Curves Balls, Knuckleballs, and Fallacies of Baseball

Revised and Updated

"Provides the layman with entertaining explanations of some of baseball's most cherished assumptions."

—David G. Baldwin, Ph.D., Enterprise Data Solutions

Robert G. Watts/A. Terry Bahill
Bat Meets Ball: Collisions

It has been said many times that batting a baseball is the single most difficult act in all of sports. At any given moment only a half-dozen players in the combined major leagues are accomplishing the task of getting a base hit as often as once in every three attempts. Paul Kirkpatrick, a physicist at Stanford University, pointed out that this is at least partly attributable to the fact that in the attempt to hit a baseball solidly with a bat there are so many things that can go wrong. Let us suppose that for a given pitch there is an ideal way for the bat to meet the ball in a collision. This means that there is an ideal location of the bat at the instant that the collision occurs. The location of the bat is determined by three variables: its height above the ground, its position along a line between home plate and the pitcher's mound and its position in the direction across home plate. There is also an ideal angular position of the bat (three more variables), an ideal speed (three more, one component in each direction), and an ideal angular speed (still three more). Obviously, if the batter adjusts all these things perfectly, but swings too early or too late, it would do his cause no good. Thus, he can also fail in his task through the mismanagement of time. Taken together with the fact that any of the above
13 variables can be missed on either the high side or the low side, this means that there are 26 ways to fail.

Not all the variables are equally important, of course. A baseball bat is a cylindrical object, and its correct position when it strikes a baseball is approximately horizontal and perpendicular to the path of the approaching ball. A small error in the rotational position of the bat about a vertical axis may cause an otherwise perfectly hit home run to go into the left or right field bleachers instead of the center field bleachers, while a larger error would transform a home run into a long but harmless foul ball. On the other hand, an error in the rotational position about the axis (length) of the bat is of no importance at all. The most critical variable is the vertical position of the bat. Conventional wisdom is that a very tiny error here (a few millimeters) can spell the difference between success and failure. However, we will scrutinize this few millimeters assumption in the last section of this chapter and again in Chapter 6.

An interesting aspect of the game of baseball is the fact that the batter, the offensive player, is not essentially in control of the ball. This is a situation quite different from that in any other sport played with a ball. In baseball, the defensive team controls the ball perhaps 95 percent of the time. The hitter's job is to hit the ball in such a way that the defensive team loses control long enough for him or one of his teammates to circle the bases. A team scores not so much by controlling the ball as by forcing his opponents to lose control. The ultimate method of doing this is to hit the ball in such a way that it goes out of the playing field (from fair territory) as a home run. In a sense, the batter has momentarily gained full control of the ball and the defensive team has completely lost control. Even as the ball is thrown toward the batter's box, the pitcher has a certain amount of control over the path of the ball. The batter's task of causing the defensive team to lose control is made more difficult because the pitcher can manipulate the path of the ball in a way presumably known only to himself and the catcher. In addition to imposing a variety of forces on the ball by both legal and illegal means, most pitchers expose batters to some added psychological stress by occasionally reminding them how much a baseball thrown at 85 to 95 miles per hour hurts when it hits them. Most batters already know this, of course, so the reminder can be indirect. Ryne Duren, a flame-throwing relief pitcher for the New York Yankees during the 1960s, sometimes warmed up by throwing several pitches over the catcher's head. He would then remove his thick glasses and, while wiping them with his handkerchief, squint at the batter taking his place in the batter's box. Don Drysdale, the former hard-throwing right-hander for the Los Angeles Dodgers, is said to have once quipped, "The pitcher has to find out if the hitter is timid. And if the hitter is timid, the pitcher has to remind the hitter that he's timid." Thus, another variable, fear (ballplayers use the term respect), enters the batter's formula for failure.

Hitting a baseball can be thought of as consisting of five interrelated parts: (1) seeing the ball as it approaches the plate, (2) deciding when and where to swing the bat, (3) actually swinging the bat, (4) the collision between the ball and the bat and (5) the path of the ball after it leaves the bat. In this chapter, we will discuss only the fourth of these, the collision between the bat (a modified right circular cylinder) and the ball (a sphere). In Chapter 6 we will discuss the path or trajectory of the ball after it leaves the bat. In Chapter 7, we will study the head and eye movements of a batter trying to follow a pitch.
Chapter Five

Momentum, Impulse, and Collisions

In order to explain the collision process, we must introduce another idea from physics: the concept of momentum. The momentum principle stems directly from Newton's second law:

\[ F = ma \]

Suppose a constant force \( F \) is applied to an object of mass \( m \) so that its speed increases from \( v_0 \) to \( v \) over a time interval \( t \). Since the average acceleration is the change in speed divided by the change in time,

\[ F = m \frac{v - v_0}{t} \]

or, after rearranging the terms,

\[ Ft = mv - mv_0 \]

The quantity \( mv \) is the momentum of the object; \( mv_0 \) is its initial momentum, and \( mv \) is its momentum after a force \( F \) has been applied to it for a time \( t \). The quantity \( Ft \) is called the impulse. The impulse on an object during a collision is equal to the change of momentum resulting from the collision. If there is no force, the momentum remains unchanged.

Consider now what happens when two objects (a bat and a ball) collide head on. To simplify matters, we will assume the ball and bat velocity vectors are colinear, as shown in Figure 34. Assume the ball has mass \( m_1 \) and speed \( v_{1b} \), and the bat has mass \( m_2 \) and speed \( v_{2b} \) before the collision. Since the collision is head on, \( v_{1b} \) and \( v_{2b} \) are in opposite directions. This is indicated in the figure by placing a minus sign in front of the ball’s velocity, \( v_{1b} \). In a typical collision of bat and ball, the force is very large and the time period over which the forces act is very small. These forces greatly deform one or both objects. However, the deformations cannot be seen by the naked eye because they happen so fast. Figure 35 is a picture of a baseball-bat collision taken with a high-speed camera. The baseball, being considerably softer than the bat, is deformed to a surprising degree during the collision. It is obviously subjected to a very large force. The force can be as large as 1500 pounds for a period as short as 0.002 second. After this time interval, the force between the ball and bat returns to 0 and the ball springs back to its nearly spherical shape.

According to another law of motion, Newton's third law, if the force imposed by the mass \( m_1 \) on the mass \( m_1 \) during the collision is \( F_1 \), then the force imposed by \( m_1 \) on \( m_2 \) is \( -F_1 \). Using \( F_1 \) in the equation for the principle of momentum, the impulse equation gives

\[ F_1 t = m_1 v_{1a} - m_1 v_{1b} \]

Since the ball is moving to the left, \( v_{1b} \) is a negative number. Similarly, applying the momentum principle to the mass \( m_2 \) gives

\[ -F_1 t = m_2 v_{2a} - m_2 v_{2b} \]

Adding the right- and left-hand sides of these equations and rearranging produces the conservation of momentum equation:

\[ m_1 v_{1b} + m_2 v_{2b} = m_1 v_{1a} + m_2 v_{2a} \]
The total momentum of the two objects taken together is the same before and after the collision. When you think about it, this is not surprising. Each object exerts a force on the other, but these forces cancel, and there is no net force on the two objects when taken together. The equation represents the law of the conservation of momentum: the total momentum must remain unchanged, when there is no externally applied force.

In the collision between a baseball and a bat, there is another force, the force that the batter's hands exert on the bat. If, however, it were anywhere near as large as the force acting between the bat and the ball, it would sting the batter's hands badly. This might happen, for example, when the ball hits the bat close to the batter's fists. Usually (if the ball is hit properly) the effect of the force from the batter's hands on the collision is small, and the immediately preceding equation is accurate. There is another problem, however. If the collision between the ball and the bat does not occur at the bat's center of mass, the collision will induce rotational motion in the bat. We will consider such collisions in the last section of this chapter. For now, we will consider only the velocities of the centers of mass of the bat and ball.

The conservation of momentum equation above tells us a lot about head-on collisions, but it cannot tell us all we want to know. Usually in collision problems we know the masses \( m_1 \) and \( m_2 \) and the speeds \( v_{1i} \) and \( v_{2i} \) of the two objects before the collision. We wish to determine the speeds \( v_{1f} \) and \( v_{2f} \) of the objects after the collision. There are two unknowns. We cannot find them both from only one equation. To determine either of the speeds after the collision we need another equation.

We need an equation that describes the physical characteristics of the two bodies that are colliding. Clearly, it is going to make a great deal of difference whether object \( m_1 \) is a baseball or a lump of clay, and whether \( m_2 \) is a wooden bat or a foam-rubber pillow. In other words, the "bounciness" of both objects is involved. A baseball will bounce higher when dropped on a concrete floor than will a softball or a lump of clay. None of these will bounce high when dropped on a thickly carpeted floor.

The property that scientists use to describe the "bounciness" associated with the collision between two objects is the coefficient of restitution \( e \). Its value is

\[
e = \frac{v_{1f} - v_{2f}}{v_{1i} - v_{2i}}
\]

In our case,

\[
e = \frac{-v_{1a} - v_{2a}}{v_{1b} - v_{2b}}
\]

To get some feeling for what this equation tells us, let us construct a simple example. Suppose we drop an object (of mass \( m_1 \)) on a concrete floor (of mass \( m_2 \)). In this special case both \( v_{2b} \) and \( v_{2a} \) are obviously zero (the concrete floor does not move either before or after the collision) and

\[
e = \frac{v_{1a}}{v_{1b}}
\]

Suppose the object strikes the floor at \(-10\) feet per second (negative because it is going down). If the ball-floor combination were perfectly
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"bouncy," $e = 1$, the floor would just reverse the ball's direction, and $v_{1a}$ would be +10 feet per second. Conversely, a ball of clay would not bounce at all. In that case, $e = 0$. The baseball-bat collision lies somewhere between these two extremes. The manufacture of baseballs is carefully controlled to ensure that the coefficient of restitution is 0.55. From the definition of the coefficient of restitution and from the equations of Chapter 2, it can be seen that if you drop a professional league baseball onto a concrete floor, it will rebound $e^2$ of the original distance; for example, if you drop it from 6 feet, it will rebound about 22 inches. The coefficient of restitution depends on the velocities of the objects before the collision, but these effects are small so we will use a constant value of $e$ throughout most of this book.* Assuming $e$ to be constant also makes the mathematics much simpler. The coefficient of restitution for the collision of two objects depends on properties of both objects. However, for a bat-ball collision most of the potential variability of the coefficient of restitution is due to the ball. So people often ignore the bat and speak of the coefficient of restitution of the ball.

The Standard Major League Baseball

A baseball is currently required to weigh between 5 and 5.25 ounces and to have a diameter between 2.86 and 2.94 inches. Before 1973, major league baseballs had been for many years assembled in the Spalding factory in Chicopee, Massachusetts. Then the work was done for a few years in Haiti, and since 1976 in Taiwan. The balls are constructed in layers. At the center is a composition cork ball encased in two thin layers of rubber, one black and one red. On this is tightly wound 121 yards of blue-gray wool yarn, 45 yards of white wool yarn, another 53 yards of blue-gray wool yarn, 150 yards of fine cotton yarn, and a coat of rubber cement. It is enclosed in a cowhide cover hand-stitched with 216 red cotton stitches.

The weight and diameter of a baseball have been standardized since 1872, when machines for the manufacture of balls came into use. However, this did not solve the problem of standardizing the coefficient of restitution of the balls. A debate over this elusive physical property has been going on at least since the 1860s, when Henry Chadwick charged that the baseballs in use at the time were "overelastic." During those early years, the color, texture and "liveliness" of the balls varied widely according to team preference. There were many manufacturers of baseballs. Almost every city sporting a baseball team had at least one.

In 1875, the Ryan "dead-ball" was adopted as the official baseball. However, in 1876 Albert G. Spalding and his brother J. Walter Spalding of Spalding Bros., Inc., began manufacturing a ball with uniform specifications, and in 1878, the Spalding League Ball became the official baseball of the National League. The balls were given to the league. In fact, Spalding Bros., Inc., paid the league $1 a dozen for the privilege. The advertising paid off handsomely. When the company began operating, it boasted $800 in capital. By 1892, it had absorbed several of the largest sporting goods companies and had a capital stock worth $4 million.

In the 1950s, the tidal wave of home runs renewed speculation about the coefficient of restitution. Was the ball getting livelier? It is indeed true that home run--hitting increased consistently after the early 1990s. Figure 36 is a graph showing how the number of home runs per game per team has changed from year to year. A value of 0.2 means that teams hit an average of two home runs every 10 games, or one homer in every five games played that year. This number increased dramatically between about 1920 and 1960, reaching a value around 0.8 which translates into about 3 or 4 percent of the balls hit in fair territory being home runs. Note the steep rise in the home run rate between 1919 and 1922, the decline during World War II and the recovery after the war. Recently there has been another sharp rise.

The reason or reasons for the long-term increase in the number of home runs are difficult to pin down. Unfortunately (although Spalding Bros., Inc., claimed the manufacturing methods and materials were standard), actual quality control through regular measurements of the coefficient of restitution had not been practiced before the mid-1950s. In an article in Collier's magazine, Tom Meany reported that Spalding Bros., Inc., claimed that there had been no changes in the specifications in manufacturing their baseballs for at least three decades. Conversely, there is a National Bureau of Standards report stating that official major league balls in 1943 were found to have coefficients of restitution of 0.41. It has been speculated that during World War II, the quality of the material used in the manufacture of baseballs was inferior to that used in other

*Our computer programs use the following equations for the coefficient of restitution (Coe): for a CJ31 aluminum bat and a softball Coe = 1.17 (0.61 - 0.001(v_{ib} - v_{ip})), and for a wooden bat and a hardball we use Coe = 1.17 (0.61 - 0.001(v_{ib} - v_{ip})) where the collision speed is in mph.
years. This coefficient of restitution of 0.41 is much lower than the value of 0.55 that is required of the present-day ball. The fact that the home run explosion was already well on its way by the 1940s casts some doubt on the "livelier ball" theory.

The year 1987 was a banner year for home run hitting, and speculations about the increased coefficient of restitution continued to abound. Baseball manufacturers continued to deny allegations of "rabbit" balls. USA Today reported on July 3, 1987, that tests of 1987 and 1977 baseballs performed by Haller Testing Laboratories showed only the slightest changes. The coefficient of restitution, according to their results, declined by 0.4 percent during that 10-year period.

A more reasonable explanation of what is behind the trend toward more and more home runs is the "livelier ball player" theory. Babe Ruth started the trend toward more home runs in 1919. When it was pointed out to Ruth in 1930 that he made more money than President Hoover, Ruth reportedly responded, "I had a better year." Home run hitters generally began having much better years (financially) than those who merely hit singles for higher averages. As Meany said, "The money's in the big end of the bat." When someone told former Pittsburgh Pirate first baseman and power hitter Ralph Kiner that he could raise his batting average by choking up on the bat, Kiner replied, "Cadillacs are down at the end of the bat." Hitters are concentrating more on hitting home runs. As is the case in other sports, diet and other factors have also led to healthier, stronger players.

The Best Bat Weight: From the Principles of Physics

The bat might have played at least as important a role as the ball in the home run explosion. According to statistics compiled by Hillerich and Bradsby, manufacturers of the Louisville Slugger bat, the average weight of bats used by top players decreased from about 40 ounces in the 1920s to about 32 ounces in the 1950s and has kept this value to the present day. Home run production increased dramatically while the bat weight was dropping.

Baseball players, for example, Babe Ruth, have used bats as heavy as 54 ounces, but physicists have said that the optimal bat weight is only 15 ounces. Because no one really knew what bat weight was best, over the years there has been a lot of experimenting with the bat. Most of this experimentation was illegal, because the rules say that (for professional players) the bat must be made from one solid piece of wood. To make the bat heavier, George Sisler, who was elected to the Hall of Fame in 1939, pounded Victrola phonograph needles into his bat barrel and in the 1950s Ted Kluszewski of the Cincinnati Reds hammered in tenpenny nails. To make the bat lighter, many players have drilled a hole in the end of the bat and filled it with cork. Detroit's Norm Cash admits to using a corked bat in 1961 when he won the American League batting title by hitting .361. However, the corked bat may have had little to do with his success, because he presumably used a corked bat the next year when he slumped to .243. Some players have been caught publicly using doctored bats. In 1987 Houston's Billy Hatcher hit the ball and his bat split open spraying cork all over the infield.
Bat Meets Ball

\[ m_1 v_{1b} + m_2 v_{2b} = m_1 v_{1a} + m_2 v_{2a} \]

with the equation for the coefficient of restitution

\[ e = -\frac{v_{1a} - v_{2a}}{v_{1b} - v_{2b}} \]

to obtain expressions for both the bat and ball speed immediately after the collision. We find that

\[ v_{1a} = \frac{(m_1 - em_2) v_{1b} + (m_2 + em_2) v_{2b}}{m_1 + m_2} \]

and

\[ v_{2a} = \frac{(m_1 - em_1) v_{1b} + (m_2 + em_1) v_{2b}}{m_1 + m_2} \]

Much can be learned from these two equations, so let us dwell on them for awhile.

First, since \( v_{1b} \) is a negative number and \( v_{2b} \) is a positive number (the objects are moving in opposite directions), \( v_{1a} \) is the speed of the ball after the collision, always increases with \( e \). Also, as long as \( m_1 - em_2 \) is negative (the weight of the bat is larger than \( 1/e \) times the weight of the ball), \( v_{1a} \) increases when \( -v_{1b} \) increases. This means that a fastball can be hit harder than a change-up, all other things being equal.

Finally, the equation for \( v_{1a} \) tells us that, all other things being constant, the speed of the ball as it leaves the bat increases as the weight of the bat increases. Suppose, for example, that the bat is much lighter than the ball. Omitting the term \( m_1 \) from the immediately preceding equations, that is, assuming \( m_2 \) is close to zero, shows that in that case

\[ v_{1a} = v_{1b} \]

which means the ball zooms past with undiminished speed. We also find that

\[ v_{2a} = (1 - e) v_{1b} + ev_{2b} \]
(the bat flies backwards). Suppose, on the other hand, that the bat weighs very much more than the ball. In such a case, terms involving $m_1$ in the equations for $v_{1a}$ and $v_{2a}$ can be dropped. The results are then

$$v_{1a} = -e v_{1b} + (1 + e) v_{2b}$$

and

$$v_{2a} = v_{2b}$$

The collision with the ball does not affect the speed of the huge bat. For a given bat speed, this is the largest velocity that can be imparted to the ball. According to this reasoning, bats should be as heavy as the rules will allow.

There is, of course, a problem with this kind of analysis. A little thought tells us that if the bat is too heavy, the batter cannot control it well enough to make good contact with the ball. Even if he could make contact with the ball, the bat speed before contact would be smaller than that which could be attained with a lighter bat. What the analysis above does not account for is that the larger $m_2$, the smaller the bat speed before the collision, $v_{2b}$. What we have here is a case of conflicting effects.

This is as good a time as any to introduce a much-overlooked fact about the practical use of scientific theories. Scientific ideas can be used to explain what is happening in the world around us and, in many cases, to predict better ways of doing things. But we must be quite specific in the way we ask questions. Almost all interesting scientific problems involve conflicting factors. In the case of hitting a baseball with a bat, we found that, strictly from the point of view of momentum considerations, the speed of a baseball leaving the bat with a given bat speed is maximized by making the bat mass (or weight) as large as possible. However, a very large bat would be hopelessly unwieldy. From the standpoint of bat control and accuracy, the bat should be extraordinarily light. The equation

$$v_{1a} = v_{1b}$$

and the equation

$$v_{2a} = (1 - e) v_{1b} + e v_{2b}$$

as well as our intuition, tell us that such a bat would simply be knocked from a batter's hands. Surely there is an optimum bat weight between these two extremes. But optimum in what sense?

Momentum effects associated with the collision itself tell us that for a given speed, we need a massive bat. We also know, however, that the smaller the bat, the higher the bat speed that can be obtained. The speed with which a particular batter can swing his weapon depends on how much energy he can put into his swing. To resolve our conflict, and to learn more about the optimum bat and the optimum swing, we need to stop looking at only the bat and the ball. We must now consider the human being swinging the bat.

The Best Bat Weight: From the Principles of Physics and Physiology

The speed of a baseball after its collision with a bat depends on many factors, not the least of which is the weight of the bat. One professional baseball team (St. Louis Cardinals) says the weight of the bat is determined by “the player’s personal preference,” while another (New York Yankees) says, “Each individual player determines the style of bat he prefers.” These players have very little real scientific data to help them support their preferences. In this section, we present data to help an individual player to decide if his or her preference is the most effective bat weight. Knowing the ideal bat weight can eliminate time-consuming and possibly misleading experimentation by ballplayers.

To find the best bat weight we must first reexamine the conservation of momentum equations for bat-ball collisions. For the science of baseball, the distinction between mass and weight is not critical, and so we will substitute weight for mass in the equation for the conservation of momentum to produce

$$w_1 v_{1b} + w_2 v_{2b} = w_1 v_{1a} + w_2 v_{2a}$$

Keep in mind that we are assuming the weight of the batter's arms has no effect on the collision (this may be an important assumption). We want to solve for the ball's speed after its collision with the bat, called the batted-ball-speed, but first we should eliminate the bat's speed after the collision, because it is not easily measured. We can use the equation for the coefficient of restitution to solve for $v_{2a}$, substitute the result into the equation
for the conservation of momentum and solve for the ball's speed after its collision with the bat. The result is

\[ v_{1a} = \frac{(w_1 - ew_2)v_{1b} + (w_2 + ew_2)v_{2b}}{w_1 + w_2} \]

This means that the ball's speed after the collision will depend on the weight of the ball and bat, the coefficient of restitution, and the precollision speeds of the ball and bat.

Paul Kirkpatrick assumed that the optimal bat weight would be the one that "requires the least energy input to impart a given velocity to the ball." This definition in conjunction with the immediately preceding equation yields

\[ \left[ \frac{w_2}{w_1} \right]_{\text{optimal}} = \frac{v_{1a} - v_{1b}}{v_{1a} + e v_{1b}} \]

If we now make the reasonable assumptions that

- \( w_1 = 5.125 \text{ oz.} \), the weight of the baseball
- \( e = 0.55 \), the coefficient of restitution of a baseball-bat collision
- \( v_{1b} = -80 \text{ mph} \), a typical pitch speed
- \( v_{1a} = 110 \text{ mph} \), the ball speed needed for a typical home run

we can solve the immediately preceding equation to find that the optimal bat weight is 15 ounces!

Peter J. Brancasio has written an excellent theoretical analysis of bat-ball collisions. He considered not only the bat's translation but also its angular rotation about two axes. He found that the ball's speed after the collision with the bat depends on

1. the energy imparted by the body and arms;  
2. the energy imparted by the wrists;  
3. the speed of the pitch;  
4. the point of collision of the ball with respect to  
   a. the center of percussion,  
   b. the center of mass,  
   c. the end of the bat,  
   d. the maximum energy transfer point, and  
5. the weight of the bat.

However, by assuming that a professional baseball player exhibited normal values for each of these dependencies, he also concluded that the optimal bat weight is about 15 ounces.

These conclusions cannot help professional baseball players, who must use solid wood bats, because a 15-ounce solid wood bat would only be about 15 inches long! Such a bat would be far smaller than any bat that is now used in professional baseball. A typical major league bat weighs about 32 ounces. Babe Ruth normally used a 44-oz bat, and sometimes used bats weighing more than 50 ounces. On the other hand, a fungo bat, a bat used for hitting fly balls in practice sessions, weighs about 23 to 24 ounces. One might take this to mean it is closer to the optimum weight. However, a fungo bat is used to hit balls that have initial speeds \( v_{1b} \) of practically zero, so a reexamination of the conservation of momentum equation indicates that for that case, the bat should weigh the same as the ball, about 5.25 ounces.

These conclusions may help explain why people choke up on the bat; choking up makes the bat effectively shorter, moves the center of mass closer to the hands, thereby reducing the moment of inertia, and in essence makes the bat act like a lighter bat. Several reasons have been advanced for buying a long bat and choking up on it. First, a longer bat must be made from wood that has straighter grain. Therefore bat manufacturers use the best wood for the longer bats, and bats made from the best wood do not break as easily. Secondly, using a longer bat allows the batter to change the effective weight of the bat during his time at bat. Al Rosen recalled that Ted Williams and Mickey Mantle did not choke up with no strikes. If the pitcher got one strike on them, they choked up a half inch. If the pitcher got two strikes, they choked up an inch. This con-
clusion could also help explain the great popularity of aluminum bats. The manufacturers can make them lighter while maintaining the same length and width.

Both Kirkpatrick's and Brancacio's physics studies were limited by their explicit assumptions. Kirkpatrick assumed that the optimal bat was the one that required the smallest bat kinetic energy. Brancacio's calculations of the optimal bat weight were based on the assumption that the "batter generates a fixed quantity of energy in a swing," independent of the bat weight. We will now extend these studies by allowing the amount of energy imparted to the bat by the batter to depend on bat weight.

Physiologists have long known that muscle speed decreases with increasing load. This is why bicycles have gears. The rider can keep muscle speed in its optimal range while bicycle speed varies greatly. Therefore, to discover how muscle properties of individual ballplayers affect their best bat weights, we measured the bat speeds of many batters swinging bats of various weights. We plotted the data of bat speed versus bat weight, and used this to help calculate the best bat weight for each batter.

The Bat Chooser Instrument

Our instrument for measuring bat speed, the Bat Chooser, has two vertical light beams, each with associated light detectors (similar to the electric eyes on elevator doors). The subjects were positioned so that when they swung the bats the center of mass of each bat passed through the light beams. A computer recorded the time between interruptions of the light beams. Knowing the distance between the light beams and the time required for the bat to travel that distance, the computer calculated the speed of the bat's center of mass for each swing. Our computer sampled every 16 microseconds. In all cases our velocities are accurate to better than 1 percent.

Note: This book is a scientific analysis of baseball. To make the mathematics easier to follow, in the early part of this chapter, we make our calculations for a ball that hits the bat at its center of mass. Consequently, all of the bat speeds given in this chapter are speeds for the center of mass of the bat. Many experimental studies of baseball give bat speeds for the sweet spot of the bat. (There are many definitions for the sweet spot of the bat.) To compare our speeds for the center of mass to experimental studies giving the speed of the sweet spot, multiply our numbers by about 15 percent. (Because the swing of the bat is a combination of translation and rotation, a combination that varies from person to person and from bat to bat, it is impossible to analytically specify this correlation factor. Our 15 percent figure is based on a melding of theoretical analyses and experimental measurements. In our experiments with 340 swings by 11 people the difference was 12 percent with a standard deviation of 6 percent.) For example, for a bat swing where we report a center of mass bat speed of 50 mph, the speed of the sweet spot would be about 58 mph.

To hit a home run in most major league parks it takes a center of mass bat speed of about 50 mph, which combined with a pitch speed of about 90 mph would produce an initial batted-ball speed of 100 mph, which would put the ball 15 feet high, 330 feet from the plate.

As an aside, in 1999, television programs started reporting "bat speeds." These numbers must be viewed with suspicion. They often reported consecutive swings with speeds of, for example, 74, 84 and 94 mph. Professional baseball players do not have such variability in their swing speeds. Consecutive swings typically vary by only a few mph. Batters are trained to make their swings repetitive, that is with low variability. When the speed of the pitch varies from 70 to 80 to 90 mph, the batters adjust the time of onset of their swing, not the speed of the swing. These television reports are probably measuring the speed of the sweet spot on one swing, the speed of the tip of the bat on the next swing and the speed of the reflection of the tip of the bat on the next. But they do not tell us what they are measuring, because they do not know what they are measuring. When the television reports get into the range of 50 to 60 mph, or when they tell us what they are actually measuring, then we can start to believe them.

In our experiments, each player was positioned so that bat speed was measured at the point where the subject's front foot hit the ground. This is the place where most players reach maximum bat speed and therefore where they hit the ball with maximum force.

We told the batters to swing each bat as fast as possible while still maintaining control. We told the professionals to "Pretend you are trying to hit a Randy Johnson fastball."

In our experiments, each adult subject swung six bats through the light beams. The bats varied from superlight to superheavy, yet they had similar lengths and weight distributions. In our experiments we used

*Bat Chooser is a trademark of Bahlil Intelligent Computer Systems.