not a replacement. The workbook has the full lessons and diagrams, the concept questions, practice problems, data challenges, hands-on labs, the Midgame and Final Reviews, the Capstone Project, and the complete answer key. None of those are reproduced here.

WAYS TO USE IT

- **Before a chapter:** read the big question and the key ideas so you know what to look for.
- **While you read:** keep the formulas table beside you. Check that you can say what every symbol means and what its unit is.
- **After a chapter:** cover the worked example's solution and try it yourself, then do the self-check without looking at your notes.
- **Before a test:** use the quick-reference page and the vocabulary lists as flash cards.
- **With the videos:** each Ground Up Learning lesson on YouTube matches a chapter. Watch the lesson, then do that chapter's self-check.

FIVE STEPS FOR EVERY PROBLEM (FROM THE BOOK)

- Sketch the situation and list what you know, with units.
- Convert to SI units.
- Write the equation that links what you know to what you want.
- Substitute and solve.
- Check: are the units right, and is the size of the answer reasonable?

A NOTE ON NUMBERS

As the book explains, values such as drag coefficients, spin rates, contact times, and collision efficiencies vary from ball to ball, bat to bat, and player to player. The book uses typical, rounded figures so the physics is clear, and this guide uses the same figures. Your answers may differ from ours in the last digit because of rounding; that is nothing to worry about. Carry extra digits through a calculation and round only the final answer, usually to two or three significant figures.

WHAT YOU NEED

First-year algebra, a calculator with sine, cosine, and square-root keys (set to degrees; a quick test is sin 30 = 0.5), a pencil, and some curiosity about why the game works the way it does.

Quick Reference: Units, Conversions, and Constants

From the book's Physics Toolkit. Keep this page beside you for every chapter.

SI UNITS USED IN THE BOOK

Quantity	Baseball unit	SI unit	Conversion
Length	foot (ft), inch (in)	meter (m)	1 ft = 0.3048 m; 1 in = 2.54 cm
Speed	mile per hour (mph)	meter per second (m/s)	1 mph = 0.447 m/s
Mass	ounce (oz)	kilogram (kg)	1 oz = 0.02835 kg
Force	pound (lb)	newton (N)	1 lb = 4.448 N

CONVERSIONS

1 ft = 0.3048 m	1 m = 3.28 ft	1 in = 2.54 cm
1 mph = 0.447 m/s	1 m/s = 2.24 mph	1 mph = 1.47 ft/s
1 oz = 0.02835 kg	1 kg = 2.2 lb (weight on Earth)	1 lb = 4.448 N
1 rev = 2π rad = 360°	1 rpm = 0.105 rad/s	1 hp = 746 W

CONSTANTS AND BASEBALL DATA

Quantity	Value
Acceleration due to gravity, g	9.8 m/s^2
Mass of a baseball	0.145 kg (5 to 5¼ oz)
Weight of a baseball	1.42 N
Radius and cross-sectional area of a baseball	0.0366 m; A = 0.0042 m^2
Density of air at sea level, ρ	1.2 kg/m^3
Drag coefficient of a baseball, Cd	about 0.35
Speed of sound in air	343 m/s
Bat–ball contact time	about 0.0007 s
Distance between bases	90 ft = 27.4 m
Pitching rubber to home plate	60 ft 6 in = 18.4 m (release point about 16.8 m from the plate)
Home plate to 2nd base	127 ft 3 in = 38.8 m
Mound height	10 in = 0.254 m

GREEK LETTERS

Δ (delta) change in; θ (theta) angle; ω (omega) angular velocity; α (alpha) angular acceleration; τ (tau) torque; ρ (rho) density; μ (mu) coefficient of friction; λ (lambda) wavelength.

Quick Reference: Every Equation in the Book

From the book's Physics Toolkit, with the chapter where each one is explained.

Idea	Equation	Chapter
Average speed	$v = d / t$	1
Acceleration	$a = \Delta v / \Delta t$	2
Motion with constant acceleration	$v = v0 + at$; $d = v0t + \frac{1}{2}at^2$; $v^2 = v0^2 + 2ad$	2
Newton's second law	$Fnet = ma$	3
Weight	$W = mg$	3
Velocity components	$vx = v \cos \theta$; $vy = v \sin \theta$	4
Projectile hang time, height, range	$t = 2v \sin \theta / g$; $H = (v \sin \theta)^2 / 2g$; $R = v^2 \sin 2\theta / g$	4
Momentum	$p = mv$	5
Impulse–momentum theorem	$F\Delta t = \Delta p = m\Delta v$	5
Conservation of momentum	$m1v1 + m2v2 = m1v1' + m2v2'$	5
Work	$W = Fd$	6
Kinetic energy	$KE = \frac{1}{2}mv^2$	6
Gravitational potential energy	$PE = mgh$	6
Power	$P = W / t$	6
Coefficient of restitution	e = speed of separation / speed of approach = $\sqrt{(h2 / h1)}$	7
Exit velocity	$EV = q$(pitch speed) + $(1 + q)$(bat speed), $q \approx 0.2$	7
Speed of a rotating point	$v = r\omega$	8
Torque	$\tau = rF$; $\tau = I\alpha$	8
Moment of inertia (point mass)	$I = mr^2$	8
Rotational energy and momentum	$KErot = \frac{1}{2}I\omega^2$; $L = I\omega$	8
Drag force	$Fdrag = \frac{1}{2}C\rho Av^2$	9
Magnus force	$FMagnus = \frac{1}{2}CL\rho Av^2$	10
Friction	$f = \mu N$	12
Waves	$v = f\lambda$	12

Watch the letter W: in the book it stands for weight ($W = mg$, Chapter 3), for work ($W = Fd$ and $P = W / t$, Chapter 6), and as the symbol for the watt unit. Read the chapter to know which one is meant.

CHAPTER 1

Measuring the Game

THE BIG QUESTION

How fast is fast, and how do we know?

KEY IDEAS

- Baseball's rulebook uses feet, inches, ounces, and miles per hour. Physics uses the International System of Units (SI): the **meter** (length), the **kilogram** (mass), and the **second** (time).
- The book's routine: convert baseball numbers into SI units first, do the physics, then convert back when it helps.
- To convert, multiply by a conversion factor so the unwanted unit cancels. Always write the units. If the units come out wrong, the answer is wrong.
- Average speed is distance divided by time: v = d / t. Rearranged: d = v t and t = d / v.
- Velocity is speed together with a direction. A fastball and a line drive back at the pitcher can have the same speed but opposite velocities.
- The batter does not get the full 60 ft 6 in. A typical release point is about 55 ft (16.8 m) from home plate, so a 95 mph fastball arrives in about 0.40 s.
- A swing takes roughly 0.15 s, leaving about 0.25 s to see the pitch and decide. Human reaction time is about 0.2 s by itself.

KEY VOCABULARY

SI units
The International System of Units, built on the meter, the kilogram, and the second.

Conversion factor
A ratio such as 0.447 m/s per 1 mph, used so the unwanted unit cancels.

Speed
Distance traveled divided by time.

Velocity
Speed together with direction.

Average speed
Total distance divided by total time; a runner who speeds up and slows down still has one average speed.

Reaction time
The delay between a signal and the start of a response.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

v = d / t	Average speed (m/s) = distance (m) ÷ time (s)
d = v t t = d / v	The same equation rearranged for distance or time
1 ft = 0.3048 m; 1 in = 2.54 cm	Length
1 mph = 0.447 m/s	Speed
1 oz = 0.02835 kg; 1 lb = 4.448 N	Mass; force
90 ft = 27.4 m	Base to base
60 ft 6 in = 18.4 m	Pitching rubber to home plate
127 ft 3 in = 38.8 m	Home plate to 2nd base
10 in = 0.254 m	Mound height
about 55 ft (16.8 m)	Typical release point, measured from the plate

WORKED EXAMPLE · HOW LONG DOES A 75 MPH CHANGEUP TAKE?

A changeup leaves the hand at 75 mph from a typical release point, 16.8 m from the plate. How long does the batter have?

Step 1. Convert. 75 mph × 0.447 = 33.5 m/s.

Step 2. Choose the equation. We know distance and speed and want time: t = d / v.

Step 3. Solve. t = 16.8 m ÷ 33.5 m/s = 0.50 s.

Step 4. Check. It is slower than a 95 mph fastball, so it should take longer than 0.40 s. It does.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. An outfielder sprints 24 m in 4.0 s. Find the average speed in m/s and then in mph (1 m/s = 2.24 mph).

2. A home-run ball travels 120 m. How far is that in feet (1 m = 3.28 ft)?

3. A pitch at 30 m/s heads toward home plate, and a batted ball at 30 m/s heads toward the outfield. Do they have the same speed? The same velocity?

4. Why does the book time a pitch over about 55 ft instead of the full 60 ft 6 in?

5. A pitch leaves the hand at 36 m/s from 16.8 m away. Ignoring air, how long does it take to reach the plate?

CHAPTER 2

Motion on the Basepaths

THE BIG QUESTION

How do we describe exactly how a runner steals second base?

KEY IDEAS

- Kinematics describes motion without yet asking what causes it.
- **Distance** is the total path length. **Displacement** is the straight-line change in position, with direction. A home-run trot is 360 ft of distance but zero displacement.
- Velocity is displacement divided by time; speed is distance divided by time. In straight-line motion, use a + or − sign for direction.
- Acceleration is the rate at which velocity changes, in m/s². Slowing down is also acceleration; it has the opposite sign from the velocity.
- The three equations of motion work only while acceleration is constant. Pick the one that contains the three things you know and the one you want.
- On a velocity–time graph, the slope is the acceleration and the area under the line is the displacement.
- Every freely falling object accelerates downward at g = 9.8 m/s². At the top of a pop-up the velocity is zero for an instant, but the acceleration is still 9.8 m/s² downward.
- Every pitch is a falling object: gravity pulls it below the line it was thrown along.

KEY VOCABULARY

Kinematics
The description of motion using position, velocity, and acceleration.

Distance
The total length of the path traveled.

Displacement
The straight-line change in position, with direction.

Acceleration
The rate at which velocity changes; measured in m/s².

Δ (delta)
Means “change in.”

Free fall
Falling with only gravity acting; the acceleration is g = 9.8 m/s² downward.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

$a = \Delta v / \Delta t = (v - v0) / t$	Acceleration (m/s²)
$v = v0 + a\,t$	Constant acceleration: velocity after time t
$d = v0\,t + \frac{1}{2}\,a\,t^2$	Constant acceleration: displacement after time t
$v^2 = v0^2 + 2\,a\,d$	Constant acceleration: links velocity and displacement (no time)
$g = 9.8$ m/s² downward	Acceleration of every freely falling object near Earth's surface
$d = \frac{1}{2}\,g\,t^2$	Drop of an object that starts with zero vertical velocity

WORKED EXAMPLE · THE FIRST STEPS OF A STEAL

A runner starts from rest and accelerates at 3.0 m/s² for 2.5 s. How fast is the runner going, and how far has the runner gone?

Velocity. $v = v_0 + a\,t = 0 + (3.0)(2.5) = 7.5$ m/s.

Displacement. $d = v_0\,t + \tfrac{1}{2}\,a\,t^2 = 0 + \tfrac{1}{2}(3.0)(2.5)^2 = 9.4$ m.

Check. On a velocity–time graph this is a triangle: ½ × 2.5 s × 7.5 m/s = 9.4 m. Same answer.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. A batter hits a double and runs home → first → second along the base paths. Using the book's distances, find the distance run and the size of the displacement.

2. A runner slows from 6.0 m/s to a stop in 1.2 s. Taking forward as positive, find the acceleration.

3. A ball is tossed straight up at 9.8 m/s. Ignoring air, how long until it stops rising, and how high does it go?

4. A pitch is thrown horizontally and takes 0.50 s to reach the plate. Ignoring air, how far does gravity pull it down?

5. On a velocity–time graph, what does the slope tell you? What does the area under the line tell you?

CHAPTER 3

Forces and Newton's Laws

THE BIG QUESTION

What makes a baseball start, stop, or change direction?

KEY IDEAS

- Chapter 2 described motion; this chapter explains it. A force is a push or a pull, measured in newtons (N). A baseball weighs about 1.4 N.
- What matters is the **net force**, the combined effect of all forces. Add forces in the same direction and subtract opposite ones. Forces at right angles combine with the Pythagorean theorem.
- **First law (inertia):** an object at rest stays at rest, and an object in motion keeps moving in a straight line at constant speed, unless a net force acts on it. Mass is the measure of inertia.
- **Second law:** the acceleration of an object equals the net force on it divided by its mass. One newton gives a 1 kg mass an acceleration of 1 m/s².
- Weight is the force of gravity: mg. Mass and weight are different. On the Moon a baseball still has 0.145 kg of mass, but its weight drops to about one-sixth.
- **Third law:** when A pushes on B, B pushes back on A with a force of equal size in the opposite direction. The two forces act on different objects.
- In flight, only three forces act on a baseball: gravity, air drag, and the Magnus force. There is no “force of the hit” traveling with the ball.

KEY VOCABULARY

Force
A push or a pull; measured in newtons.

Newton
The SI unit of force; the force that accelerates 1 kg at 1 m/s².

Net force
The combined effect of all the forces on an object.

Inertia
The tendency of an object to resist changes in its motion.

Mass
The amount of matter in an object and the measure of its inertia; measured in kilograms.

Weight
The force of gravity on an object; mg.

Free-body diagram
A sketch showing all the forces acting on one object.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

a = Fnet / m or Fnet = m a	Newton's second law (N = kg·m/s²)
W = mg	Weight (the chapter writes it as weight = m g)
Fnet = √(Fx² + Fy²)	Net force from two forces at right angles
g = 9.8 m/s²	Acceleration due to gravity
0.145 kg; 1.42 N	Mass of a baseball; weight of a baseball

WORKED EXAMPLE · THROWING FROM THE OUTFIELD

An outfielder takes a 0.145 kg ball from rest to 30 m/s in 0.12 s. What average net force acts on the ball?

Acceleration. $a = \Delta v / \Delta t = 30 \text{ m/s} \div 0.12 \text{ s} = 250 \text{ m/s}^2$.

Force. $F_{net} = m\,a = (0.145 \text{ kg})(250 \text{ m/s}^2) = 36 \text{ N}$.

Third-law check. While the hand pushes the ball forward with 36 N, the ball pushes back on the hand with 36 N.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. What is the weight of a 0.90 kg bat on Earth?

2. A net force of 2.9 N acts on a baseball. What is its acceleration?

3. Two forces act on a ball at right angles: 3.0 N and 4.0 N. What is the size of the net force?

4. A baseball is taken to the Moon. What is its mass there? About what is its weight?

5. A runner pushes backward on the ground with her cleats. What is the other force in that third-law pair, and what does it do?

CHAPTER 4

Projectile Motion

THE BIG QUESTION

Why does a fly ball follow a curved path, and which launch angle sends it farthest?

KEY IDEAS

- A projectile is an object moving through the air under the influence of gravity. This chapter ignores air; Chapters 9 and 10 put it back.
- Two motions happen at once and do not affect each other: horizontal velocity stays constant (no horizontal force), while the vertical motion has a constant downward acceleration of 9.8 m/s².
- Together they make a curved path called a parabola. A dropped ball and a ball thrown horizontally from the same height land at the same time.
- **Time is the link:** vertical motion decides how long the ball is in the air; horizontal motion decides how far it goes in that time.
- Without air, range is greatest at 45°. Angles that add up to 90° (such as 30° and 60°) give the same range, but the higher one stays up longer.
- Range depends on v²: hit the ball 10% faster and it goes about 21% farther. In real air the best home-run angle is lower, about 25° to 30°.
- At the top of its path a projectile is still moving: vertical velocity is zero, horizontal velocity is unchanged, and the acceleration is still 9.8 m/s² downward.

KEY VOCABULARY

Projectile
An object moving through the air under the influence of gravity.

Parabola
The curved path of a projectile when air is ignored.

Component
The part of a vector that points along a chosen direction, such as horizontal or vertical.

Launch angle (θ)
The angle above horizontal at which the ball leaves the bat.

Exit velocity
The speed of the ball as it leaves the bat.

Barrel
The book's term for a best-struck ball: exit velocity of at least 98 mph and, at that speed, a launch angle of 26° to 30°.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

$v_x = v \cos\theta$	Horizontal component (m/s)
$v_y = v \sin\theta$	Vertical component (m/s)
$t = 2 v \sin\theta / g$	Hang time (s), no air, same landing height
$H = (v \sin\theta)^2 / 2g$	Maximum height (m), no air
$R = v_x t = v^2 \sin 2\theta / g$	Range (m), no air, same landing height

WORKED EXAMPLE · A TOWERING FLY BALL

A ball leaves the bat at 32 m/s at a launch angle of 50°. Ignoring air, find its hang time, maximum height, and range.

Components. $v_x = 32 \cos 50° = 20.6$ m/s. $v_y = 32 \sin 50° = 24.5$ m/s.

Hang time. $t = 2(24.5) \div 9.8 = 5.0$ s. **Height.** $H = (24.5)^2 \div (2 \times 9.8) = 30.6$ m.

Range. $R = v_x t = (20.6)(5.0) = 103$ m. Check: $v^2 \sin 2\theta / g = (1024)(\sin 100°) \div 9.8 = 103$ m.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. A ball hit at 25° (no air) lands at a certain distance. What other launch angle, at the same speed, gives the same range? Which of the two stays in the air longer?

2. A ball leaves the bat at 20 m/s at 60°. Find its vertical component and its hang time (no air, same landing height).

3. With no air, by what percent does the range grow if exit speed rises by 20%?

4. At the very top of a fly ball's path, what are its vertical velocity, its horizontal velocity, and its acceleration?

5. One ball rolls off a table and another is dropped from the same height at the same moment. Which lands first?

CHAPTER 5

Momentum and Impulse

THE BIG QUESTION

How can a bat reverse a 90 mph pitch in less than a thousandth of a second?

KEY IDEAS

- The bat–ball collision lasts about 0.0007 s. In that time the ball stops, squashes, springs back, and leaves faster than it came in.
- Momentum is mass times velocity, measured in kg·m/s. It is a vector, so in straight-line problems direction is handled with signs.
- Turning a ball around takes a bigger change in momentum than just stopping it, because the sign changes.
- Impulse is FΔt. The impulse–momentum theorem says the change in momentum equals the average force times the time it acts. On a force–time graph, impulse is the area under the curve.
- Stretch out the stopping time and the force shrinks: a glove hand that “gives,” a catcher's mitt, a helmet liner, wall padding, and a bunter's loose grip.
- A follow-through does not keep the bat on the ball longer; contact is over in 0.0007 s no matter what.
- In a collision the bat and ball get equal and opposite impulses, so total momentum is conserved whenever outside forces are small compared with the contact forces.

KEY VOCABULARY

Momentum (p)
Mass times velocity.

Vector
A quantity with both size and direction.

Impulse
Force multiplied by the time it acts; equal to the change in momentum.

Impulse–momentum theorem
The change in an object's momentum equals the average force on it multiplied by the time the force acts.

Average force
The constant force that would give the same impulse (area) in the same time.

Conservation of momentum
The total momentum of a system stays constant when outside forces are negligible.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

p = mv	Momentum (kg·m/s)
F Δt = Δp = m Δv	Impulse–momentum theorem
m1v1 + m2v2 = m1v1' + m2v2'	Conservation of momentum (before = after)
about 0.0007 s	Bat–ball contact time
0.145 kg	Mass of a baseball

WORKED EXAMPLE · WHY A CATCHER'S MITT IS PADDED

A catcher stops a 0.145 kg pitch moving at 34 m/s. Compare the average force if the stop takes 0.008 s and if the mitt and hand stretch it to 0.025 s.

Change in momentum. $\Delta p = m(v \text{ after} - v \text{ before}) = 0.145(0 - 34) = -4.9$ kg·m/s. Its size is 4.9 kg·m/s either way.

Quick stop. $F = \Delta p / \Delta t = 4.93 \div 0.008 = 620$ N.

Longer stop. $F = 4.93 \div 0.025 = 200$ N. About three times the time means about one-third the force.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. What is the momentum of a 0.145 kg ball moving at 30 m/s?

2. A 30 m/s pitch is sent straight back at 30 m/s. What is the size of the change in momentum? How does it compare with simply stopping the ball?

3. A 0.145 kg ball arrives at 32 m/s and leaves at 38 m/s in the opposite direction. Contact lasts 0.0007 s. Find the average force.

4. Use impulse to explain why outfield walls are padded.

5. Does a long follow-through keep the bat on the ball longer? What does it show?

CHAPTER 6

Work, Energy, and Power

THE BIG QUESTION

Where does a home run's energy come from, and where does it go?

KEY IDEAS

- Energy can move from one object to another and change form, but the total is never created or destroyed.
- Work is done when a force moves an object through a distance in the direction of the force. A fielder standing still holding a ball does no work on it.
- Kinetic energy depends on v^2, so speed matters more than mass. Double the speed and kinetic energy quadruples.
- **Work–energy theorem:** the net work done on an object equals its change in kinetic energy.
- Lifting a ball stores gravitational potential energy, mgh. Ignoring air, kinetic plus potential energy stays constant during flight.
- Power is the rate of doing work. Athletic performance is mostly about power: the same energy delivered in less time means a harder throw.
- Energy flows from food → muscles → bat or ball → elastic energy in the collision → ball's kinetic energy, plus thermal energy, sound, and vibration. A bat brings roughly 400 J; a well-hit ball leaves with only about 170 J.
- A 100 mph pitch is only 5% faster than a 95 mph pitch but carries about 11% more energy.

KEY VOCABULARY

Work
Force times the distance moved in the direction of the force.

Joule
The SI unit of work and energy; one newton-meter.

Kinetic energy
Energy of motion; $\frac{1}{2}mv^2$.

Potential energy
Stored energy, such as energy due to height (mgh).

Conservation of energy
The law that the total energy of an isolated system never changes.

Power
The rate of doing work; measured in watts (one joule per second).

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

$W = Fd$	Work (J = N·m)
$KE = \frac{1}{2}mv^2$	Kinetic energy (J)
$PE = mgh$	Gravitational potential energy (J)
$\frac{1}{2}mv1^2 + mgh1 = \frac{1}{2}mv2^2 + mgh2$	Conservation of energy, no air
$P = W / t$	Power (W = J/s)
$1\ hp = 746\ W$	Horsepower conversion

WORKED EXAMPLE · HOW HIGH COULD THAT THROW GO?

A 0.145 kg ball leaves a fielder's hand at 30 m/s. Find its kinetic energy. If it were thrown straight up (no air), how high would it rise?

Kinetic energy. KE = ½mv² = ½(0.145)(30)² = 65 J.

Energy conservation. At the top all 65 J is potential energy: mgh = 65 J, so h = 65.25 ÷ (0.145 × 9.8) = 46 m.

Note. The mass cancels: h = v² / 2g = 900 ÷ 19.6 = 46 m. Energy methods did not need the time or the path.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. Find the kinetic energy of a 0.145 kg ball moving at 20 m/s.

2. A fielder lifts a 0.145 kg ball 2.0 m straight up. How much potential energy does it gain?

3. A throw gives a ball 65 J of energy in 0.10 s. What average power is that, in watts and in horsepower?

4. If a ball's speed triples, by what factor does its kinetic energy change?

5. A player holds a ball perfectly still at arm's length for a minute. How much work is done on the ball? Why?

CHAPTER 7

Collisions and the Bounce

THE BIG QUESTION

Why does a baseball jump off a bat but thud to a stop in the grass?

KEY IDEAS

- In a perfectly elastic collision no kinetic energy is lost (e = 1). In a perfectly inelastic collision the objects stick together and as much kinetic energy as possible is lost (e = 0). Real collisions fall in between.
- Momentum is conserved in every collision. Kinetic energy is conserved only in perfectly elastic ones.
- A baseball is a surprisingly unbouncy ball: internal friction in its wound yarn turns kinetic energy into thermal energy.
- The coefficient of restitution (COR, e) compares speed of separation with speed of approach. A drop test measures it: $e = \sqrt{(h2 / h1)}$.
- Against a hard, heavy surface at game speeds a baseball's COR is about 0.55, so it keeps only about $(0.55)^2 = 0.30$ of its kinetic energy.
- COR is not fixed: it drops at higher collision speeds, and cold or humid-stored balls are less bouncy. Since the 2022 season, all 30 professional clubs store game balls in a humidor.
- Exit velocity: each extra 1 mph of bat speed adds 1.2 mph; each extra 1 mph of pitch speed adds only 0.2 mph (with q = 0.2). Bat speed matters six times as much.
- Hollow bats flex like a trampoline. BBCOR limits the bat–ball COR to 0.50 for U.S. high school and college baseball.

KEY VOCABULARY

Elastic collision
A collision in which no kinetic energy is lost.

Inelastic collision
A collision in which kinetic energy is changed to other forms.

Coefficient of restitution
A measure of bounciness; speed of separation divided by speed of approach.

Exit velocity (EV)
The speed of the ball as it leaves the bat.

Collision efficiency (q)
The number in the EV rule; depends on the COR and the bat's mass and how it is distributed. About 0.2 for a wood bat on the sweet spot.

Trampoline effect
A thin bat wall flexes and springs back, so the ball deforms less and loses less energy.

BBCOR
Batted Ball Coefficient of Restitution; the standard that limits the liveliness of high school and college bats.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

e = speed of separation / speed of approach	Coefficient of restitution (no units)
e = √(h2 / h1)	COR from a drop test
fraction of kinetic energy kept = e²	The book: “The fraction of kinetic energy that survives a bounce is e²”
EV = q(pitch speed) + (1 + q)(bat speed)	Exit velocity; q ≈ 0.2. Use the same speed unit throughout
about 0.55; 0.50	Baseball COR on a hard, heavy surface at game speeds; BBCOR limit

WORKED EXAMPLE · EXIT VELOCITY OFF A WOOD BAT

A 78 mph pitch is hit on the sweet spot by a bat moving at 66 mph. Take q = 0.2.

EV. EV = (0.2)(78) + (1.2)(66) = 15.6 + 79.2 = 94.8 mph.

Add 4 mph of bat speed (70 mph). EV = 15.6 + 84 = 99.6 mph, a gain of 4.8 mph.

Add 4 mph of pitch speed instead (82 mph). EV = 16.4 + 79.2 = 95.6 mph, a gain of only 0.8 mph.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. A ball dropped from 1.8 m bounces to 0.45 m. Find e and the fraction of kinetic energy that survives the bounce.

2. Find the exit velocity for an 80 mph pitch and a 74 mph bat, with q = 0.2.

3. Is momentum conserved when a pitch snaps into a catcher's mitt? Is kinetic energy?

4. Why do high school and college leagues require BBCOR bats?

5. Name two conditions that make a baseball less bouncy.

CHAPTER 8

Rotation and Torque: The Swing

THE BIG QUESTION

Why is a heavier bat harder to swing, and why does choking up help?

KEY IDEAS

- Angular velocity ω tells how fast something turns, in rad/s. One full turn is 2π radians (about 6.28).
- Every point on a rotating bat has the same ω but not the same speed: v = rω. Same rotation rate, bigger radius, greater speed. That is why you hit with the barrel.
- Torque is the turning effect of a force; it depends on the size of the force and how far from the axis it is applied (think door knob vs. hinge).
- Moment of inertia I is rotational mass. It depends on where the mass is; because r is squared, mass far from the axis counts enormously.
- Rotational second law: τ = Iα. For the same torque, a larger moment of inertia means the bat speeds up more slowly.
- Swing weight is a bat's moment of inertia about the handle. End-loaded bats are harder to get moving; a typical adult bat is about 0.20 kg·m² about a point near the knob.
- Choking up moves the axis closer to the center of mass, lowering I for a quicker, more controlled swing, at the cost of a slightly shorter radius.
- Angular momentum L = Iω is conserved when no outside torque acts. Hitters and pitchers keep things close to spin up, then extend.

KEY VOCABULARY

Angular velocity (ω)
How fast an object rotates, in radians per second.

Pivot point
The point on the bat that the rotation is measured about.

Torque (τ)
The turning effect of a force; force times distance from the axis. Measured in N·m.

Moment of inertia (I)
An object's resistance to changes in rotation; depends on mass and how far it is from the axis.

Angular acceleration (α)
The rate of change of angular velocity, in rad/s².

Swing weight
A bat's moment of inertia about a pivot point on the handle.

Angular momentum (L)
The rotational form of momentum; moment of inertia times angular velocity.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

$v = r\omega$	Speed of a rotating point (m/s); r in m, ω in rad/s
$\text{rad/s} = \text{rpm} \times 2\pi / 60$	Converting spin rates (toolkit: 1 rpm = 0.105 rad/s)
$\tau = rF$	Torque (N·m), force applied perpendicular to r
$I = mr^2$	Moment of inertia of a point mass (kg·m²)
$\tau = I\alpha$	Rotational form of Newton's second law
$KE_{rot} = \frac{1}{2}I\omega^2 \quad L = I\omega$	Rotational kinetic energy; angular momentum
$1 \text{ rev} = 2\pi \text{ rad} = 360°$	Angle conversion

WORKED EXAMPLE · A YOUTH SWING

A bat rotates at 35 rad/s, and the contact point is 0.70 m from the pivot point. How fast is the contact point moving?

Speed. $v = r\omega = (0.70\text{ m})(35\text{ rad/s}) = 24.5\text{ m/s}$, about $24.5 \times 2.24 = 55$ mph.

Torque needed to spin it up. If the bat's moment of inertia is 0.20 kg·m^2 and it gains angular speed at $\alpha = 150\text{ rad/s}^2$, then $\tau = I\alpha = (0.20)(150) = 30\text{ N·m}$.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. Convert a spin rate of 1,800 rpm to rad/s.

2. Find the moment of inertia of a 0.50 kg mass located 0.60 m from the axis.

3. A 50 N force is applied perpendicular to a handle 0.30 m from the axis. What torque does it produce?

4. Explain in one or two sentences why choking up gives a quicker swing.

5. A pitcher keeps the arm tucked early, then extends it. What is conserved, and how does it help?

CHAPTER 9

Air Resistance

THE BIG QUESTION

Why don't home runs travel 580 feet?

KEY IDEAS

- With no air, a ball hit at 100 mph (44.7 m/s) and 30° would travel about 580 ft. In a real game it lands about 400 ft away. The air took the missing 180 ft.
- Air is a fluid with mass (about 1.2 kg per cubic meter at sea level). Drag always points opposite to the ball's velocity, so it always slows the ball.
- Drag grows with the square of speed: double the speed and the drag becomes four times as large.
- At about 90 mph (40 m/s) drag on a baseball is about 1.4 N, as large as its weight. A 95 mph fastball crosses the plate at about 87 mph.
- For fly balls, drag cuts the range to roughly 60% to 70% of the no-air value, makes the ball come down more steeply than it went up, and drops the best launch angle to about 25°–30°.
- Less dense air means less drag: altitude (Denver, about 82% as dense; fly balls 5% to 10% farther), warm air, and humid air (a small effect). Wind changes the ball's speed relative to the air.
- Terminal velocity is reached when drag equals weight; for a baseball it is near 40 m/s, about 90 mph.
- The seams make the ball rough, which leaves a smaller wake and less drag. A perfectly smooth baseball would not fly as far.

KEY VOCABULARY

Drag
The force of air resistance; it points opposite to the velocity.

Drag coefficient (Cd)
A number describing how much drag an object's shape and surface produce. Roughly 0.35 for a baseball at game speeds.

Air density (ρ)
Mass of air per cubic meter; about 1.2 kg/m³ at sea level.

Cross-sectional area (A)
The area of the circle the ball presents to the air: $\pi r^2 = 0.0042$ m².

Terminal velocity
The constant speed reached when drag equals weight.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

$F_{drag} = \frac{1}{2} C_d \rho A v^2$	Drag force (N)
$F_{drag} = 0.000882\, v^2$	Shortcut for a baseball at sea level (v in m/s, F in N)
$v_{terminal} = \sqrt{(2mg / (C_d \rho A))}$	Terminal velocity
$C_d \approx 0.35;\ \rho = 1.2$ kg/m³	Drag coefficient of a baseball; air density at sea level
$r = 0.0366$ m; $A = 0.0042$ m²	Radius and cross-sectional area of a baseball

WORKED EXAMPLE · DRAG ON A SOFT LINER

A ball moves through sea-level air at 25 m/s. Find the drag force and the deceleration it causes.

Drag. $F_{drag} = 0.000882\ v^2 = 0.000882 \times (25)^2 = 0.55$ N.

Deceleration. $a = F / m = 0.55 \div 0.145 = 3.8\ m/s^2$.

Compare. At 40 m/s the drag is 1.4 N. Going from 25 to 40 m/s (1.6 times faster) multiplies drag by $1.6^2 \approx 2.6$.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. If a ball's speed is cut in half, what happens to the drag force?

2. Use the shortcut to find the drag on a ball moving at 15 m/s.

3. Give two reasons a fly ball might carry farther on a hot afternoon in Denver than on a cold night at sea level.

4. Why is the best home-run launch angle in real air lower than 45°?

5. At terminal velocity, what is the net force on a falling ball? Why?

CHAPTER 10

Spin and the Magnus Effect

THE BIG QUESTION

What makes a curveball curve?

KEY IDEAS

- The curve is real. A spinning ball drags a thin layer of air around with it, which tilts the wake. The ball pushes air one way; by Newton's third law the air pushes the ball the other way.
- This spin force is the Magnus force, named for the German physicist Gustav Magnus, who studied it in 1852.
- **Direction rule:** the Magnus force pushes the ball in the direction that the front of the ball is turning. Backspin → up; topspin → down; sidespin → sideways.
- The Magnus force is perpendicular to both the velocity and the spin axis. Gyro spin (axis along the direction of travel) gives no Magnus force.
- The lift coefficient CL grows with spin rate; for typical pitches it is 0.15 to 0.25. With CL = 0.20 at 40 m/s the force is about 0.8 N, more than half the ball's weight.
- Deflection grows as t^2. At the halfway point in time a pitch has made only one-quarter of its break, which is why the break looks late.
- Four-seam fastball: backspin, falls less than expected (no pitched fastball actually rises). Curveball: topspin, drops more. Slider: sidespin plus gyro spin. Knuckleball: almost no spin; the seams make it flutter.

KEY VOCABULARY

Magnus force
The force on a spinning ball caused by the air it deflects; perpendicular to the velocity.

Backspin / topspin / sidespin
Spin that turns the front of the ball up / down / to the side.

Gyro spin
Spin about an axis along the direction of travel; it produces no Magnus force.

Lift coefficient (CL)
The number in the Magnus equation; it grows with spin rate (0.15 to 0.25 for typical pitches).

Wake
The stream of air leaving the ball.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

$F_{Magnus} = \frac{1}{2} C_L \rho A v^2$	Magnus force (N)
$a = F / m$	Sideways acceleration from the Magnus force
$d = \frac{1}{2} a t^2$	Deflection, starting with no sideways velocity
17 inches (0.43 m)	Width of home plate
$\rho = 1.2$ kg/m³; $A = 0.0042$ m²	Air density at sea level; ball cross-section

WORKED EXAMPLE · A MODEST SLIDER

A pitch feels a sideways Magnus force of 0.30 N during a 0.42 s flight. How far does it move sideways?

Acceleration. $a = F / m = 0.30 \div 0.145 = 2.1$ m/s².

Deflection. $d = \frac{1}{2} a t^2 = \frac{1}{2}(2.07)(0.42)^2 = 0.18$ m, about 7 inches.

Break timing. At 0.21 s (half the flight) it has moved only one-quarter of that, about 0.05 m.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. A pitch has topspin. Which way does the Magnus force point, and what does the batter see?

2. Find the Magnus force on a ball moving at 35 m/s with CL = 0.15 at sea level.

3. A pitch breaks 12 inches in total. About how much of that break has happened at the halfway point in time?

4. Why does a ball with pure gyro spin feel no Magnus force?

5. Why is a knuckleball so hard to predict?

CHAPTER 11

The Physics of Pitching

THE BIG QUESTION

How does a human being throw a ball 95 miles per hour?

KEY IDEAS

- No single muscle can move a hand at 95 mph. A pitch is a timed chain in which large, slow body parts hand off energy and momentum to smaller, faster ones.
- Kinetic chain, from the ground up: legs (push against the rubber; the ground pushes back), hips then trunk (hip–shoulder separation stores elastic energy), then shoulder, elbow, wrist, and fingers.
- Each link starts moving just as the one before reaches top speed. Momentum flows from heavy segments to lighter ones, which end up moving faster, like a cracking whip.
- The arm is a lever: hand speed follows $v = r\omega$, so a longer arm helps. The 10-inch-high mound lets the pitcher turn some potential energy into kinetic energy.
- Extension (releasing closer to the plate) gives the batter less time, so the pitch seems faster: perceived velocity.
- A changeup uses the same arm speed as a fastball but arrives 8 to 10 mph slower. “Hitting is timing. Pitching is upsetting timing.” (Warren Spahn)
- Velocity comes from the ground up. The elbow feels a twisting load of roughly 60 to 100 N·m on every hard pitch; when legs and trunk supply the energy, the arm does not have to. To throw 5% faster takes about 10% more kinetic energy.

KEY VOCABULARY

Kinetic chain
The sequence of body segments that pass energy from the ground to the ball.

Hip–shoulder separation
The hips rotate open before the shoulders, stretching the torso and storing elastic energy.

Extension
How far in front of the rubber a pitcher releases the ball.

Perceived velocity
How fast a pitch seems to the batter, taking the release distance into account.

Changeup
A pitch thrown with fastball arm speed but a deep grip, so it arrives 8 to 10 mph slower.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

$v = r\omega$	Hand speed from arm rotation
$a = \Delta v / \Delta t;\ F = ma$	Force on the ball in the final whip
$t = d / v$	Time to the plate from the release point

A SCOUTING REPORT IN NUMBERS (FROM THE BOOK)

Pitch	Typical speed (mph)	Typical spin (rpm)	Main spin	What the batter sees
Four-seam fastball	90–100	2,200–2,500	backspin	stays up; arrives early
Changeup	80–88	1,500–2,000	backspin with sidespin	looks like a fastball; arrives late and low
Slider	82–90	2,200–2,700	sidespin and gyro spin	sharp, late sideways break
Curveball	74–83	2,400–2,900	topspin	big downward break
Knuckleball	65–80	under 200	almost none	flutters unpredictably

Pitch table values are the book's typical professional values; high school pitches are slower but follow the same pattern.

WORKED EXAMPLE · WHAT EXTENSION IS WORTH

A 90 mph pitch is released 55 ft from the plate by one pitcher and 52 ft from the plate by a pitcher with a longer stride. How much sooner does the second pitch arrive?

Convert. 90 mph × 0.447 = 40.2 m/s. 55 ft = 16.8 m. 52 ft × 0.3048 = 15.85 m.

Times. t1 = 16.8 ÷ 40.2 = 0.418 s. t2 = 15.85 ÷ 40.2 = 0.394 s.

Difference. About 0.024 s less for the batter, so the same 90 mph looks faster.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. List the kinetic chain in order, from the ground up.

2. Two pitchers' arms rotate at the same rate, but one pitcher's hand is 10% farther from the shoulder. How do their hand speeds compare?

3. In the last 0.040 s before release, a ball speeds up from 15 m/s to 39 m/s. Find the average force on the 0.145 kg ball.

4. Using the book's pitch table, which pitch typically has the most spin, and which has the least?

5. Why does fatigue raise the risk of arm injury?

CHAPTER 12

Fielding, Friction, and Vibrations

THE BIG QUESTION

Why does a mishit sting, and why do runners slide?

KEY IDEAS

- Catching uses $F\Delta t = \Delta p$. The ball fixes the change in momentum, so the only thing a fielder controls is the stopping time. “Soft hands” stretch the stop and shrink the force.
- Friction opposes sliding. $f = \mu N$, and on level ground the normal force equals the weight, so $f = \mu mg$. Without friction, no one could run.
- A slide uses friction on purpose to stop in a short distance while staying low and hard to tag; the bag is only 15 inches wide.
- A sliding runner's deceleration is $a = \mu g$: the mass cancels.
- A struck bat vibrates in a standing wave. Points that do not move are nodes. One node lies in the barrel about 5 to 7 inches (13 to 18 cm) from the tip: the sweet spot.
- Hit at the node and almost no energy goes into vibration, so more goes into the ball and the hands feel nothing. Hit near the tip or the hands and the vibration stings.
- Sound waves obey $v = f\lambda$. Sound travels about 343 m/s. A wood bat's main vibration is near 170 Hz; a hollow metal bat also rings at about 2,000 Hz (the “ping”).
- Light travels almost a million times faster than sound, so far from the plate you see contact before you hear it.

KEY VOCABULARY

Friction
A force that opposes sliding between surfaces.

Normal force (N)
The support force a surface exerts perpendicular to itself.

Coefficient of friction (μ)
A number describing how strongly two surfaces resist sliding.

Node
A point on a vibrating object that does not move.

Sweet spot
The region of the barrel where contact produces the least vibration and the greatest ball speed.

Frequency (f)
The number of vibrations per second; measured in hertz (Hz).

Wavelength (λ)
The distance between one wave crest and the next.

FORMULAS AND CONSTANTS (AS STATED IN THE BOOK)

$\mathbf{f = \mu N}$	Friction force (N)
$\mathbf{f = \mu mg;\ a = \mu g}$	On level ground: friction; a sliding runner's deceleration
$\mathbf{d = v0^2 / 2a}$	Stopping distance, from $v^2 = v0^2 + 2ad$
$\mathbf{F\,\Delta t = \Delta p}$	Catching: same impulse, longer time, smaller force
$\mathbf{v = f\lambda}$	Wave speed = frequency × wavelength
343 m/s	Speed of sound in air

WORKED EXAMPLE · A SHORT SLIDE INTO SECOND

A 65 kg runner starts a slide at 6.0 m/s. The coefficient of friction between uniform and dirt is 0.50. Find the friction force and the sliding distance.

Friction. $f = \mu mg = (0.50)(65)(9.8) = 320$ N.

Deceleration. $a = \mu g = (0.50)(9.8) = 4.9$ m/s². The mass canceled.

Distance. $d = v0^2 / 2a = (6.0)^2 \div (2 \times 4.9) = 3.7$ m.

SELF-CHECK

Original questions for review. Answers are at the back of this guide.

1. Find the friction force on a 55 kg runner sliding on level dirt with $\mu = 0.45$.

2. A fielder doubles the time it takes to stop a line drive. What happens to the average force on the hand?

3. A fan sits 100 m from home plate. About how long after seeing contact does the fan hear it?

4. A sound wave in air has a frequency of 686 Hz. What is its wavelength?

5. Why does a ball hit on the sweet spot not sting the hands?

Self-Check Answers

Answers to this guide's own self-check questions. For the workbook's exercises, use the answer key in the book.

Chapter 1: Measuring the Game

1. 6.0 m/s; 6.0 × 2.24 = 13.4 mph.
2. 120 × 3.28 = 394 ft (about 390 ft).
3. Same speed (30 m/s), but not the same velocity: the directions are opposite.
4. The pitcher strides forward and releases the ball well in front of the rubber, about 55 ft (16.8 m) from the plate. That shorter distance is what the batter actually gets.
5. t = d / v = 16.8 ÷ 36 = 0.47 s.

Chapter 2: Motion on the Basepaths

1. Distance = 2 × 27.4 m = 54.8 m (180 ft). Displacement = 38.8 m (127 ft 3 in) from home plate toward 2nd base.
2. a = (0 − 6.0) ÷ 1.2 = −5.0 m/s². The minus sign means it points opposite the velocity.
3. t = 9.8 ÷ 9.8 = 1.0 s. From $v^2 = v0^2 + 2ad$: $0 = (9.8)^2 - 2(9.8)d$, so d = 4.9 m.
4. $d = \frac{1}{2} g t^2 = \frac{1}{2}(9.8)(0.50)^2 = 1.2$ m.
5. Slope = acceleration. Area under the line = displacement.

Chapter 3: Forces and Newton's Laws

1. W = mg = (0.90)(9.8) = 8.8 N.
2. a = Fnet / m = 2.9 ÷ 0.145 = 20 m/s².
3. Fnet = $\sqrt{(3.0^2 + 4.0^2)} = \sqrt{25} = 5.0$ N.
4. Mass is still 0.145 kg. Weight is about one-sixth of 1.42 N, roughly 0.24 N.
5. The ground pushes forward on the runner with an equal force. That forward push is what moves her.

Chapter 4: Projectile Motion

1. 65° (the two add up to 90°). The 65° ball stays up longer.
2. vy = 20 sin 60° = 17.3 m/s; t = 2(17.3) ÷ 9.8 = 3.5 s.
3. Range depends on v^2: $1.2^2 = 1.44$, so about 44% farther.
4. Vertical velocity is zero; horizontal velocity is unchanged from launch; acceleration is still 9.8 m/s² downward.
5. They land at the same time. Horizontal motion does not change the vertical fall.

Chapter 5: Momentum and Impulse

1. p = mv = (0.145)(30) = 4.4 kg·m/s.
2. Δp = 0.145 × (30 − (−30)) = 8.7 kg·m/s, twice the 4.35 kg·m/s needed to stop it.
3. Δp = 0.145 × (38 − (−32)) = 0.145 × 70 = 10.2 kg·m/s. F = 10.15 ÷ 0.0007 ≈ 14,500 N.
4. The player's change in momentum is fixed. Padding makes the stop take longer, so the average force on the player is smaller.
5. No. Contact lasts about 0.0007 s regardless. A full follow-through shows the bat was still at full speed at contact.

Chapter 6: Work, Energy, and Power

1. $KE = \frac{1}{2}(0.145)(20)^2 = 29$ J.
2. PE = mgh = (0.145)(9.8)(2.0) = 2.8 J.
3. P = W / t = 65 ÷ 0.10 = 650 W; 650 ÷ 746 ≈ 0.87 hp.
4. KE depends on v^2: $3^2 = 9$ times as much.
5. Zero. The ball does not move, so there is no distance in the direction of the force.

Chapter 7: Collisions and the Bounce

1. e = √(0.45 ÷ 1.8) = √0.25 = 0.50. Energy kept = e^2 = 0.25, or 25%.
2. EV = (0.2)(80) + (1.2)(74) = 16 + 88.8 = 105 mph (104.8).
3. Momentum, yes (it is conserved in every collision). Kinetic energy, no; this is close to perfectly inelastic.
4. Hollow bats' trampoline effect sends the ball off faster, which is dangerous for pitchers and infielders. BBCOR limits the bat–ball COR to 0.50 so a metal bat performs about like a good wood bat.
5. Any two of: higher collision speed, a cold ball, a ball stored in humid air.

Chapter 8: Rotation and Torque: The Swing

1. 1,800 × 2π ÷ 60 = 188 rad/s (about 189 rad/s with the 0.105 shortcut).
2. $I = mr^2 = (0.50)(0.60)^2 = 0.18$ kg·m².
3. τ = rF = (0.30)(50) = 15 N·m.
4. It moves the axis closer to the bat's center of mass, lowering the moment of inertia, so the same torque produces a larger angular acceleration.
5. Angular momentum (L = Iω). A small I early lets the body spin up quickly; extending at the end sends that rotation out to the hand, where r is large.

Chapter 9: Air Resistance

1. Drag depends on v^2: $(½)^2 = ¼$, so drag becomes one-quarter as large.
2. Fdrag = 0.000882 × 15^2 = 0.000882 × 225 = 0.20 N.
3. High altitude: the air is less dense (about 82% as dense). Warm air is also less dense. Less dense air means less drag.
4. A high fly ball spends a long time in the air, fighting drag the whole way, so a lower angle (about 25°–30°) goes farther.
5. Zero. The upward drag equals the downward weight, so the ball stops accelerating.

Chapter 10: Spin and the Magnus Effect

1. Downward. The pitch drops more than gravity alone would make it.
2. $F = ½(0.15)(1.2)(0.0042)(35)^2 = 0.46$ N.
3. One-quarter: about 3 inches. The other 9 inches come in the second half.
4. Its spin axis points along its direction of travel, so the front of the ball is not turning toward any side.
5. With almost no spin there is no steady Magnus force. As the ball slowly turns, the seams change where the air breaks away, and the wake swings from side to side.

Chapter 11: The Physics of Pitching

1. Legs → hips → trunk → shoulder → elbow/forearm → wrist → fingers (ball).
2. From v = rω with the same ω, the longer arm gives a 10% faster hand.
3. a = (39 − 15) ÷ 0.040 = 600 m/s²; F = ma = (0.145)(600) = 87 N.
4. Most: the curveball (2,400–2,900 rpm). Least: the knuckleball (under 200 rpm).
5. When a pitcher is tired, the legs and trunk contribute less energy, and the shoulder and elbow try to make up the difference.

Chapter 12: Fielding, Friction, and Vibrations

1. f = μmg = (0.45)(55)(9.8) = 240 N.
2. It is cut in half. The impulse (change in momentum) is the same, so twice the time means half the force.
3. t = d / v = 100 ÷ 343 = 0.29 s.
4. λ = v / f = 343 ÷ 686 = 0.50 m.
5. The sweet spot is at a node of the bat's main vibration, so that vibration is not set off. Little energy goes into shaking the bat and nothing travels down the handle.

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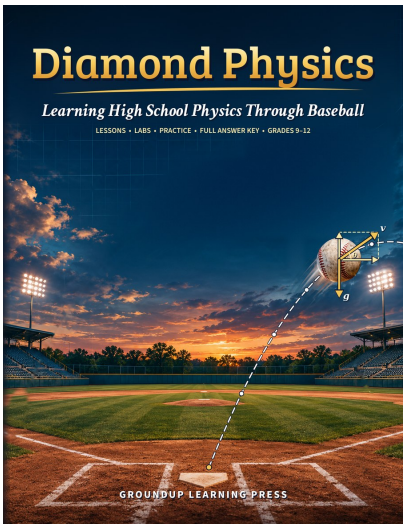
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