The Sweet Spot: Instructor Guide

Title

The Sweet Spot

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Discipline

Physics and Astronomy

Target Audience

Introductory, majors and nonmajors

Keywords

Baseball, force, graphing, kinematics, trajectory, velocity

Length of Time/Staging

Two to three class periods, homework problem

Abstract

A frightening incident of a high school baseball pitcher being struck in the temple by a ball sets the context of this problem. Students use two-dimensional kinematics to estimate reaction times for pitchers, distance ranges, and trajectories of baseballs. Graphical data of ball exit speed at various positions on a bat are used to compare the size of the sweep spot for aluminum and wood bats. The properties of these two types of bats are further investigated and the potential impact

on player safety, game statistics, and economics if amateur baseball were to switch to wood bats is explored.

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Format of Delivery

The problem can be given as a homework assignment to an individual or a small group of two or three. Stages are given separately over two lecture periods. Students should be familiar with kinematics. Most of the work is done outside of class. A wrap-up could include presentations by some individuals/groups during lecture time. Students benefit if part 2 is delivered along with a discussion of the art of setting constraints and making approximations (see the Teaching Notes).

Student Learning Objectives

Basic science

1. Velocity and two-dimensional kinematics are put into practice.
2. The range equation for simple projectile motion is either derived or used.
3. Practice in interpreting graphical data and plotting trajectories.

Real world context

1. Physics is applied to baseball.
2. Students make approximations and recognize the limits of their applicability.
3. Students also get a sense of how science can shape policies and regulations of a sport.

Student Resources

The modern day shape of a baseball bat evolved over 70 years. It began in the 1830s as a wooden stick and in the 1850s, the familiar handle and barrel design emerged. In the early 1970s, aluminum bats began to appear. Although the major leagues continue to use exclusively wooden bats, college baseball and little leagues switched to aluminum bats. The main reason had to do with economics; aluminum bats do not break. However, recent innovations and stronger/lighter materials are causing concern in softball and baseball governing bodies.

A great deal of discussion has centered on whether balls are hit faster and farther with aluminum bats. A limited amount of empirical evidence seems to support this claim. For instance, the Central Illinois Collegiate League (CICL) has reported measurable differences in game statistics. In order to protect its historical records, major league baseball has not permitted the use of aluminum bats. Faster hit balls also leave less time for infielders, particularly the pitcher, to react defensively. A notable is example is Wellesley High School pitcher, Billy Hughto, who needed surgery after he was hit in the head by a baseball hit off an aluminum bat. Out of concern for potential injury the governing body of collegiate sports, the NCAA, at one point considered reverting to wooden bats. More recently, the Massachusetts Interscholastic Athletic Association barred the use of aluminum bats in the 2003 Massachusetts high school baseball tournament. The pros and cons of using aluminum bats continue to be debated.

Popular Press

Aluminum vs. Wood bats related to the Billy Hughto incident.

1. CBS News: "Banned In Boston?"

Baseball and Sports Organizations

1. National Federation of State High School Associations

   Information on bat exit speed ratio (BESR).

2. Major League Baseball
3. Philadelphia Phillies
4. Central Illinois Collegiate League

   Some game statistics comparing seasons in which either aluminum or wood bats were used.

5. Massachusetts Interscholastic Athletic Association

Physics of Baseball

1. Prof. Alan Nathan: "The Physics of Baseball"
2. www.npl.uiuc.edu/~a-nathan/pob/
3. Exploratorium: "Science of Baseball"
4. www.exploratorium.edu/baseball/
5. Harvard Science Review, Winter 1997
6. Adam M. Kleinbaum: "The Physics of Baseball"
7. www.people.fas.harvard.edu/~bechis/99_hsr_webpage/hsr/winter97/bball.html

Baseball Bat Manufacturers

1. Easton bats
2. Louisville Slugger

Selected Published Research on the Physics of Baseball Bats

1. Brody, H. (1986). The sweet spot of a baseball bat. *American Journal of Physics*, 54(7), 640-643.
2. Brody, H. (1990). Models of baseball bats. *American Journal of Physics*, 58(8), 756-758.
3. Cross, R. (1998). "The sweet spot of a baseball bat," American Journal of Physics, 66(9), 771-779.
4. Nathan, A.M. (2000). The dynamics of the baseball-bat collision. *American Journal of Physics,* 68(11), 979-990.
5. Greenwald, R.M., Penna, L.H., and Crisco, J.J. (Aug. 2001). Difference in batted ball speed with wood and aluminum baseball bats. *Journal of Applied Biomechanics*, 17, 241.
6. Crisco, J.J., Greenwald, R.M., Blume, J.D., and Penna, L.H. (Oct. 2002). Batting performance of wood and metal baseball bats. *Medicine and Science in Sports and Exercise*, 34, 1675.

Instructor Resources

Prof. Alan Nathan: "The Physics of Baseball"

> Nathan, A. (23 January 2002). A comparative study of wood and aluminum baseball bats [Invited talk at AAPT Meeting Philadelphia, PA]. [ppt]
>
> Nathan, A. (20 September 2002). The physics of hitting a home run [Lecture]. [ppt]

The Science of the Swing, courtesy of Robert Adair, Yale University. Useful for gauging physiological times required for looking, thinking, deciding, and acting during the process of a swing.

Author's Teaching Notes

The problem can be introduced during a section on kinematics either before or shortly after Newton's second law (forces) is introduced. Part 1 is relatively quick with the help of the Student Resources, but students should be encouraged to produce a one page write-up to avoid trivial answers.

The main issue that arises in later parts is that many students are uncomfortable with making approximations. Consequently, they fail to constrain the problem and cannot make progress. Approximations and assumptions are made explicit in the above questions and should mitigate this concern. Alternatively, those assumptions can be left out, and students can be encouraged to make approximations, justify them, and find what results those approximations lead to. Extensive resources are provided to assist those students who lack sufficient background in baseball to form reasonable assumptions.

Students can use Excel, or some other spreadsheet software with graphing capabilities, to compute the coordinates and plot the trajectories for question 13.

Assessment Strategies

The logic and content of the task force report can be used to judge whether its conclusions/recommendations are supported by quantitative results. Test or quiz questions on two-dimensional motion, trajectory of simple projectile motion, or finding the range of a projectile range seem to suffice.

Solution Notes

1. Game statistics for wood vs. aluminum bats taken from Central Illinois Collegiate League. Differences in runs and home runs per game are evident.

	Aluminum 1987-90	Wood 1990-00	Percent Difference
Runs/Game	12.3	9.3	-24.6%
Hits/Game	18.0	16.3	-9.2%

HR/Game	1.5	0.6	-58.9%
TB/Game	26.5	21.9	-17.5%
Batting Average	0.288	0.259	-10.2%
ERA	5.71	3.92	-31.4%
K's/Game	9.6	11.7	22.1%
Field PCT	0.944	0.953	1.0%
Game Length	3.5 hrs	2.5 hrs	-28.6%

2. Some coaches estimate that a season's worth of wood bats will cost nearly three times the amount of aluminum bats. Wood bats cost anywhere from $25 to $75, but they do break. Assuming an average of three wood bats per player per season at $50 per bat amounts to $150 per player or $1500 per season for a modest roster of 10 players. The price of good aluminum bats, on the other hand, ranges from $170 to $270 and usually last a season or two. Assuming three new aluminum bats are bought every season for the team at $225 per bat amounts to $675 per season. Budgets may double if there are varsity and junior varsity teams.
3. Factors include post-impact velocity (speed and angle), distance between pitcher and batter, physiological reaction time, position and follow-thru of the pitcher after releasing the ball.
4. The trajectory of the ball is determined by the post-impact speed and angle, and the forces (Newton's second law) acting on the ball during its flight. These forces primarily include gravity and air drag.

   Whether the hit will result in a home run depends on the details of the bat-ball collision and the forces acting on the ball after impact. The collision is short, one or two milliseconds, but the process is complex. The details depend on the speed of the pitched ball, where and at what angle the ball strikes the bat, the speed of the bat at impact, and the mass and mechanical properties (elastic and inelastic) of the ball and bat. After the ball leaves the bat, air has a significant effect on the trajectory even in the absence of wind and ball spin (magnus force). The viscosity of air leads to a drag force that is directed opposite to the instantaneous velocity of the ball. The drag force depends on the shape and speed of the ball and the viscous properties of air which in turn vary with density, temperature, humidity, and altitude.
5. The mass, moment of inertia, and elastic properties of the bat do affect the post-impact velocity of a ball. Lighter bats are generally preferred by power hitters who believe that they give them a faster bat speed, better control of their swing, and a fraction of a second longer to judge the pitch. The hollow nature of aluminum bats also leads to the "trampoline" effect. Under the "trampoline" effect, an aluminum bat compresses when a ball hits it. The stored elastic energy is later returned to the ball imparting it with more

exit velocity. With a wood bat, the ball compresses more, resulting in greater loss of energy as heat and, consequently, less exit velocity.

6. and 7. Assume a batter to pitcher distance of 60 feet and 6 inches, a horizontal post-impact velocity vector, and no wind, air resistance, or ball spin.

	Max. velocity (ft/s)	Shortest travel time (s)	Remaining reaction time (s)	% Difference
Wood	142.27	0.425	0.200	+16.3%
Aluminum-2	152.53	0.397	0.172	-14.0%

Note: even in 0.4 s, the ball drops by 2.5 feet, so a ball hit parallel to the ground is more likely to hit a pitcher's shins.

Human physiological response time to visual stimulus is approximately 0.2 s. The travel time is nearly twice as long. The travel times differ by 0.028 s and it is 7% longer for the wooden bat.

8. If the minimum required time to travel 60.5 feet is 0.225 + 0.250 = 0.475, then this corresponds to approximately 87 mph. (Again, we have ignored air resistance.)

   Aluminum bats seem to be less forgiving since a batter can exceed this velocity threshold over a 7 inch long section of the bat, compared to 5 inch section for a wooden bat. Hence one may expect more balls to be hit faster than 87 mph off of aluminum bats.

9. For a 40 degree angle, the ball must have a post-impact speed of 78.3 mph. Here, I assumed the ball was hit from an initial height of 1 meter.
10. The 78.3 mph velocity threshold is exceeded in a section of the aluminum bat that ranges approximately from 23 and 32 inches, and between 25 and 31.5 inches on the wood bat. The sweet spot is 2.5 inches longer on the aluminum bat.
11. The minimum velocity corresponding to a 6.5 inch long sweet spot on the aluminum bat is 90 mph.
12. Keeping the 6 foot wall the straightaway center distance in the Phillies' new ballpark would have to be increased to 528 ft.

    Keeping the straightaway center distance fixed at 401 feet, the wall would need to be increased to 86.4 ft!

13. For a 40 degree angle the ball spends 4.50 seconds in the air. In the absence of air resistance, the optimal angle is 45 degrees.
14. Based on the velocities in Fig. 1, the maximum range for a wood bat is 627 ft and 721 ft for an aluminum bat. Ballparks are considerably less deep because air resistance has a significant effect on the trajectory and range of a baseball. The spin of the hit ball also affects its range but less so than air resistance.