108 Stitches

The Physics in Baseball

45/49 wneo · weao

A Teacher's Utilization Guide

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Credits

Project Manager:
Dave Benson, Educational Technology Consultant, PBS 45 & 49

Instructional Designer
Alan Evans, Ph.D., Kent State University (Emeritus)

Content Experts
Ryan Dye, Wooster High School
Alan Golden, Hudson High School
Jon Secaur, Theodore Roosevelt High School, Kent

Producer
Duilio Mariola, Producer/Director, PBS 45 & 49

Graphic Design
Paula Kritz, Graphic Designer, PBS 45 & 49

Editor
Diane Steinert, Writer/Editor, PBS 45 & 49

Scripted By
Larry Chance, Last Chance Productions

Produced By
PBS 45 & 49 (WNEO/WEAO, Youngstown/Akron OH)

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Kinston Indians

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108 Stitches

The Physics in Baseball

Introduction

www.pbs4549.org/baseball

108 Stitches: The Physics in Baseball

Introduction

108 Stitches: The Physics in Baseball is a science-based curriculum focusing on students in grades 6 through 10. The series uses the game of baseball to demonstrate basic principles of physics as set forth by the National Science Education Standards.

108 Stitches: The Physics in Baseball is centered on four videos: ***The Pitch***, ***The Hit***, ***Running the Bases*** and ***The Flight***. The series is designed to enrich the classroom with powerful learning modules that are relevant and engaging to students. The hands-on, minds-on activities will revolve around topic areas that have been selected because of their relevance to the demonstration of physics and the sport of baseball.

In addition to the videos and Web site, ***108 Stitches: The Physics in Baseball*** also has a teacher-developed teachers guide available in a downloadable format.

The Goal

It is the goal of ***108 Stitches: The Physics in Baseball*** to enhance classroom learning conditions by:

- Using diverse instructional strategies and settings that offer students many ways to think about and construct their knowledge.
- Analyzing information that students have gathered and presenting it in a new form.
- Providing multiple opportunities for students to demonstrate their knowledge and skills in connecting science and mathematics to real-world applications as well as their own lives.

Video Overviews

Baseball is a game played with beautiful simplicity. But beneath that simplicity lay some rather complex physics.

The Pitch

The first program in this series takes a look at the physics of the pitch. There's a lot of exciting physics to explore in the 60-feet-6-inch path from the pitching rubber -- 10 inches above the playing field -- to the batter standing at home plate. **The Pitch** takes a look at gravity, air drag and the Magnus force (three forces controlling trajectory once the pitcher releases the ball) and how the pitcher can use these forces to manipulate the path of the ball.

The Hit

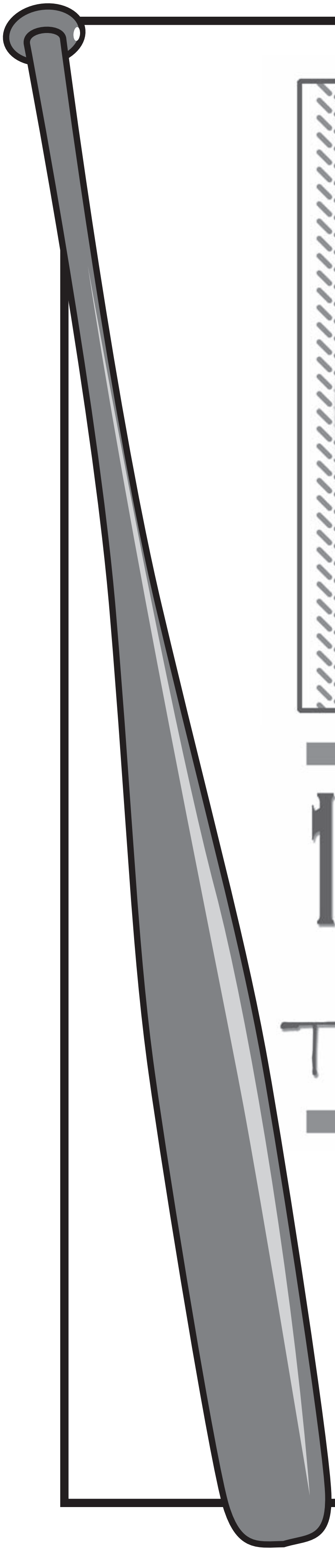
The second video picks up where the first one left off; this one emphasizes the perspective of energy. **The Hit** focuses on kinetic energy, the coefficient of restitution and Newton's laws of motion, as well as how the quantity of energy of speed and mass changes as a result of the batter hitting the ball.

Running the Bases

What's baseball without players running the bases? The third program looks at how ball players apply Newton's first and second laws when they are running the bases. While base running is strictly between the runner and the clock and has nothing to do with the forces between the bat and ball, there's still plenty of physics to explore. **Running the Bases** takes a look at the concepts of force, mass, inertia and acceleration.

The Flight

The final program is devoted to the ball's flight after the batter's hit. **The Flight** takes into consideration perfect projectile motion, launch angle, air drag, turbulence, temperature, air density and, of course, the Magnus force -- all the factors that go into sending a baseball from home plate over the fence more than 350 feet away.



108 Stitches

The Physics in Baseball

The Pitch

www.pbs4549.org/baseball

Drag Simulation Activity

The Pitch

Overview of Lesson

The focus of this lesson is air drag. Students will role-play the part of an object (baseball) fighting its way through the air molecules.

Goal

Students will get a feel for the mechanism responsible for air drag and for the variables that factor in.

Objectives

- The students will simulate the complex processes associated with air drag.
- The students will list the variables that contribute to the calculation of air drag.
- The students will predict the effect of changing variables within the simulation.
- The students will be able to discuss the limitations of simulations.

Materials

A large, open area in a classroom or gymnasium.

Procedure

1. Clear as large an area as possible in your classroom or, better yet, take the students to the gymnasium or outside.
2. Explain to the students that they are going to be role-players in a simulation that will give them a feel for the mechanism and variables associated with the phenomenon of air drag as it relates to the flight of a baseball.
3. **Simulation Stage 1:** Assign two or three students to hold hands in a small circle. They will act as the “ball” in the simulation. Ask the remaining students to stand to one side and just observe for the time being. Ask the “ball” to walk from one side of the room to the other. Tell the class that this represents a baseball thrown in a vacuum with nothing to affect it along the way.
4. **Simulation Stage 2:** Now ask the remaining students, or a portion of them, to act as molecules of air. Have them spread out at least arms-length apart and randomly scattered around the open area of the floor. Have the “air molecules” begin milling around in a sort of slow-motion slam dance. Now have the “ball” walk from one side of the room to the other again. Let students observe and describe the fact that the “ball’s” progress is now impeded by collisions with the air molecules. Explain that in a rough way this simulates the flight of a baseball pitched through the air on its way to home plate.
5. **Simulation Stage 3:** Through a series of “What if?” questions posed by the teacher and/or coaxed out of the students, the simulation can be modified to investigate all of the variables that factor into the calculation of air drag.

   a. **What if the density of the air were to change due to a change in temperature or humidity?** *Simulate an increase in air density by adding more “air molecules” into the group and/or having them move closer together.*

   b. **What if the size of the ball changed, from a baseball to a softball?** *Simulate this by adding a few more students to the “ball,” making a larger circle. They should see that this larger “ball” will interact with more “air molecules.”*

c. **What if the shape of the ball were to change?** *Simulate the effect of aerodynamic properties by having the "ball" flatten out or become more streamlined like the nose cone of a rocket. The overall aerodynamics of an object are expressed as its* ***drag coefficient****.*

d. **What if the ball were thrown faster?** *Simulate this by having the "ball" move faster across the room. Students should see that if the ball moves faster it will collide with "air molecules" more often and more violently, slowing it down even more.*

6. After the group has acted out all of the "What if?" scenarios, the teacher can introduce the equation that physicists use to calculate the **air drag force** on objects such as baseballs.

$$F_d = C_d A \rho \frac{V^2}{2}$$

The equation states the **drag force (F_d)** is directly proportional to the **drag coefficient (C_d),** the **cross sectional area of the object (A)**, the **air density** (ρ), and one-half of the square of the **velocity (V)** of the object. Have the students relate their experiences in the simulation to each of the variables.

*One aspect that is not so obvious to deduce from the simulation is the proportionality with the <u>square</u> of the velocity; just explain that it is a result of empirical data. Another factor mentioned in the videos that is very counterintuitive for students is the fact that a rough ball (like a baseball with its 108 stitches or a golf ball with its dimples) is actually aerodynamically superior (having a lower C_d value) to a smooth ball. To explain this apparent discrepancy one must look at the idea of a **boundary-layer** of air being pushed ahead of a smooth object, effectively increasing its cross-sectional area (**A**). Ask the students how you might adjust your simulation to include the boundary-layer variable.

7. As a follow-up, the teacher can lead a discussion of the limitations of this simulation and simulations in general. *The obvious points to emphasize are the relative size and number of the objects involved, and the simplification of the interactions. More accurate computer simulations can be found online and viewed to add to the discussion.*

Evaluation

The evaluation for this activity is informal. The questions posed in the process by the teacher and fellow students will allow the teacher to gauge the level of understanding. The concepts investigated here will be recalled and applied in the graphing lesson.

Note

Although a simulation such as this may seem grossly oversimplified and somewhat juvenile, the kinesthetic aspect provides a strong memory hook of the concepts, which makes the process very worthwhile.

The Magnus Force Activity

The Pitch

Overview of Lesson

This lesson will focus on the Magnus force. Students will create an apparatus and perform an experiment to answer the central question: How does spin affect the trajectory of a thrown ball?

Goal

Students will investigate and develop an understanding of the Magnus force.

Objectives

- The students will construct an apparatus to throw a ball with significant spin.
- The students will conduct an experiment to answer the central question.
- The students will list the variables that contribute to the calculation of the Magnus force.
- The students will predict the effect of changing variables within the investigation.
- The students will summarize the findings from their experimentation.
- The students will discuss the limitations of their experiment.

Materials

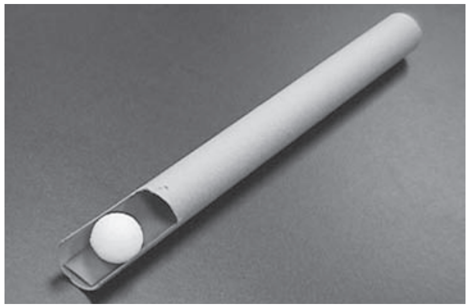
- Assortment of lightweight balls: Styrofoam craft balls (1- to 2-inch diameter), ping-pong balls, practice golf balls, Wiffle balls, etc.
- Assortment of tubes: cardboard shipping tubes, paper towel tubes, wrapping paper tubes, plastic golf club tubes, PVC pipe, etc.
- Assortment of materials to add friction: sand paper, thin craft foam rubber, bicycle inner tube scraps, etc.
- Glue
- Tape
- Scissors
- Markers
- 2-foot-square white boards and dry erase markers for use in the reporting-out phase (optional)

Procedure

1. Split your students into groups of two to four students and introduce them to the central question that will guide them in their investigation: How does spin affect the trajectory of a ball?

2. Ask students to make a workable apparatus that allows the ball to spin. Show the groups the assortment of materials they have to work with, mention the safety precautions of using scissors and turn them loose.

   A workable apparatus is simply a tube with a short sandpaper or rubber strip affixed to the inside of one side of the tube, near one end. The tube may also be cut in half lengthwise to form a throwing scoop.



3. As the activity progresses the teacher's job is to give helpful hints and ask focusing questions only when groups seem to be sputtering. Resist the natural instinct to show them how to construct a workable apparatus.

Examples of helpful hints and focusing questions:

- Can the tube be used somehow to throw the ball?
- How can you tell in which direction the ball is spinning?
- What could you do to get the ball to spin faster?
- What is the relationship between spin direction and the curve of the ball?
- What is the relationship between spin speed and the amount of curve?
- If a pitcher wants to throw a ball that breaks to the right, which way does the ball need to be spinning?
- Is there a simple way to summarize your results?

4. When all groups have completed their investigation and summarized their findings (use 2-foot-square white boards or chart paper for this part of the process), bring the class back together and ask each group to report out what they discovered and how they discovered it. Most groups will have discovered the correct relationships, but it is good for them see how various groups constructed their apparatus and performed their investigations. It is also important to discuss how the results can best be simplified into a simple set of relationships. *(For example, the amount of break is proportional to the rate of spin, and the direction of the break is the same as the direction that the leading edge of the ball is turning. A more subtle relationship also exists between the linear speed at which the ball is thrown and the amount of break that occurs over a given distance, like the 60 feet 6 inches from the pitcher's mound to home plate. If the students did not think of this during their initial investigation it can be posed and assigned as a follow-up investigation.)*

5. As a follow-up to the ball and tube activity, the teacher may ask students to do some research on the topic of the Magnus force and/or give a short lecture introducing them to the concept of the Magnus force and the equation that physicists use to calculate it. Below is an outline of the basics:

- **Historical Information:** The effects of spin on a ball's trajectory have been studied since the time of Newton, who in 1671 wrote a paper concerning the spin effects on the flight of lawn tennis balls. In 1852 the German physicist Gustav Magnus performed experiments confirming that a spinning ball experiences a "sideways" force; this force is now known as the Magnus force and is the fundamental principle behind the curved flight of any spinning ball.
- Results should show that the Magnus force acts in the direction that the front of the ball is turning toward, i.e., a ball thrown with backspin will experience an upward Magnus force, causing it to rise somewhat from its normal trajectory.
- **Variables:** velocity, roughness (orientation of seams), air density (atmospheric conditions), drag, rate of spin.
- $F_m = kfvC_d$ Where F_m is the Magnus force, k is a constant, f is the spin rate, v is the velocity, and C_d is the drag coefficient.
- **Explanation:** As a spinning ball moves through the air, the boundary layer separates from the ball at different points on opposite sides of the ball: farther upstream on the side of the ball that is turning into the airflow, and farther downstream on the side turning backward. The result is an asymmetric wake behind the ball and a pressure difference across the ball, creating a lateral force component at right angles to the motion of the ball.
- By properly orienting the spin direction, the pitcher can orient the Magnus force in any direction he chooses.
- The rates of spin for a major league pitcher can approach 2000 rpm and the Magnus force can be equal to about half of the weight of the ball. This means that a curve ball thrown with topspin experiences a downward force 1.5 times that of gravity alone; therefore, it will drop 1.5 times as far as it would without spin.

Note: Be sure to have enough materials on hand to allow groups to make several modifications and reengineering steps along the way.

Evaluation

The evaluation for this activity is informal. The questions posed in the process by the teacher and fellow students will allow the teacher to gauge the level of understanding during the experimental phase. The reporting of group findings will allow the teacher to see how well each group answered the central question. The concepts investigated here will be recalled and applied in the graphing lesson.

Note

- This activity may be changed to include a more traditional lab write-up.
- There is a toy from the good old days called Tracball by Wham-O. It is a curved throwing scoop with sharp teeth that grips the ball and gives it incredible spin. The old commercials had kids playing catch around a tree. Sets have been found on eBay for about $10.

Pitch Trajectory Activity

Overview of Lesson

In this exercise students will construct a graph of the trajectory of a pitched ball using the equations of kinematics. The graph will have multiple plots representing a ball thrown with different initial conditions.

Goal

Students will apply their understanding of two-dimensional kinematics, gravity, air drag and the Magnus force to make a meaningful graphical representation of a real-world event.

Objectives

- The students will apply the equations of kinematics to a two-dimensional motion situation.
- The students will apply Newton's laws of motion to an object subjected to multiple forces.
- The students will calculate and plot a baseball's trajectory for several different sets of starting conditions.
- The students will predict the effect of changing variables.
- The students will discuss the limitations of their graphical representation.

Materials

- Graph paper: use at least 11-by-17-inch or chart-sized paper if it can be found
- Assorted colored pens or pencils
- Calculators
- Rulers
- French curves (optional)

Procedure

1. Give each student or small group of students a sheet of graph paper, and tell them that you want the graph to represent the side view of a pitched baseball in a big league park. See Appendix A for graph paper (page 65).

2. Give them as much or as little help as they need setting up the axes of the graph. The x-axis should represent about 70 feet to accommodate the distance from the pitcher's mound to home plate (60 feet 6 inches) and the y-axis should represent about 8 feet to accommodate the release point of the pitch to be about 6 feet above the ground. These distances may be given to the students or they can do research on their own to find them. In addition they might want to draw in the dimensions of the strike zone (bottom edge at 19 inches and the top edge at 45 inches above the ground for the average 6-foot-tall batter), and sketch in the silhouettes of the pitcher and catcher.

   Note: It is best to stay in the English unit system for this entire exercise because all of the measurements common in baseball are in feet and inches.

3. **Graph plot #1**: (no forces acting on the ball)
   Have the students plot a straight horizontal line at the 6-foot mark on the y-axis. This represents a ball thrown with an initial velocity in the horizontal direction without the influence of any forces. It will be used as a reference line as the rest of the graph is plotted.

4. **Graph plot #2**: (gravity only)
   Given that the ball is released with a velocity of 90 mph in the horizontal direction from an initial height of 6 feet, have students calculate the vertical position of the ball every 5 feet along the way from the mound to home plate if gravity is the only force acting on the ball. This is done using the equations of kinematics for uniformly accelerated motion.

Method: Use the horizontal velocity (constant 90 mph) and horizontal distance to determine the elapsed time at each of the 5-foot horizontal intervals.

Using the zero gravity line as a reference and the elapsed times, determine the vertical distance the ball would have fallen from that line at each of the 5-foot intervals along the way. With a pen of a different color, draw a smooth curve through the points you have plotted.

5. **Graph plot #3:** (gravity and air drag)
   In this plot we introduce the force of air drag. Air drag acts in the horizontal direction, slowing the ball down as it moves toward the plate. Have students recall the equation that is used to calculate the force of air drag (see page 18). Explain that because of its complexity we will not use this formula to calculate the air drag. Instead, we will use a ballpark value for the deceleration of the ball that holds true to this relationship when it is applied using the aerodynamics of a baseball and average atmospheric conditions. The ballpark value for the deceleration that we will use is .5 g. That is, it will act as a horizontal deceleration with a magnitude of –16 ft/s^2.

   Method: The method to make the plot is similar to the previous one but the calculations are a bit more tricky as the motion now includes an acceleration in both dimensions. Begin by using the equations of kinematics to determine the elapsed time when the ball has moved 5 feet horizontally toward the plate; repeat this for each additional 5-foot interval. Using the elapsed times and the zero gravity reference line, determine how far the ball would have fallen from the reference line at each of the intervals. With a pen of yet another color, draw a smooth curve through the points you have plotted.

6. **Graph plot #4**: (the curveball: gravity, air drag and top spin)
   In this plot we introduce an additional acceleration in the downward direction caused by the Magnus force (see page 20). Have students recall the equation used to calculate the Magnus force. Again explain that because of its complexity we will not use this formula to calculate the Magnus force. Instead, we will use a ballpark value for the acceleration of the ball that holds true to this relationship when it is applied using the mass and aerodynamics of a baseball, average atmospheric conditions and a spin velocity comparable to a curve thrown by a major leaguer. The value we will use will again be .5 g, so the downward acceleration becomes 1.5g or 48 ft/s^2.

   Method: The elapsed times calculated for plot #3 are used again for this plot as the horizontal motion of the object is not affected by the vertically acting Magnus force. Using the elapsed times from plot #3 and the zero gravity reference line, determine how far the ball would have fallen from the reference line at each 5-foot interval. With a pen of yet another color, draw a smooth curve through the points you have plotted.

7. **Graph plot #5**: (the rising fastball: gravity, air drag and back spin)
   This plot is nearly identical to that of the curveball (plot #4) except that the Magnus force acts in the upward direction. Therefore, the downward acceleration of the ball is reduced by a factor of .5 g, making it 16ft/s^2.

   Method: Again the horizontal motion is not affected by the Magnus force so the elapsed-time values from plot #3 may be used. Using the elapsed times from plot #3 and the zero gravity reference line, determine how far the ball would have fallen from the reference line at each 5-foot interval. With a pen of yet another color, draw a smooth curve through the points you have plotted.

8. **Follow Up**: After completion of all five plots on the graph, have students add a legend with a color code and any other labels needed. The graph can then be a reference when discussing age-old baseball questions like:

   Does a curveball really curve?

   Does a rising fastball really rise?

   Does a curveball break sharply in the last few feet before it reaches the plate? (Players describe the ball as "falling off the table.")

Another part of the follow-up discussion should be about the simplifications and generalizations that were used in making the graph. Important things to point out are:

- *The starting velocity of a real pitch is not likely to be purely horizontal. Most pitches are thrown with a downward angle.*
- *The starting velocity of a breaking pitch like a curve ball is more likely to be in the 75-80 mi/hr range.*
- *Air drag will act on the vertical motion of the object as well, although its magnitude is small in comparison to the horizontal drag.*
- *The values for both the air drag and Magnus forces are approximate and derived using a drag coefficient that represents an average orientation of the seams on the ball and average atmospheric conditions.*

Evaluation

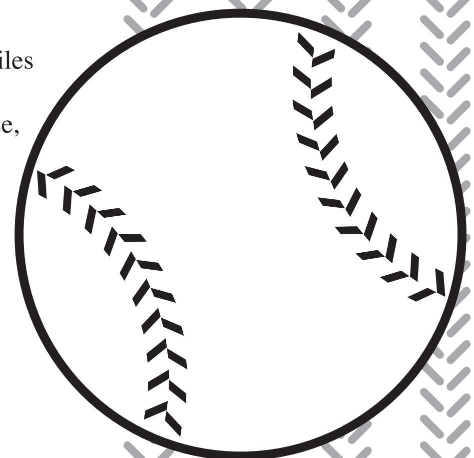
The evaluation for this activity is the completion, accuracy and quality of the graph. See Appendix B (page 66) to evaluate graph.

Note

- An old-fashioned paper-and-pencil approach to making this graph seems to be superior to using graphing software or graphing calculators. There is something about the extra time invested in making it from scratch that gives students more time to ponder the concepts. Students seem to develop a sense of accomplishment when they can hang the final product on the wall.

Graphing Calculator Activity

The Pitch



Calculator skill -- basic graphing. You wouldn't take your calculator to the ballpark ...but you can bring the ballpark to your calculator!

Directions are based on the use of a TI83 graphing calculator.

The distance from the mound to the plate is measured in feet, the ball's speed is measured in miles per hour and most measurements in science classes are expressed in meters! We need to have one system of units to make sense of what we're doing, so let's decide to use meters for distance, meters per second (m/s) for speed, and meters per second per second (m/s^2) for acceleration.

Starting points:

- Distance from mound to plate = 60 ft 6 in = 60.5 ft
- One meter equals 3.28 ft, so 60.5 ft (1 m/3.28 ft) = **18.4 m**

- Speed of a good fastball = 95 mph
- One meter per second equals 2.24 mph, so
- 95 mph (1 m/s / 2.24 mph) = **42.5 m/s**

- The acceleration due to gravity = **- 9.8 m/s^2**

- Suppose that the ball is moving exactly horizontally, not aimed up or down, at the instant it leaves the pitcher's hand, 2.0 meters above the level of the field.

Let's graph the motion of the ball from the instant the pitcher releases it until it crosses the plate. The ball's drop is given by $d = 1/2\ at^2$, where d is how far it drops from its starting height because of the acceleration due to gravity. (The initial velocity term often seen in this familiar equation is on vacation this time, because the *vertical* initial velocity is zero – remember, we're supposing that the ball moves horizontally in the beginning!)

Since one-half of -9.8 equals -4.9, enter $-4.9t^2$ in your calculator's equation editor. The ball starts 2.0 m above the field, so add 2 at the end.

To set the graphing window, remember that x stands for time and y stands for distance above the field. Set x_{min} to zero, since we start watching just as the ball is released. The time to reach the plate is x_{max}, and since d = vt for the horizontal motion of the ball, t = d/v. From our assumptions above, that means you'd enter 18.4/42.5 for x_{max}. The calculator will instantly figure the value for you when you move to the next line. The x_{scl} tells how often to make tick marks along the x axis. You don't need to set the scale, but a value of .1 will make a mark every tenth of a second of the ball's flight. The level of the field is our reference, so $y_{min} = 0$ and $y_{max} = 2.5$ or so, so that we can see the ball's whole flight. For y_{scl} enter .25 so we can check the ball's position to the nearest quarter of a meter.

Here's the pitch! Press [GRAPH] and watch the pitch come in. Your view is from the third base side of the field; the pitcher is at the left edge and the batter at the right. Press [TRACE], hold down the right arrow and the cursor will follow the pitch. The bottom of the screen will show the time (x) and the height off the field (y).

Going Further

1. So far we have the basic arc of the ball, ignoring the Magnus force from spin the pitcher puts on the ball. The force can be as great as one quarter of the ball's weight and can act up, down or to either side.

   Want to throw a curve ball that drops more than the batter expects? How about a rising fast ball? Just add a second equation for the Magnus correction. The greatest acceleration that the Magnus force can create is one-fourth of 9.8 m/s^2, or 2.45 m/s^2. Since the motion equation requires you to take half of the acceleration, you could use any value from -1.225 for a sharply biting curve to 1.225 for a fastball with the maximum "pop." For an example, let's use -1 for a pretty good curve ball. Enter $-x^2$ for the second equation. Then for the third equation, add the first and second equations:

   $$Y3 = Y1 + Y2$$

   De-select Y2; move the cursor to the equals sign after Y2 and press [ENTER]. That way the calculator will graph Y1, the pitch with no spin, and Y3, the curve ball. Press [GRAPH] to see both pitches.

   How different are they? Doesn't look like much, but it's sure enough to matter! Press [TRACE] and hold down the right arrow to follow the pitch. At any time, press the up or down arrows to switch between the two graphs. Notice the numbers by the Y coordinate; the curve ball drops nearly 20 centimeters below where the batter would expect the ball! There's a strike, or at least a grounder!

2. If you'd prefer a fast ball, change the value in equation Y2. Let's go with the maximum upward Magnus force – enter $1.225x^2$ for Y2. (Remember to de-select it again by moving the cursor to the equals sign and pressing [ENTER].) You can see that since the Magnus force is no greater than one quarter of the ball's weight, the fast ball can never really rise above where it was released – but it does come in higher than the batter expects.

3. Draw a strike zone! For a medium-sized batter, the strike zone starts about 0.50 m above the plate and reaches to about 1.35m. Enter these equations for Y4 and Y5 to graph that zone:

   $$Y4 = .5\ (x>.4)$$
   $$Y5 = 1.35\ (x>.4)$$

   To make the "greater than" sign, press [2nd][MATH]3. Set both of these graphs to dot mode; to do that, move the cursor all the way over to the left margin in front of Y4 and then press [ENTER] six times. Do the same for Y5. (What's the .4? Remember, for the calculator, x represents time, so the horizontal bars made by these graphs only appear after the ball has traveled for 0.4 second, when it's near the batter.)

   Your calculator is probably set to plot the graphs one after the other, so you'll see the first graph of the ball with no spin, then the ball with spin, and then the strike zone. It is more fun to plot all the graphs at once. To do that, press [MODE] then move the cursor down to Simul and press [ENTER], then [2nd][MODE] to quit. Then press [GRAPH] for a different kind of show! The strike zone will appear just as the ball gets there.

108 Stitches

The Physics in Baseball

The Hit

www.pbs4549.org/baseball

Bat Type Activity

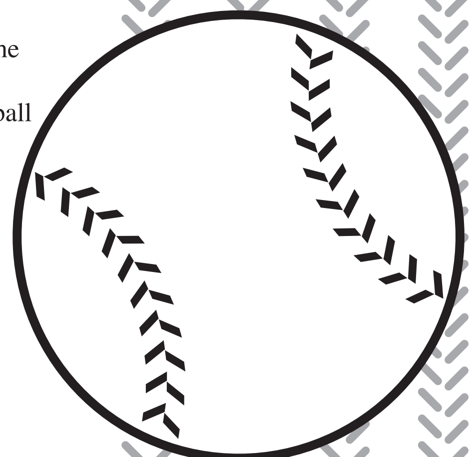
Overview of Lesson

This activity is designed to explore how different bat lengths affect the hitting distance of the ball. Students will use various types of baseball bats to observe the effect they have on hitting distances.

Goal

Students will learn a relatively easy way to determine the effects different types of bats have on hitting distances.

The Hit



Objectives

- The students will determine the average hitting distance for each bat type.
- The students will plot bar graphs of average hitting distances versus bat type.
- The students will draw conclusions about the effectiveness of various bat types based on the data collection and graphs they have made.
- The students will make inferences about the energy transformations that occur between a ball and bat, and how these vary with different bat materials.

Materials

- Wooden bats
- Aluminum bats
- Tape measure
- Batting tees
- Softballs

Procedure

1. Divide students into groups of three. Assign each student one of the following specific tasks to begin the activity: batter, ball spotter/retriever, tape measurer. These job assignments will rotate after each student has hit the ball five times (one rotation for each bat type).

2. One student begins by hitting the ball off of the tee a total of five times (batter). The ball spotter marks the location where the ball lands, and the tape measurer records the distance in the group's data table.

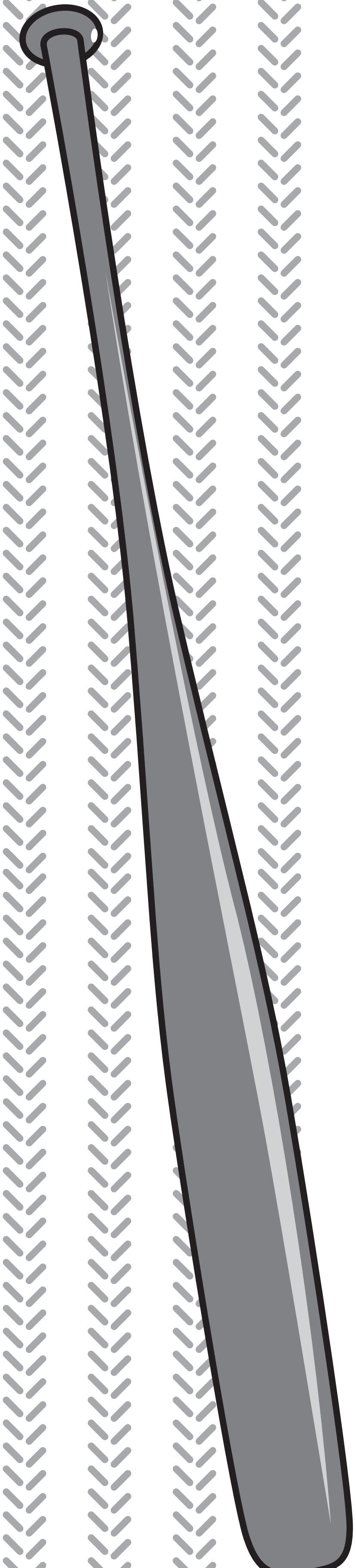
3. Rotate students until each group member has hit the ball five times with each bat type.

4. Have each group determine the average hitting distance for each bat type, and plot a bar graph of average hitting distance (y-axis) versus bat type (x-axis).

5. As an extension, each group can average its data with the entire class and plot a class graph. Discuss any differences between the groups' graphs and the class graph. Why do scientists always take so many samples of data before drawing conclusions?

Evaluation

This activity can be evaluated using informal observations as students work together to perform the tasks. This is also an activity in which a formal evaluation can be registered by assessing the students on their ability to accurately collect data, plot graphs and reach conclusions. See Appendix B (page 66) to evaluate graphs.



Bat Length Activity

Overview of Lesson

This activity is designed to explore how different bat lengths affect the hitting distance of the ball. Students will use a baseball bat with tape markings (hitting lengths) to observe the effects on hitting distances.

Goal

Students will learn a relatively easy way to determine the effect bat length has on hitting distance.

Objectives

- The students will determine the average hitting distance for each bat length.
- The students will plot a graph of average hitting distances versus bat length.
- The students will draw conclusions about the effectiveness of various bat lengths based on the data collection and graphs they have made.
- The students will make inferences about the energy transformations that occur between a ball and bat, and how these vary with different batting lengths.

Materials

- Wooden bats with tape markings every 3 inches beginning at the end of the barrel
- Tape measure
- Batting tees
- Softballs

Procedure

1. Divide students into groups of three. Assign each student one of the following specific tasks to begin the activity: batter, ball spotter/retriever, tape measurer. These job assignments will rotate after each student has hit the ball five times (one rotation for each bat length).
2. One student begins by hitting the ball off the tee a total of five times (batter). The ball spotter marks the location where the ball lands, and the tape measurer records the distance into the groups data table.
3. Rotate students until each group member has hit the ball five times for each batting length.
4. Have each group determine the average hitting distance for each batting length, and plot a bar graph of average hitting distance (y-axis) versus batting length (x-axis).
5. As an extension, each group can average its data with the entire class and plot a class graph. Discuss any differences between the groups' graphs and the class graph. Why do scientists always take so many samples of data before drawing conclusions?

Evaluation

This activity can be evaluated using informal observations as students work together to perform the tasks. This is also an activity in which a formal evaluation can be registered by assessing the students on their ability to accurately collect data, plot graphs and reach conclusions. See Appendix B (page 66) to evaluate graph.

Coefficient of Restitution (COR) Exploration

The Hit

Overview of Lesson/Goal

This activity is designed to explore the different COR values for three different types of balls (baseball, golf ball and Superball).

Enrichment

Students will observe how temperature changes affect the COR of each ball.

Objectives

- The students will describe the concept of COR.
- The students will conduct an experiment by collecting data to determine COR values of various types of balls.
- The students will plot graphs of COR values and determine which ball has the best elastic properties.

Materials

- Baseball, golf ball, Superball
- Meter stick
- Graphing paper (or graphing software)
- Calculator
- Ruler

Procedure

1. Keep each ball at room temperature for 24 hours prior to this lab.
2. Have students work in pairs and drop each ball from an initial height of 0.25 meters. Have one student record this value in a data table. See Appendix D (page 68) for data sheet.
3. Have the other student mark the rebound height of the ball and record this value in the data table.
4. Students should repeat this procedure for each ball for the following initial heights: 0.50, 0.75 and 1.00 meters.
5. Ask students to calculate the square root of each initial height and each rebound height and record these values in their data tables.
6. Have students plot a graph of the square root of rebound versus square root of initial height. (Dependent variable or the square root of the height of the rebound should be graphed on the y axis.) They should do this for each type of ball dropped.
7. Students should then draw a line of best fit through their data points and determine the slope of the line for each graph. Have them show all work.
8. This slope of the line value is their average COR for each ball. Have the students compare these values and answer the analysis questions below.

Enrichment

Repeat this experiment after placing the balls in a freezer for a 24-hour period.

Important Terms for This Activity

- Gravitational Potential Energy (GPE)
- Kinetic Energy (KE)
- Coefficient of Restitution (COR)
- Initial Height
- Rebound Height

Important Equations for This Activity

- GPE = mgh
- $KE = 1/2mv^2$
- COR = v’/v = sqrt(h’/h)

Data Tables

See Appendix D (page 68) for Student Sheet.

Analysis Questions

1. Based on your data/graphs, which type of ball had the highest COR?
2. In terms of energy, what would it mean to have a ball with a COR of 1.00?
3. Which type of ball would you be able to hit the furthest? Explain why.

Enrichment

1. What effect did lowering the temperature of the balls have on their COR?
2. Would major league baseball players be able to gain any hitting advantages by playing a game on a hot summer day rather than an extremely cold day?

Evaluation

This activity can be evaluated using informal observations as students work together to perform the tasks. This is also an activity in which a formal evaluation can be registered by assessing the students on their ability to accurately collect data, plot graphs, and reach conclusions. See Appendix B (page 66) for a rubric to evaluate the graph.

Advanced Activity

Graphing Calculator Activity

Calculator skills – finding the maximum of a function and the area under a curve

Directions are based on the use of a TI83 graphing calculator.

Starting points:

- Speed of a typical pitch = 90 mph
- One meter per second equals 2.24 mi/hr, so
- 90 mph (1 m/s / 2.24 mph) = **40.2 m/s**

- Speed of a hard line drive = 110 mph
- 110 mph (1 m/s / 2.24 mph) = **49.1 m/s**

- Since the line drive is moving in the opposite direction of the pitch, we'll call its velocity negative, or **-49.1 m/s**

Momentum is a physicist's best measure of motion – it's the *essence* of motion because it tells *how much* is moving, *how fast* it's going and *where* it's going, all in just two little symbols, m and v. The product of the mass, m, and the velocity, v, is defined as momentum. Isaac Newton (hero of fans of both physics and baseball) explained that force is the rate of change of momentum, or the change in momentum over time.

F = change in (mv) / T

If we're talking about baseball, the time, T, is the contact time between the bat and the ball, which is typically about 0.7 millisecond (ms), or 0.0007 second. The mass of a baseball is 145 grams, or 0.145 kg. Using the speeds (above) of a typical pitch and a hard liner, the change in velocity is 40.2 m/s - (-49.1 m/s) or 89.3 m/s. (Do you see why the change in velocity is not just 6.9 m/s?)

The change in momentum, then, is (0.145 kg)(89.3 m/s) = 12.95 kg-m/s. That doesn't seem like so much, but since the contact time is so small, the force is

F = 12.95 kg-m/s / 0.0007 s

= 18,500 N

Wow, more than 18,000 N! Since one pound is the same as 4.45 N, that's a force of about two tons! No wonder you hear such a loud CRACK! from the impact.

But wait, there's more! That number is the average force during the contact time. The force changes during the contact in a sort of bell-shaped curve given by this equation:

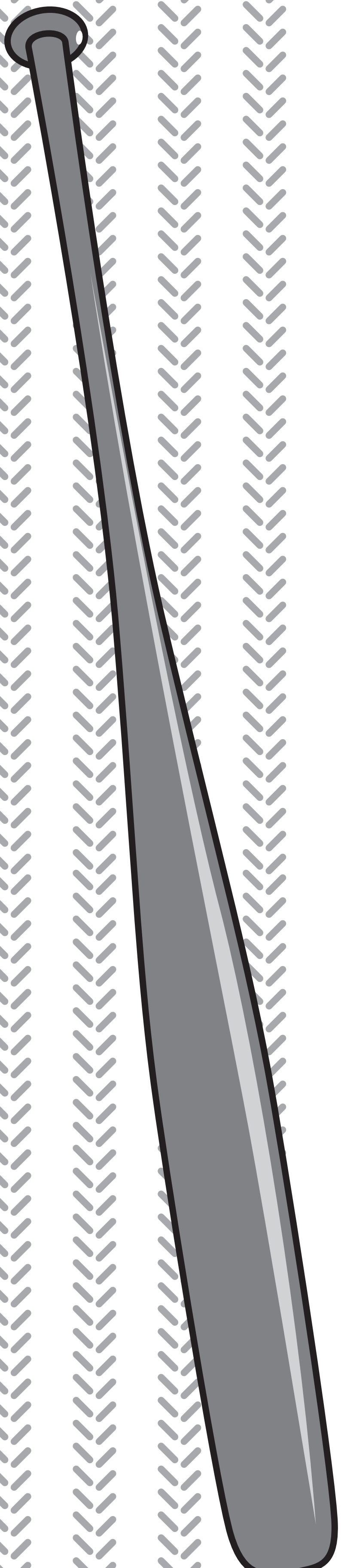
$$F_{(t)} = \frac{2\ m\ ()v)[\sin(Bt/T]^2}{T}$$

where $F_{(t)}$ means the force as it changes over time, T is the contact time between the bat and ball, t is the elapsed time, and ()v) means the change in velocity.

To graph that equation, first be sure your calculator is in RADIAN mode. Don't know how to check that? Go to the mode button next to the 2nd key.

Enter this equation in your function editor to graph the example we've considered so far, where the ball of mass 0.145 kg changes its velocity by 89.3 m/s in just 0.0007 second:

The Hit



$y1 = 2*.145*89.3/.0007*(\sin(Bx/.0007))^2$

Press [WINDOW] to set the viewing rectangle. Since x is time, set $x_{min} = 0$ and $x_{max} = .007$. The variable y represents force, which will range from zero to about twice the average force, so let $y_{min} = 0$ and $y_{max} = 40000$. Press [GRAPH] and have a look. Pretend you are watching the force between the bat and the ball in *super* slow motion. The actual impact moves along about ten thousand times faster than we see it on the screen!

Going Further

1. Just how big is that maximum force? Use the CALC function – that's [2nd][TRACE] – and choose item 4 from the menu. Use the left arrow key to move the cursor anywhere to the left of the peak and press [ENTER]. Then move the cursor anywhere to the right of the peak and press [ENTER] again. Press [ENTER] once more, and the screen will show the coordinates of the maximum force. Remember that, in our example, x is time and y is force, so we see that the maximum force of about 37,000 N occurs about halfway through the swing. Remember, too, to round severely the numbers that you see, because *we* know that the contact time is only accurate to one significant figure, but *the calculator* doesn't know about that limitation in accuracy.

   Note that the maximum force is just twice the average force we calculated earlier. That's true because the force varies with time through a sine-squared function. If it had been a quadratic equation, for example, then the peak would not have been twice as high as the average. It seems that nature happens to use the sine-squared function for baseball! *(See "Physics and Acoustics of Baseball and Softball Bats" at www.gmi/edu/~drussell/bats-new/impulse.htm.)*

2. Want to see about the coolest thing your calculator can do? The area under the force vs. time curve is the product of the force multiplied by the time, which is called the *impulse*. It's numerically equal to the change in momentum. It's easy to calculate the area under a rectangle or triangle, but how can you find the area under a funky curve like this one?

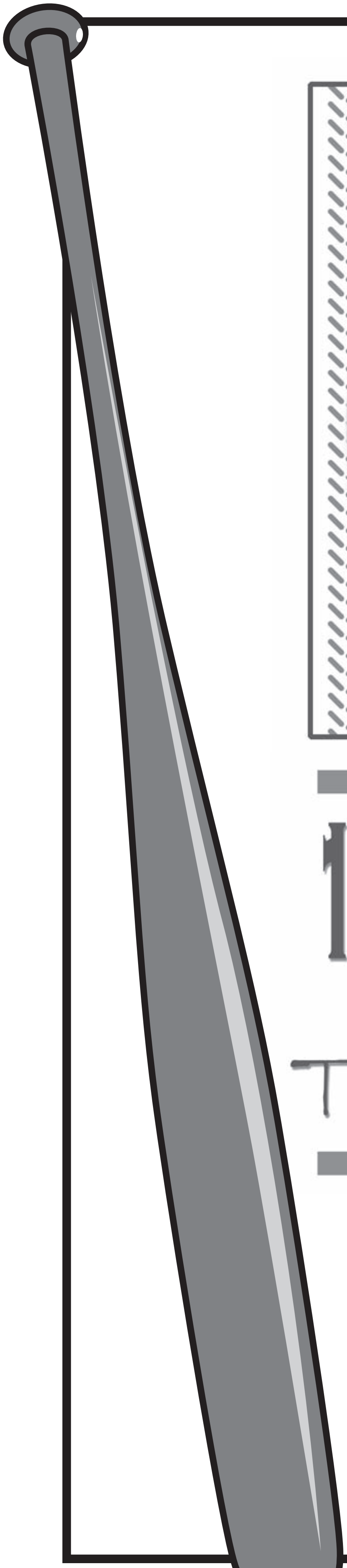
   Your calculator can do it easily. Again, use the CALC function, but this time choose item 7 from the menu. The symbols you see there stand for the calculus function of integration, which is the way to find the area under any curve. When the calculator asks for the lower limit -- that means the starting time -- just press zero. For the upper limit (that is, the ending time), enter .0007. Then watch what happens when you press [ENTER]! After an amazing display, the bottom of the screen shows the total area under the curve, which for us is the impulse between the bat and the ball, which is also the change in momentum of the ball, about 12.95 kg-m/s.

3. Try some other combinations of pitches and swings. Estimate (that means, make up some reasonable numbers for) the speed of the pitch and the speed of the ball after the hit. Surprisingly, the contact time depends more on the elasticity of the ball than on how you swing, so don't change the contact time by more than a few ten-thousands. What do you find for the maximum force in each case?

4. Calculate the acceleration of the ball. We used Newton's second law earlier in the form where force equals the rate of change of momentum. More commonly, the second law is written as force equals mass times acceleration, or

   $$F = ma$$

   Divide the average force we found above (about 18,500 N) by the mass of the ball (0.145 kg) to find the acceleration. It's an amazing value of nearly 128,000 m/s^2, or about 12,800 times the acceleration due to gravity, or 12,800 g's! That much acceleration applied to your body would squish you like a bug on a windshield.



108 Stitches

The Physics in Baseball

Running the Bases

www.pbs4549.org/baseball

Advanced Activity

Graphing Calculator Activity

Running the Bases

Calculator skills – curve fitting and simultaneous equations

Directions are based on the use of a TI83 graphing calculator.

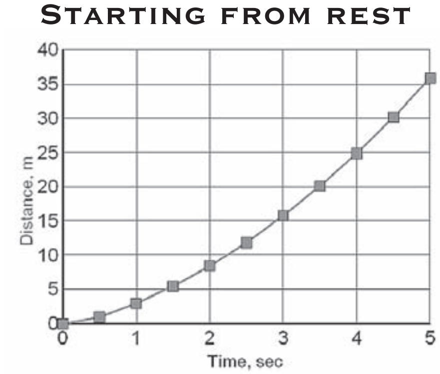
Starting points:

- Distance from home plate to first base = 90 ft
- 90 ft (1 m/3.28 ft) = **27.4 m**

- Time for a ground ball to reach third base = 1.2 second
- Time for the third baseman to field and throw = 1.0 second
- Distance from third to first = 127 ft = 38.7 m
- Speed of an infielder's throw to first = 80 mph
- 80 mph (1 m/s / 2.24 mph) = **35.7 m/s**

- Motion of a base runner to first base -- as shown (From *The Physics of Baseball*, Robert Adair)

Runner's position vs. time
Starting from rest



A graphing calculator takes an equation and produces a graph. But here we have a graph from an authoritative book on baseball, and we can use the calculator to go backwards and make an equation from the graph. Then we can have some fun with it!

Any time you need to find an equation that fits some data, press the [STAT] key and [ENTER] to edit your data lists. In list L1, enter the time values, from zero through 5, by steps of .5. In list L2, enter your best guess of the distance the base runner has moved by that time. So, your first value in L2 will be zero. How far has the runner moved in the first half second? Looks like about 1 m, so enter that as the next item in list L2. After 1 second, it looks like the runner is now 3 m away. Enter that number and keep going, making your best estimate from the graph for the distance reached at each time. Be sure that you have 11 items in each list.

The calculator can use about 10 different kinds of equations to compare with your data for the best fit. To see how well any test curve fits, turn on Diagnostics. Go to CATALOG; that's [2nd][zero]. Cursor down to Diagnostics On and press [ENTER].

You can see that the curve is not a straight line, so a linear fit is probably not the best. Let's try a quadratic curve. Press [STAT] and move the cursor to CALC, then down to 5 and press [ENTER] two times. The screen will quickly display the values for the equation that best fits your data points. Using data from the graph above, you might have come up with this equation, rounding off to three significant figures:

$$y = .953x^2 + 2.48x - .266$$

Your numbers might be a little different, depending on how you estimated the distance the runner traveled at each time.

Notice the value of R^2, which tells how well the equation fits the points. A value of 1.00 would be a perfect fit, and anything close to that value means a good fit. In general, when you explore some data set, you could try many different kinds of curves and the one with the highest R value fits the data the best.

To plot the graph, first set the graphing mode of your calculator. Press [MODE] and move to Func, press [ENTER], and then Simul and [ENTER] again. That sets your calculator to plot ordinary functions and to plot them simultaneously. Press [2nd][MODE] to go on.

Since first base is the goal that both the batter and the thrown ball will try to reach, let's use the x axis, where y = 0, to represent the first base bag. Press [Y=] and enter the equation as shown above, but include one more term for the distance from home plate to first:

$$y_1 = .953x^2 + 2.48x - .266 - 27.4$$

You could, of course, combine those last two terms into one. Press [WINDOW] to set the viewing rectangle. Since x stands for time, graph from zero to 5 seconds with one-second intervals. Y represents the distance "behind" first base, so plot from about -30 to 5 meters or so with a scale of, say, 5 meters. Press [GRAPH] to see your work! It should, of course, look just like the one pictured above, but with the x axis near the top of the graph. You have digitized the graph and now can use it!

How much time will the runner need to reach first base safely? You can press [TRACE] and move along until the cursor is near the intersection. Or go to CALC – that's [2nd][TRACE] – and choose menu option 2 to find the zero or root of the function. Press [ENTER] with the cursor anywhere below the x axis, and then press the cursor-right key until the cursor pops anywhere above the axis and press [ENTER] twice more. The x value on the screen shows that the runner will arrive in about 4.25 seconds.

Going Further

What matters in the game is not how long it takes the runner to reach first, but if he or she gets there before or after the ball! Let's suppose the batter hits a grounder down the third base line. The third baseman fields the ball cleanly, wheels and throws to first. Does the runner beat the throw?

To find out, check the assumptions at the top of the page. Suppose the ball needs 1.2 seconds to reach third base and the third baseman needs 1.0 second to field the ball and make the throw to first at 80 mph or 35.7 m/s. Ignoring air friction for the throw, its motion is uniform and not accelerated, so the equation for the ball's motion is:

$$y_2 = 35.7(x - 2.2) - 38.7$$

The 35.7 is the ball's velocity in m/s, the 2.2 is the time after the batter makes contact until the third baseman releases the ball and the 38.7 m is how far the ball must travel from third to first. Again, it's negative because we are using the x axis to represent first base.

Imagine the crack of the bat when you press [GRAPH]. You'll see the runner hustling toward the safety of the axis before the graph of the ball appears. Then suddenly, there's the ball, too, moving *so* fast, and it reaches the axis well before the batter's graph hits the axis. It's an easy out! When does the ball arrive at the base? Again, use [2^{nd}][TRACE], menu option 2, to see.

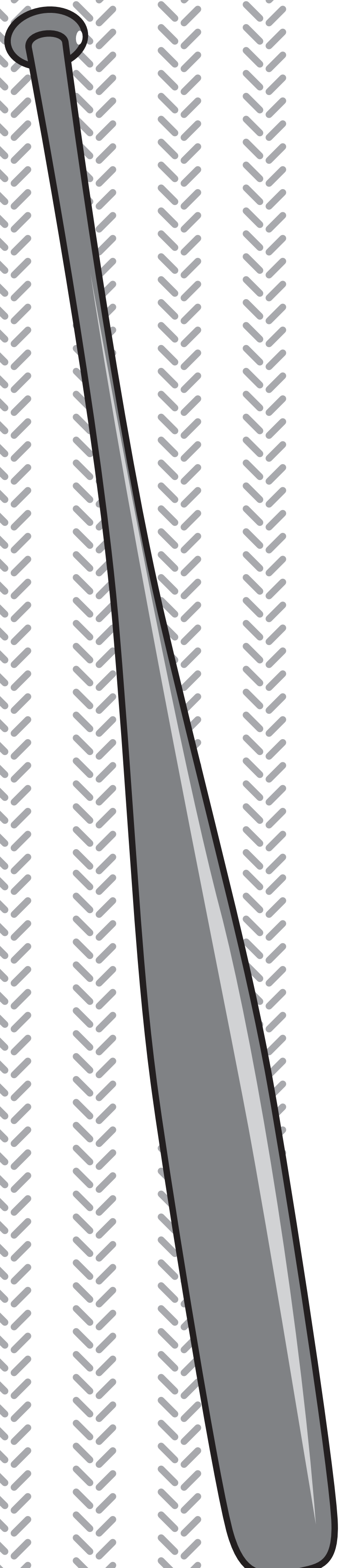
You'll need to press the cursor-down key once to switch to the second graph, the graph of the ball. Press [ENTER] with the cursor on the ball's graph but anywhere below the axis, then cursor-right until the ball moves above the axis, and press [ENTER] twice more. Only about 3.25 seconds! You can see why routine ground balls turn into easy outs. But if anything happens to cost the third baseman just one additional second -- chasing a slow roller, having to dive for the ball and standing back up, losing the ball in the glove or bobbling the ball before the throw -- then it's a close call.

Change equation 2 to graph that new situation, where the third baseman takes one extra second to field the ball. Your equation would read:

$$y_2 = 35.7(x - 3.2) - 38.7$$

When you graph the motions this time -- it looks too close to call! Find the runner's time to reach first once again and now press cursor-down one time to switch to the ball's graph. It still has over a meter to travel before it's in the first baseman's glove, and any umpire could see that difference! Baseball is a game of inches, and that's why you should run out every ground ball.

To get an ump's-eye view, change the WINDOW. Try graphing x from 4 to 4.5 seconds, and y from -5 to 1 meter or so. Now it's easy to see that runner reaches the safety of the x axis before the ball arrives. How much faster would the third baseman have to throw to still get the runner out? Use a larger speed in equation 2 to see how a faster throw could compensate for a slight bobble.



Notes