Rod Cross

Physics of Baseball & Softball

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Preface

The number of baseball and softball fans in the world is probably around 100 million. The number of people who are interested in physics might also be about 100 million. In theory, therefore, this book should appeal to somewhere between 100 million and 200 million people. However, the number of people who are seriously interested in both physics and baseball or softball is somewhat less than this. Only a handful of physicists in the world have actually conducted serious studies of the physics of baseball and softball. Not because the subject does not interest them, but because they are usually too busy doing other serious physics work. If they were caught out doing fun baseball experiments on the side, it might give the false impression that they were not being properly employed. Partly because of the nature of the subject, there have been many more engineers and biomechanists and even historians and economists who have engaged in academic studies of baseball and softball.

While baseball is known as the national pastime in the USA and softball is even more popular in terms of the total number of players, sport is not a high priority area when it comes to government or even private funding of physics research. Nevertheless, physics laboratories are usually sufficiently well equipped for anyone who is so inclined to sneak in some sports research on the side. That is how I first managed to get involved, in 1995. I found it absolutely fascinating and I still do. Part of the fascination is in discovering things that were not previously known. The physics of sport is not a rich field for "new" physics, but it is fun using "old" physics to provide new insights into some of nature's mysteries. The bounce of a ball is just one of those mysteries. Very little was known about the subject when I started in 1995, apart from some early work done by Sir Isaac Newton around 1670 and a few additional studies during the next 300 years. Much more was known about the flight of balls through the air. My background before getting sidetracked into the physics of sport was 30 years experience in high temperature plasma physics research. It had no particular relevance to baseball or softball, apart from the fact that it helps to teach and study physics for 30 years or more to get on top of the subject.

In 1990, Professor Robert Adair at Yale University wrote a very popular book called "The physics of baseball." It is currently in its third edition and provides an easy-to-read and entertaining account of the subject. During the last 15 years there have been many advances in our understanding of the physics and engineering of baseball and softball, and there is now room for a second book on the subject. Given that baseball and softball are both very similar sports, the physics of one is essentially the same as the physics of the other. In fact, the physics of sport is essentially the same as the physics of many other topics and likely to be a lot more interesting to anyone with an active interest in sport. Basic mechanics features prominently in this book, almost all of the examples being taken from baseball and softball. I would have achieved a useful objective if some of the material finds its way into classrooms.

The wide range of interests and abilities of the 100 million baseball and softball fans in the world presented me with a problem. Even if I assumed that only 10 million of those fans were interested in physics, only a tiny fraction of that number would have studied physics at University level. I have, therefore, written the book assuming that most readers will have a basic understanding of high school physics, but are not necessarily proficient at that level. One of my objectives is to try to boost that proficiency by emphasizing the physics issues in baseball and softball in more detail than in Adair's book. Professor Adair achieved an excellent result in explaining baseball in terms of the known laws of physics. A difference between his book and mine is that I have placed greater emphasis on explaining the physics in terms of the known behavior of bats and balls. I have tried to discuss the physics in a conversational manner, using simple equations where necessary, but I have also included more advanced material in the Appendices at the end of each chapter. That way, the reader can skip the hard parts or can refer to them later, depending on his or her prior knowledge of, and interest in, physics and mathematics.

I am especially grateful to Professor Alan Nathan at the University of Illinois for his assistance in helping me prepare this book. Alan and I have collaborated on many physics of sports projects over the years, despite living 9,240 miles apart. Both of us maintain web sites that contain additional material on the physics of baseball and softball, including some interesting video film of various topics described in this book. The sites are www.physics.usyd.edu.au/~cross and http://go.illinois.edu/physicsofbaseball. Professor Lloyd Smith also provided valuable assistance, especially on the physics of softball, and has a very nice site at www.mme.wsu.edu/~ssl, as does Professor Dan Russell at http://paws.kettering.edu/~drussell/bats.html. A web search on "physics of baseball" will reveal thousands of other sites, indicating that there are indeed many thousands of people actively interested in the topic.

Sydney University
August 2010

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Chapter 1
Basic Physics

Most of the physics in this book can be understood in terms of basic high school mechanics and slightly beyond. This chapter is provided for those who might need some extra guidance or a kick-start. The author has taught a course in sports mechanics for physical education teachers for many years. Many of the students arrive at University without ever having studied physics and only a small amount of mathematics. Some arrive after being in the work force for a few years and have forgotten everything they knew from high school. Those students take a few weeks to get the hang of it and usually do quite well after extra help from their tutors. This chapter contains material that is taught to such students, and also at high school, but it comes with a warning. In most countries around the world, including the USA, physics is taught using the MKS or SI system of units, the basic units being metres, kilograms, and seconds. In baseball and softball, length is more commonly measured in inches, feet, and miles, while mass or weight is commonly measured in ounces or pounds. Many of the physics equations in this book are described using MKS units and the answers are then translated into English units. The advantage of the MKS system is that the mathematics is easier, since 10 mm = 1 cm, 100 cm = 1 m, and 1,000 m = 1 km. Similarly, 1,000 g = 1 kg. In the English system, 12 in. = 1 ft, 5,280 ft = 1 mile, and 16 oz = 1 lb, which makes the math a little more complicated. Things get even more complicated when slugs and poundals are introduced to get around the problem that a pound is commonly used both as a unit of mass and a unit of weight or a force. In physics, mass and force are very different things. A list of conversion factors is given at the end of the book.

1.1 Linear Motion

Linear motion normally refers to motion along a straight line. A batter running from one base to the next is an example. A baseball or a softball does not normally move in a straight line, but the force of gravity on the ball is vertical at all times and is zero in the horizontal direction. The effect of gravity on the ball can be treated by regarding the motion of a ball as a combination of linear motion at constant speed

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in the horizontal direction, plus linear, accelerated motion in the vertical direction. In the real world, air resistance also acts on the ball but the effect is relatively small at low ball speeds.

Speed

The average speed of an object is given by the formula speed = distance/time. For example, if a baseball takes 4 s to travel 400 ft then the average speed of the ball is $400/4 = 100\,\text{ft s}^{-1}$ (Fig. 1.1). To convert that result to other units, we can use the following conversion factors: $1\,\text{ft s}^{-1} = 0.6818\,\text{mph} = 0.3048\,\text{m s}^{-1}$. For example, if we multiply by 100, then $100\,\text{ft s}^{-1} = 68.18\,\text{mph} = 30.48\,\text{m s}^{-1}$.

We use the phrase "average speed" here because the ball slows down through the air. The ball might be struck at $110\,\text{ft s}^{-1}$ and slow down to $90\,\text{ft s}^{-1}$ by the time it lands. Using a video camera we could record the position of the ball as it travels through the air and measure the actual decrease in speed due to air resistance. Suppose that near the end of its flight, the ball moves 3 ft from one frame to the next. Video film is recorded at $30\,\text{frames s}^{-1}$, so the time between frames is $1/30 = 0.033$ s. The average speed over this time is $3/0.033 = 90.9\,\text{ft s}^{-1}$. The formula for the speed in this case is $v = \mathrm{d}x/\mathrm{d}t$ where $\mathrm{d}x$ is the change in position = 3 ft and $\mathrm{d}t$ is the change in time = 0.033 s.

Mathematically, the expression $\mathrm{d}x/\mathrm{d}t$ is called the derivative of x with respect to t. If you have studied calculus in math you will recognize this. If you haven't studied calculus then at least you now know what a derivative is. It is just a small increase in one quantity divided by a small increase in another quantity. In physics, "small" here means something that is small enough for practical purposes. In mathematics, "small" is much smaller. For example, if the ball travels 1 in. in 0.001 s, then that would definitely be small enough for a physicist, but it would still be too large for mathematicians. They would prefer that $\mathrm{d}x$ and $\mathrm{d}t$ are both infinitesimally small, but then it would be impossible to measure such tiny changes in x and t.

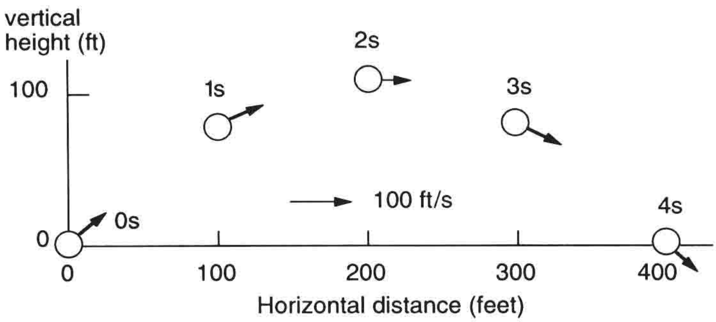


Fig. 1.1 A baseball will take about 4 s to travel 400 ft horizontally, at $100\,\text{ft s}^{-1}$ in the horizontal direction. The position of the ball is shown at 1 s intervals

When a baseball travels 400 ft horizontally through the air, it rises to a height of about 110 ft in about 2 s and drops back to the ground during the next 2 s. The average horizontal speed is 100 ft s^{-1}. The average vertical speed on the way up or on the way down is $110/2 = 55$ ft s^{-1}. When the ball gets to its maximum height it comes to a stop in the vertical direction. At that point the vertical speed is zero (since it is not actually moving up or down at that instant) but the horizontal speed is still 100 ft s^{-1}. Given that the average vertical speed is 55 ft s^{-1}, the batter actually struck the ball with a vertical speed of 110 ft s^{-1} (since the average of 0 and 110 is 55).

Batter Decision Time

In baseball, the ball can be pitched at speeds up to 90 mph or 132 ft s^{-1}. The front edge of the pitcher's plate is 60.5 ft from the rear point of home base, and 10 in. above it, but the pitcher leans forward and releases the ball about 5 ft from the pitcher's plate. Similarly, the batter strikes the ball about 2 ft in front of the rear point of home base so the ball travels about 53 ft from the pitcher's hand to the bat. The batter starts the early part of the swing even before the pitcher releases the ball, but the final decision as to where to swing the bat must wait until the pitcher releases the ball. The decision time, while the ball is in the air, can be calculated from the ball speed. If the average ball speed was 90 mph, then the time is $53/132 = 0.40$ s. But the ball slows down through the air by about 10% and arrives at home plate at about 81 mph. The average ball speed is then 85.5 mph or 125 ft s^{-1} so the ball travel time is actually about $53/125 = 0.42$ s.

Acceleration

The acceleration due to gravity is $g = 9.8$ m s^{-2} (or 32 ft s^{-2}). The value of g gives the increase in speed each second when an object falls to the ground. After 1 s, the speed of a ball dropped from a large height will be 9.8 m s^{-1} (or 32 ft s^{-1}). After 2 s the speed will be $2 \times 9.8 = 19.6$ m s^{-1}. If a ball is dropped from a small height, say 2 m, then it will take only 0.64 s to hit the ground. It starts off with zero speed. After 0.1 s, it has accelerated to 0.98 m s^{-1}. After 0.2 s, the ball speed is $0.2 \times 9.8 = 1.96$ m s^{-1}, as shown in Fig. 1.2. After 0.6 s, the ball speed is $0.6 \times 9.8 = 5.88$ m s^{-1}. The formula for the ball speed here is $v = 9.8\,t$, and the fall height is $y = 4.9\,t^2$, assuming that the ball starts at $t = 0$ with $y = 0$ and $v = 0$.

When a batter swings a bat, the tip of the bat increases in speed from about 5 m s^{-1} to about 30 m s^{-1} over the last 0.2 s of the swing. The tip moves in an approximately circular path. The average acceleration, a, of the tip along that path is given by the formula a = increase in speed/increase in time. The increase in speed is 25 m s^{-1}. The increase in time is 0.2 s. So $a = 25/0.2 = 125$ m s^{-2}, which is 12.7

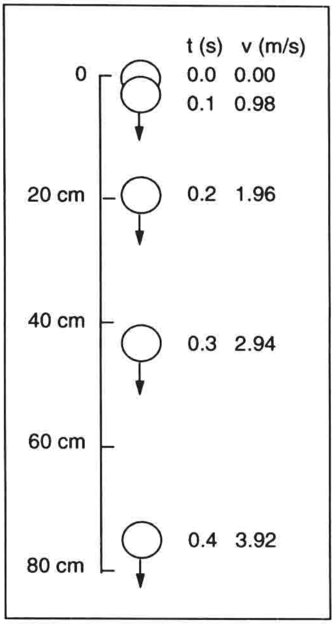


Fig. 1.2 A falling ball accelerates as it falls. The speed and position of the ball are shown here at intervals of 0.1 s after release

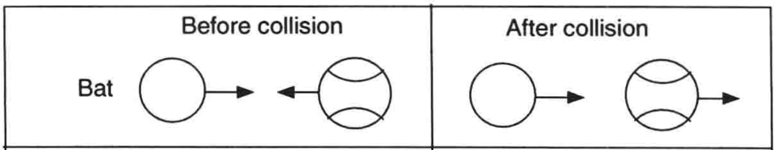
times larger than g. The average acceleration is therefore 12.7 g. The acceleration is not constant during the whole swing. Over any small interval of time, dt, the speed increases by dv and $a = dv/dt$.

Momentum

The momentum of an object of mass m moving at speed v is defined to be m multiplied by v. If an object has a large amount of momentum then it has a large mass or a large speed or both. If one object (a bat) is about to collide with another (a ball), then the total momentum of the two objects is just the sum of the two separate values, taking the sign of the momentum into account. For example, the momentum of a bat traveling left to right might be $+20\,\mathrm{kg\,m\,s^{-1}}$ and it might collide with a ball traveling in the opposite direction with momentum $-2\,\mathrm{kg\,m\,s^{-1}}$. The total momentum just before the collision is $+18\,\mathrm{kg\,m\,s^{-1}}$ (Fig. 1.3).

Momentum is an important quantity when describing collisions since the total momentum doesn't change during a collision. The bat will slow down and the ball will turn around and head off in the same direction as the bat after the collision, but the total momentum will still be $+18\,\mathrm{kg\,m\,s^{-1}}$ after the collision. Momentum lost by the bat is given to the ball. We describe this effect as "conservation of momentum."

For a baseball or softball bat, the tip and the handle of the bat usually move at different speeds. In that case, we define the momentum of the bat as the mass of



	Before collision		After collision	
m (kg) =	1.0	0.14	1.0	0.14
v (m/s) =	20	−14	13.7	30.7
mv =	20	-2	13.7	4.3

Fig. 1.3 A head-on collision between a bat and ball. The total momentum (mv) after the collision ($18\,\mathrm{kg\,m\,s^{-1}}$ here) is the same as that before the collision. The total mass remains the same, but the total v does not remain the same, nor does the relative velocity remain the same

the bat multiplied by the speed of its center of mass (CM). The CM of a bat can be found by balancing the bat across a rod or tube. The CM is directly above the balance point, on the long axis of the bat.

Force

In the absence of any force acting on an object, an object at rest will remain at rest, and an object that is moving will continue to move at a constant speed. If Newton had lived in the USA, he might have described this result as his First Law of Baseball. If there is no net force on an object then there is no acceleration. If you stand still on the ground then the force of gravity pulls you down but the ground exerts an equal and opposite force upward. The total force is zero so you remain at rest.

In order for an object to accelerate there must be a net force acting on the object. The force is given by $F = ma$ where m is the mass of the object. This is Newton's Second Law of Baseball. If there are two or more forces acting on the object, then F is the total force on the object. The object accelerates in the same direction as the total force acting on the object.

If a baseball is flying through the air then it follows a curved path since gravity pulls it back down to earth. The acceleration of the ball in the vertical direction is $g = 9.8\,\mathrm{m\,s^{-2}}$ and the vertical force on the ball is $F = mg$. If $m = 0.142$ kg then $F = 0.142 \times 9.8 = 1.39$ N.

The units here are important, at least when describing the physics of the situation. The words are also important. The mass of the baseball is 0.142 kg. The force of gravity acting on the ball is called its weight. The weight of the baseball is 1.39 N.

In everyday use, we say that a baseball weighs about 5 oz or 142 g. That is actually the mass of the ball. In everyday use, mass and weight are treated as the same thing. We might say that a bat weighs 30 oz or the batter pushes on the bat with a force of 20 lb. We know what people mean when they say this, and there is no real confusion in conversational terms, but it is technically incorrect and leads to problems when doing physics calculations. If a 160 lb astronaut weighed himself in the weightless environment of a space vehicle then he would weigh nothing on a set of scales. His mass would still be 160 lb but his weight would be zero since he would exert no force on the scales.

Force on a Baseball

The force exerted on a baseball can be estimated from its change in speed. In a big hit, the ball will be pitched at about 90 mph and will struck at about 110 mph. The collision time is only about 0.001 s. The change in velocity is $90 + 110 = 200$ mph ($89.4\ \mathrm{m\,s^{-1}}$) so the average acceleration $a = 89{,}400\ \mathrm{m\,s^{-2}}$. The mass of a baseball is 0.145 kg so the average force on the baseball is $ma = 12{,}963$ N or 2,914 lb (since $1\ \mathrm{N} = 0.2248$ lb). During the collision the force increases from zero to a maximum value and drops back to zero. The maximum force is about twice the average value and is therefore about 5,800 lb. If the collision time is as short as 0.6 ms then the maximum force could be as large as 9,700 lb.

Work and Energy

When a force is exerted on an object then the object accelerates in the direction of the force. Suppose you throw a baseball of mass m by pushing the ball forward through a distance d with a force F (Fig. 1.4). The work, W, done on the ball is defined to be $W = Fd$ and the answer is expressed in Joules. Starting from rest, the ball will accelerate up to a speed v given by $W = \frac{1}{2}mv^2$. On release, the ball will continue to travel through the air at speed v. The quantity $\frac{1}{2}mv^2$ is called the kinetic energy (KE) of the ball and it is also measured in Joules. In this case, the kinetic energy acquired by the ball is equal to the work done when you throw it. For example, if $m = 0.145$ kg (5.1 oz) and $v = 40\ \mathrm{m\,s^{-1}}$ (90 mph) then $W = KE = 0.5 \times 0.145 \times 40^2 = 116$ J. The force needed to throw the ball at this speed can be estimated in terms of the throw distance d. If $d = 2$ m, then $F \times 2 = 116$ so $F = 58$ N (13 lb).

Power

Power is a term in physics that refers to the amount of energy that is delivered or consumed in 1 s. It is measured in Watts. For example, a 100 W light bulb is one that uses 100 J of electrical energy every second. A small 2 kW engine delivers 2,000 J of energy every second.

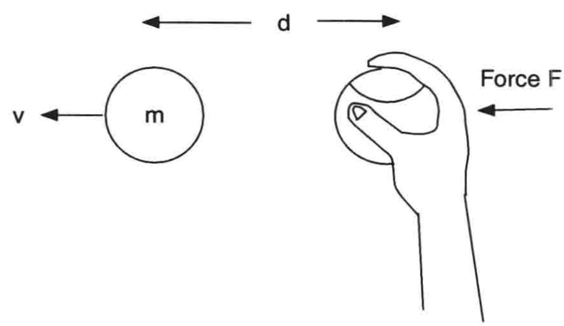


Fig. 1.4 A ball is thrown by exerting a force F on the ball and by maintaining that force over a distance d. The work done is Fd. The speed of the ball on release is given by $\frac{1}{2}mv^2 = Fd$ where $\frac{1}{2}mv^2$ is the kinetic energy of the ball

In common usage, power can mean lots of things. The USA is a powerful country in terms of its military might, and there are a lot of powerful people in the USA. An atomic bomb is a very powerful weapon. People refer to mind power or spiritual power or the power of positive thinking. A boxer can pack a powerful punch. Heavy bats are more powerful than light bats. And so on. Not all of these power terms mean the same thing as "power" in physics or engineering terms.

For example, consider the "power" of a baseball bat. All the energy gained by the bat is supplied by the batter. The bat is just an instrument that helps send the ball on its way. If it does its job well, then we usually say that the bat is powerful. In physics terms we should really describe the bat in terms of its efficiency. An efficient bat would be one that allows the batter to transfer the energy in his arms to the ball without too much loss of energy in the process. In fact, all bats are very inefficient in the sense that only a small fraction of the energy in the arms is given to the ball. Most of that energy is retained in the bat and in the arms as a result of the "follow through" after the bat strikes the ball. It is almost a case of using a sledgehammer to crack a nut, but that is what is needed to hit a ball at high speed.

The reason that bats are not very efficient is that the ball is much lighter than the bat, so the bat follows through after the collision. If the ball was as heavy as the bat then the bat would be much more efficient in terms of the transfer of energy to the ball but the ball speed would be very low. The combination of a heavy bat and a light ball is used in baseball and softball to make sure the ball comes off the bat at high speed. In common usage, the power of a bat refers to the outgoing ball speed rather than the energy transfer.

Reference Frames

If you sit in a train at rest next to another train at rest then you are not moving and neither is the other train. If you see the other train start moving, it is often difficult to tell whether your train started to move or whether the other train started moving. That is, you can't tell whether you are moving forward or the other train is moving backward or whether both trains started to move at the same time. Your train is your