# The Physics of Baseball

## *Pre-Lab: America's National Pastime*

**A Bit of History**

Filled with men, myths, and legends, the history of baseball is much too long to be described in any Bit of History. If you're interested in **A Lot of History,** check out the excellent documentary titled *Baseball – A Film by Ken Burns*. But be warned: it is 18.5 hours long. For our purposes, it is sufficient to know that sometime in the late 1860s, the first professional baseball teams formed in the U.S. (our very own St. Louis Cardinals made their debut in 1882) and since that time the sport has become intertwined with American culture. No place is this truer than here in America's greatest baseball town!

**What Is This Lab About?**

By the end of this lab you should see the tremendous number of physics topics that show up in the game of baseball. You'll get to revisit topics such as momentum, impulse, projectile motion, the drag force, moment of inertia, cross-products, constant acceleration equations, energy, center of mass, and spherical cows. You will also be introduced to the Magnus force, waves, and the center of percussion. Whew!

If you are already familiar with baseball, you can skip to the section titled "The Pitcher" at the top of page 3. The next couple sections attempt to explain some of the game to newcomers.

**The Game**

A game of baseball is played between two teams, each using nine players. The game itself lasts nine innings* with each inning being composed of six outs*. (All terms marked with * are defined in Appendix A.) Each team plays offense for three outs (i.e. half an inning) and defense for the other three outs. During each half inning, the goal of the offensive team is to score as many runs* as possible before they make their three outs, while the goal of the defensive team is to get the three outs as soon as possible, limiting the number of runs the offensive team scores. The team with the most runs after the nine innings have been played is declared the winner.

The most fundamental interaction in a baseball game – and the focus of this week's lab – is between the pitcher* and the batter*. The batter, one of the offensive players, is trying to produce runs for his team while the pitcher, one of the defensive players, is trying to get the batter out, preventing the offense from scoring runs. During game play, the pitcher stands on the pitching mound* and throws a ball (this action is called pitching – I guess athletes are the only people who come up with names less clever than physicists…) toward the batter who is standing near home plate*. As the ball approaches the batter, he decides if the pitch will be in the strike zone*. If so, he swings his bat, attempting to reverse the direction of the ball, thus putting it in play (this action is termed hitting the ball). At this point, there are three possible outcomes: the batter hits the ball, putting it in play; the batter hits the ball, but does not put it in the field of play; the batter misses the ball and it is caught by another defender named the catcher. Let's look at each of these scenarios.

- ***Batter makes contact, putting the ball in play:*** If the batter puts the ball in play he runs toward first base while the pitcher, catcher and the other seven defenders do their best to get him out. They can do this by catching the ball in the air, fielding the ball that was hit on the ground and throwing it to first base (where another defender is stationed) before the batter arrives at the base, or by fielding the ground ball and tagging the batter before he reaches first base. If any of these scenarios occur, the batter is out and must leave the field of play. However, if the defense is unable to get him out, he stays on first base. At this point, he is termed a baserunner, and the next offensive player gets his turn as a batter. The next batter will go through the same motions in the hopes of advancing the baserunner. If the baserunner is eventually advanced to home plate (after reaching second and third bases), he scores a run.
- ***The batter misses the ball and it is caught by another defender named the catcher:*** This is called a strike*. A batter is allowed three strikes before he is out.
- ***The batter hits the ball, but doesn't put it in play:*** This is termed a foul ball. If a batter hits a foul ball he is assessed one strike, unless he already has two strikes at which point there is no penalty for hitting foul ball.

## The Field

Each Major League Baseball team has a home field in which they play half of their games. The entire structure is termed a stadium. Each team's stadium is unique, often possessing quirks which can give players from the home team a bit of an advantage. Figure 1 below is a Google Maps image of Busch Stadium, which is where the St. Louis Cardinals play their home games. Look over the image to get an understanding of how the field is laid out.

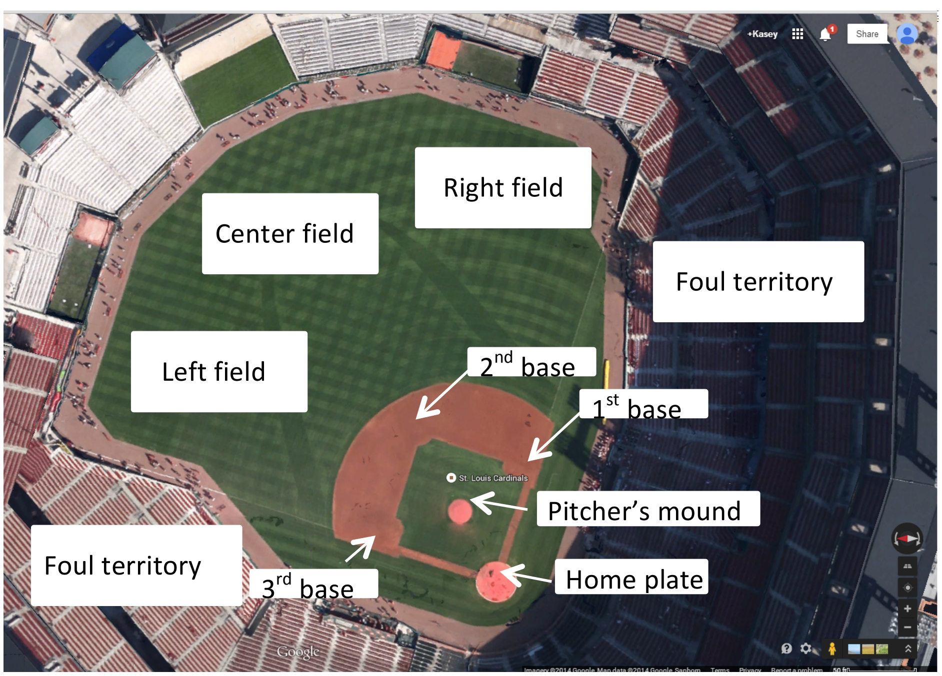



**Figure 1**: The field of play for a baseball game is three sided, bounded on two sides by lines which have been drawn on the ground and bounded on the third side by the outfield fence*. Loosely speaking, the field is one quadrant of a circle. The circle is centered on the back of home plate and has a radius of approximately 122 meters. Any point outside of the quadrant of play is said to be in foul territory.

**The Pitcher**

The pitcher is a team's primary defensive weapon. A good pitcher can deceive, overpower, and downright humiliate a hitter. One of the greatest pitchers of all time is Randy Johnson. One reason Johnson was so dominating is because he had the ability to throw the ball 100 miles per hour (mph). This meant two things. First of all, the batter had very little time to react to a pitched ball, making it very tough to hit. Secondly, if Johnson happened to throw a pitch in the wrong direction and plunk the batter, it would cause a lot of pain.

> **Do This:** There are two **optional** videos on the Pre-Lab Links page that demonstrate Randy Johnson's ability to humiliate and destroy. One of these videos demonstrates conservation of momentum at the expense of an unfortunate bird.
>
> **Read This:** It is common for a pitcher to throw a fastball that has a linear velocity of 100 mph and rotational velocity of 2000 revolutions per minute (rpm). ***A Major League baseball has a weight of five ounces and a circumference of nine inches.*** Be very careful with units in the following calculations!
>
> PL1. What is the translational kinetic energy of a baseball that is thrown at 100 miles per hour? Give your answer in joules.
>
> PL2. A baseball has a weight of five ounces and a circumference of 9 inches. Assuming it has a uniform density, what is the moment of inertia of a baseball? Give your answer in $kgm^2$.
>
> PL3. What is the rotational kinetic energy of a baseball that is spinning at 2000 rpm? Give your answer in joules.

**The Batter**

The batter is a team's primary offensive weapon. Unlike pitching, every player on the team gets a chance at batting during the game (at least in the National League). Each of the nine players comes to home plate, one at a time, attempting to get a hit off of the other team's pitcher. To get a hit, the batter must use his bat to strike the pitched baseball.

The greatest success that a batter can have is to hit a homerun. One of today's best homerun hitters is Giancarlo Stanton of the Miami Marlins. Stanton is known for hitting baseballs very hard, resulting in many long homeruns. Let's look at one such hit.

> **Do This:** Stanton hit the second hardest homerun of the 2014 season with an ***initial speed of 120 mph at an angle 20 degrees above the horizontal***. If you are interested, you can find and watch the video of Giancarlo Stanton on the Pre-Lab Links page. You can also complete the following exercises without watching the video. We will investigate this homerun in some detail.
>
> PL4. If the pitched ball was traveling 77 mph before Stanton's bat hit it and 120 mph after his bat hit it, by what amount did the speed of Stanton's bat decrease due to the collision? (Give

your response as a positive value in units of miles per hour. Assume that the bat and ball are moving in a single dimension. A baseball has a weight of 5 ounces and the bat Stanton uses has a weight of 32 ounces.)

**Read This:** According to data available through ESPN, Stanton's homerun traveled 428 feet. It's probably no surprise to you that the atmosphere significantly affects the flight of the ball. It may surprise you how large the effect can be.

PL5. Calculate how far Stanton's homerun would have traveled if the earth had no atmosphere. Assume the ball/bat collision occurred 3 feet above the ground. Give your answer in feet. (The acceleration due to gravity is 32.2 ft/s$^2$).

**Read This:** Interested students can access a fly ball simulator on the Pre-Lab Links page. Full instructions for using the simulator can be found on the website. You may either download the simulator and run it on your computer or run the simulator in your browser.

**Read This:** The default settings of the simulator are the parameters of the Giancarlo Stanton homerun from the video (120 mph at 20 degrees above the horizontal). Click the screen to hit the ball. You should see the ball travel about 428 feet.

**Read This:** There's nothing that you're required to do with the simulator, but feel free to play around with it. Can you determine the acceleration due to gravity on the moon or on Mars? Does the atmosphere on Mars have any effect on the flight of the ball? Can you get the ball to curve so much that it travels backwards? Can you investigate the effects of topspin rather than backspin? The list goes on!

## *End of Pre-Lab*

# *Part I: Fast Balls, Curve Balls, and Change-Ups*

**The Story**

Every time a pitcher takes the pitcher's mound, he's matched up with a series of formidable opponents. If this pitcher is going to have any success, he must be able to deceive these hitters. How does he do this? By developing different types of pitches, each of which travels with a different speed on a different trajectory.

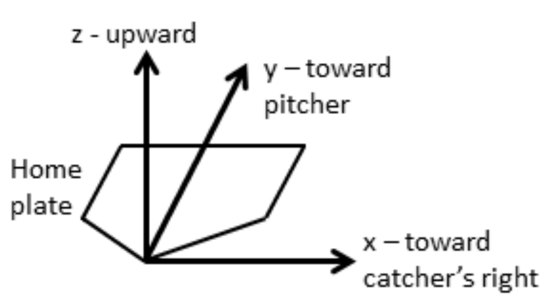
**Defining Pitches**

Shelby Miller was one of the Cardinals' promising young pitchers until he was traded to Atlanta in November of 2014. Let's investigate how he managed to be so effective by looking at some data collected from the game Shelby pitched on August 2, 2013. Though there are many types of pitches, in this week's lab we will look only at the three types that Shelby Miller threw in the summer of 2013: the fastball, the change-up, and the curveball.

> **Fastball:** The name pretty much sums it up. This is the fastest pitch thrown by a pitcher.
>
> **Change-Up:** This pitch is meant to be nearly identical to a fastball with one key exception: it travels much slower.
>
> **Curveball:** Sometimes called *Ole Uncle Charlie*, this is perhaps the most famous pitch of all! Not surprisingly, a curveball follows a curved trajectory. By twisting his wrist and imparting a large spin to the ball the pitcher makes use of the Magnus Effect (more on this later) to make the ball bend in the direction he chooses.

**Defining the Coordinate System**

Understanding the coordinate system that we will use is absolutely key. Figure 2 defines the coordinate system that we will use in this lab. You can refer to Figure 1 in the Pre-Lab for a top-down view of the entire baseball diamond.



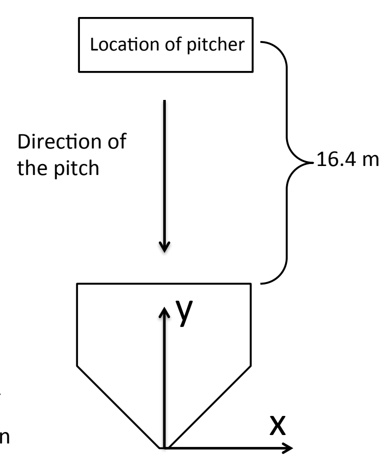




**Figure 2**: The origin of the coordinate system is at the back of home plate. All data is referenced with respect to this location (left). In a top-down view (right), we see that the pitch is thrown in the negative y-direction, travelling 16.4 m as moves toward the front of home plate.

**The Data Table**

We will be using data acquired by Major League Baseball (MLB) to analyze pitches thrown by Shelby Miller. A simplified version of the data is shown in Table 1.

| | input data from pitch f/x: the 9-parameter constant acceleration fit to the trajectory | | | | | | | | | Magnus force components | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pitch #-type | $x_0$ (m) | $y_0$ (m) | $z_0$ (m) | $v_{x0}$ (m/s) | $v_{y0}$ (m/s) | $v_{z0}$ (m/s) | $a_x$ (m/s$^2$) | $a_y$ (m/s$^2$) | $a_z$ (m/s$^2$) | $a_x$ (m/s$^2$) | $a_y$ (m/s$^2$) | $a_z$ (m/s$^2$) |
| 1 - FB | -0.32 | 16.8 | 1.87 | 0.40 | -40.9 | -1.88 | -1.52 | 7.82 | -3.82 | -1.50 | -0.37 | 5.42 |
| | | | | | | | | | | | | |
| 3 - CH | -0.41 | 16.8 | 1.85 | 2.34 | -38.1 | -2.31 | -3.46 | 6.12 | -5.97 | -3.18 | -0.45 | 3.18 |
| | | | | | | | | | | | | |
| 72 - CB | -0.30 | 16.8 | 1.80 | 0.58 | -35.9 | 0.05 | 2.27 | 6.55 | -12.0 | 2.47 | 0.30 | -2.70 |

**Table 1:** Data from three of Shelby Miller's pitches. Notice that most values contain three digits. It is unlikely that the values actually deserve to be presented with so many digits. In the original spreadsheet, some of the values had upwards of 10 digits! It is absolutely impossible that any values measured by Major League Baseball would be so precise.

This spreadsheet contains a lot of data, but don't get overwhelmed. Each row corresponds to a single pitch that Shelby Miller threw in this particular game. The first row is his first pitch of the game: a fastball (FB). The second row is his third pitch of the game: a change-up (CH). The final row is his 72nd pitch of the game: a curveball (CB).

The first nine columns give us information that can be used if we want to model the trajectory of the ball using our constant acceleration equations. The ball is modeled to follow a parabola, just like other projectiles that we have looked at, but this parabola will be tilted to some extent. The first trio of columns (blue) give us initial position data, the second trio of columns (purple) give us initial velocity data, and the third trio (green) give us the constant acceleration in each direction. The constant acceleration results from three [roughly] constant forces: gravity, drag, and the Magnus force. Each component of the net force on the baseball could be calculated by multiplying the green columns by the mass of the baseball.

The final three columns isolate information regarding the acceleration produced by the *Magnus force*. The Magnus force is the force that produces the curve of the curveball. Each component of the Magnus force can be calculated by multiplying these values by the mass of the baseball. You will learn more about the Magnus force later in this section and use those three columns to solidify your understanding.

**1A. Analyzing the Fastball**

With a handle on the coordinate system and the data table, we are ready to start analyzing a few pitches.

> **Read This:** Let's investigate the first pitch of the game. We are given the data for all three components of the initial velocity of the ball (the purple columns - the second trio) after it left Miller's hand.
>
> **Checkpoint 1.1:** Use the components of the ball's velocity to calculate the ball's initial speed.

**Read This:** As the ball travels, the drag force, gravitational force, and Magnus force (to be explained shortly) all significantly alter the various components of its velocity. By far the largest component of the ball's velocity is in the negative $y$-direction. Because drag forces increase with the velocity (or rather the square of the velocity), the largest component of the drag force will be in the $y$-direction. Let's see how much the drag force affects the pitch.

**Checkpoint 1.2:** Assuming constant acceleration in the $y$-direction, use the measured $y$-component of the acceleration (the second green column - the middle column in the third trio) to calculate the $y$-component of the ball's velocity as it crosses the front of home plate and the time that is required for the ball to reach home plate. (The ball begins at $y_i = 16.8\ \mathrm{m}$ and ends at $y_f = 0.432\ \mathrm{m}$.)

**Read This:** When a fastball leaves a pitcher's hand it has a lot of backspin. A baseball, like any spinning object moving through a fluid, experiences a force due to the Magnus Effect. The Magnus force acts in a direction that is perpendicular to both the direction of translation and the direction of rotation. More specifically, **the direction of the Magnus force is given by the direction of $\vec{\omega}\times\vec{v}$.** See Appendix B for a quick explanation of why the spinning ball feels a force.

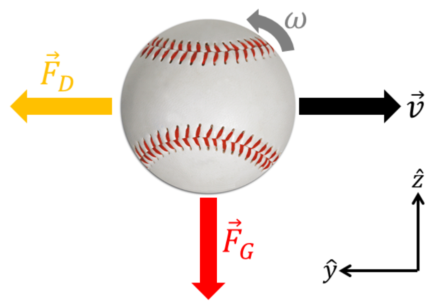



**Figure 3:** A spinning ball traveling at speed $v$ in the $-y$ direction (toward the plate) and spinning with angular speed $\omega$ in the $-x$ direction (out of the page, which corresponds to backspin). The Magnus force (not shown) is in the $\vec{\omega}\times\vec{v}$ direction.

**Checkpoint 1.3:** Knowing that a fastball has backspin (see Figure 3), *predict* whether the $z$-component of the Magnus force on Shelby Miller's first pitch was positive or negative.

**Checkpoint 1.4:** The fourth and final trio of columns (orange - rightmost trio) show the components of the acceleration of the ball due to the Magnus force. Discuss whether or not the prediction you made in Checkpoint 1.3 was accurate. If your prediction was incorrect, be sure to correct your misconception.

**1B. Analyzing the Changeup**

Shelby Miller has been quite successful early in his Major League career and this success isn't due entirely to his fastball. He has also been able to keep hitters off balance with his change-up. A change-up is a pitch designed to look like a fastball but travel slower, thus throwing off the hitter's timing. With this in mind, let's look at the first change-up Shelby threw, the third pitch of the game.

**Read This:** In Checkpoint 1.2 you calculated the amount of time that a batter has to react to a fastball. If a change-up is intended to be slower and keep the hitter off balance, we might ask how much longer the batter will need to wait for a change-up to arrive in the strike zone (also called the hitting zone). The increased amount of time it takes for a change-up to arrive compared to a fastball is usually quite small. However, when you consider that a typical Major

League hitter's bat is in the hitting zone for about 0.015 seconds, the timing difference between a fastball and change-up does not need to be very large to have a big effect.

**Checkpoint 1.5:** Calculate the time that a batter has to react to Shelby's change-up. That is, calculate the time it took for the change-up (the second row) to travel from Shelby Miller's hand to the front of home plate. (The ball begins at $y_i = 16.8 \text{ m}$ and ends at $y_f = 0.432 \text{ m}$.)

**Checkpoint 1.6:** Compare the times you found in Checkpoint 1.2 and Checkpoint 1.5. Does the difference look meaningful when compared to the time that a bat is in the hitting zone?

**1C. Analyzing the Curveball**

The final tool in Miller's arsenal is his curveball. A pitcher throws a curveball by putting a large spin on the ball, hoping to take advantage of the Magnus Effect. Shelby's curveball spins about an axis which is different than the axis about which his fastball spins. As such, the direction in which the Magnus force pushes a curveball will be different from the direction the Magnus force pushes a fastball.

**Do This:** Go to the In-Lab Links page on the lab website and watch the video of a curveball. This video shows a baseball spinning the same way that a curveball thrown by Shelby Miller would spin. This video is taken from the *pitcher's perspective.*

**Read This:** How can we calculate the distance that the curve ball actually curves? First, we must make the question a little more precise. Any pitch will follow a curved path due to the gravitational force and the drag force that act on the ball, so in a sense all pitches curve. When asking how much a curveball curves, we should be asking, "by what distance does the Magnus force change the final position of the ball." Recall that the final trio of columns (orange) isolate the acceleration that results from the Magnus force. The components of the Magnus force could be calculated by multiplying these columns by the mass of the baseball.

**S1**

**Synthesis Question 1 (30 Points):** Now that you have practice with the fastball and the change-up, analyze Shelby Miller's curveball to death. Data from one of Shelby Miller's curveballs is shown in the final row of the table. Your analysis should include…

- The time required for the curveball to reach the plate
- A meaningful comparison between the time required for a curveball and the time required for a fastball to reach the plate
- The direction that the curveball curves
- An explanation of why the curveball curves in that direction
- The distance that the ball curves. That is, the distance by which the Magnus force changes the final position of the ball.

# Part II: Physics at the Bat

**The Story**

Having the appropriate tool makes any job easier. This is especially true for a MLB hitter. Consider the cinematic classic *Major League*, where hard-hitting Pedro Cerrano loved his bats so much that he wrapped them with plush covers to keep them warm. Pedro loved his bats because they helped him hit fastballs very far. Unfortunately for Pedro, his bats struggled to hit curveballs. This led him to make sacrifices such as rum and cigars to his voodoo god, Jobu, in the hopes that Jobu might help him hit curveballs just as far as he hit fastballs. Maybe Pedro just needed to know a little physics.

**Equipment**

- Wooden bat
- Baseball hammer
- Measuring tape
- Masking tape
- Webcam

This part of the lab deals with the bat that hitters use to strike the baseball. Figure 4 shows the important parts of the baseball bat that we will refer to in this lab.


**Figure 4:** Major League hitters use bats made of wood from white ash trees. Hitters hold the bat by the handle, swinging the bat so that barrel makes contact with the baseball.

**Energy and the Baseball Bat**

The basic challenge of a baseball player who wants to hit a baseball a long way is to transfer as much energy to the ball as possible. With that in mind, we will look at two undesirable energy transfers that can take place during the ball-bat collision. In Section 2 we consider vibrations (waves) that can be created in the bat during the collision. In Section 3 we consider how rotational kinetic energy plays a role.

**2. Good Vibrations?**

When you pluck a guitar string, you create waves that travel along the string, through the air, and to your ear. These waves carry energy. A very similar process occurs when a baseball strikes a bat: the bat starts vibrating much like a guitar string. The waves that form on the bat carry energy, energy that does *not* end up in the ball. That means if you create energetic waves in the bat, the ball won't travel as far because there simply won't be as much energy transferred to the ball.

Is there any way to avoid losing energy to the vibration of the bat? The answer is yes! All the batter has to do is hit the ball on the "sweet spot" of the bat. The sweet spot is located at a *vibrational node*, a special point on the bat that stays put while the rest of the bat vibrates. When the ball hits the sweet spot, the bat does not vibrate strongly, leaving more energy available to be transferred to the ball. (As an added bonus, a batter's hands don't get stung when the ball strikes the sweet spot.)

In this section you will get to see, hear, and feel the waves that are created when the ball and bat collide. First, let's see them.

**Do This:** Find and watch the videos of vibrating bats on the In-Lab Links page of the lab website. There are three short slow-motion videos to watch.

**Read This:** Now that you should be convinced that waves can be created on the bat, it's time for you to locate the sweet spot of the bat by feeling (and maybe hearing) the presence or absence of waves on the bat.

**Do This:** Place a piece of masking tape along the length of bat, running from the knob to the end of the barrel. In upcoming steps, you will be making marks on this piece of tape, not on the bat itself.

**Do This:** One member of the lab group (Partner A) should hold the bat by the handle while the other member (Partner B) picks up the baseball hammer. When Partner B strikes the end of the *barrel* of the bat with the baseball hammer, Partner A should be able to feel the vibrations that are created in the bat.

**Do This:** In addition, when Partner B strikes the *handle* the bat, Partner A should be able to feel the ringing.

**Read This:** However, there is a point on the bat where Partner A will not feel these strong vibrations when Partner B strikes the bat.

**Do This:** Partner B should start tapping the bat with the baseball hammer at the end of the barrel of the bat. Partner A should feel strong vibrations. Partner B should continue tapping the bat with the hammer, slowly moving closer and closer to the handle in roughly 1-cm steps. At some point, Partner A should feel the vibrations disappear (or at least feel very different). When the vibrations disappear, Partner B is tapping on the sweet spot. Mark the sweet spot by writing on the masking tape (NOT on the bat itself).

**Do This:** Switch roles to get a second opinion regarding the location of the sweet spot.

**Checkpoint 2.1:** For each of the two locations that your group found, record the distance between the sweet spot and the knob end of the bat.

**Read This:** In addition to feeling the vibrations, you can hear the vibrations! Hang the bat using the s-hook suspended from the ceiling.

**Do This:** Place your ear near the bat and gently strike the bat with the baseball hammer. Please be careful not to whack the bat into your head! Can you hear the bat ring?

**Checkpoint 2.2:** Find the spot on the bat where, when struck with the hammer, the volume of the ringing is at a minimum. Record the location found by each group member.

S2

**Synthesis Question 2 (15 Points):** Create a diagram that shows the results of your little experiments to find the sweet spot of the bat. Include the average location as well.

**3. The Center of Percussion**

It turns out that the sweet spot is a very good place to hit the ball. The ball will go far *and* the batter's hands don't get hurt by the ringing of the bat. However, there's another spot on the bat that will actually cause the ball to travel a tiny bit farther. That point is known as the *center of percussion*.

Recall that there are two main ways that energy gets lost to the bat, making it impossible to transfer that energy to the ball. The first was vibration, which we looked at in the previous section. The second way is related to the rotational kinetic energy of the bat.

Consider a baseball bat that is floating in outer space. If a baseball (also in outer space!) were to strike the bat at the center of mass of the bat, the bat would not rotate. None of energy of the system would end up as rotational kinetic energy in the bat. Therefore, one might reasonably guess that in order to avoid losing energy to rotational kinetic energy of the bat, a baseball player would want to strike a ball at the center of mass of the bat. It turns out that this is NOT true.

The key difference between the bat in space and the bat being swung by a player is that the bat being swung by a player is already rotating. More precisely, a bat that is being swung is rotating about a vertical axis through the knob of the bat (to a good approximation). When the ball and bat collide, we want the bat to continue rotating about the axis through the knob. If the bat starts to rotate about any other axis, that rotation is associated with rotational kinetic energy that is essentially wasted. It carries energy that was not transferred to the ball.

So here's the question we should ask: Is there a point on the bat that the ball can strike such that the bat will continue rotating about the axis through the knob? The answer is yes! This is the point known as the *center of percussion* of the bat. So let's find it!

**Do This:** Hang the bat using the s-hook suspended from the ceiling.

**Checkpoint 3.1:** Strike the bat near the handle. As you strike the bat, pay special attention to the direction that the knob moves. Make note of it.

**Read This:** Now let's move to the other end and see what happens when a ball strikes the end of the barrel of the bat.

**Checkpoint 3.2:** Strike the bat very near the end of the barrel. Again pay special attention to the direction that the knob moves. Make note of it.

**Read This:** Your recent observations should have shown the knob of the bat moving opposite directions. That's because the bat started rotating when you hit it with the hammer. Further, the axis of rotation was not through the knob. If the axis of rotation *were* through the knob, you would see the handle remain stationary (at least initially) when the bat is struck by the hammer.

**Read This:** Striking the bat very near the end of the barrel will obviously cause the knob of the bat to move opposite the direction of the baseball hammer. As you strike the bat farther and farther from the end of the barrel, the direction of the motion of the knob becomes less obvious. Similarly, striking the bat very near the knob will cause the knob to move in the same direction as the baseball hammer. As you strike the bat farther and farther from the knob, the motion of the bat becomes less obvious.

**Read This:** Somewhere in the middle there is a "region of ambiguity" where the center of percussion lies. Once again, the center of percussion is the point where (initially) the knob does not move as the bat is struck by the hammer.

**Checkpoint 3.3:** Find the location of the center of percussion of the bat by observing the motion of the knob as you hit the bat with the baseball hammer. Watching slow motion video recorded with the webcam can help you identify the center of percussion more easily and accurately. (Appendix C gives instructions for making videos in Logger Pro.) It is perhaps easiest to try to identify the lowest location you can strike on the bat where the knob does **not** move opposite the direction of the baseball hammer. That is, working your way up from the barrel is easier than working your way down from the knob.

S3

**Synthesis Question 3 (15 Points):** Create a diagram that shows the center of percussion and the sweet spot of the bat. Are they in the same place or not? Further, indicate the region on the bat that you suspect will result in the best hits.

## 4. Center of Mass

In this section, you will compare the results of a model that you develop to the results of an experiment. Before you find the center of mass (CM) experimentally, we want you to come up with a good estimate. To do this you will use a "Spherical Cow" model in which the bat is made up of two cylinders connected end-to-end.

**Checkpoint 4.1:** Draw a picture of your "Spherical Cow" bat. Measure and label all dimensions necessary for calculating the CM of your model bat.

**Checkpoint 4.2:** Calculate the distance between the CM and the knob end of your model bat.

**Checkpoint 4.3:** Is the location you found in Checkpoint 4.2 plausible? For starters, is it on the correct half of the bat? If not, you should consider repeating the calculation.

**Read This:** You are now ready to assess the accuracy of your model by finding the CM experimentally.

**Checkpoint 4.4:** Devise and perform an experiment to locate the center of mass of the bat.

**Read This:** Let's consider how we can assess the success of your model.

**Checkpoint 4.5:** What is the distance between the center of mass of your model bat and the experimentally determined center of mass?

**Checkpoint 4.6:** A very weak model of the bat would be to treat it like a single cylinder. (We might call this a zeroth-order approximation.) Where would the center of mass of this bat be? What is the distance between this location and the experimental location of the center of mass?

**Checkpoint 4.7:** Compare your responses to Checkpoint 4.5 and Checkpoint 4.6. Did your two-cylinder model do better than the single-cylinder model? By what percentage?

**S4**

**Synthesis Question 4 (40 points):** Assess the success of your model bat in estimating the center of mass of the bat. Your response should contain the following:

- A diagram of your two-cylinder model including all important dimensions.
- A calculation of the center of mass of the model. (Show your work.)
- The procedure of an experiment to determine the center of mass of the real bat.
- The results of your experiment.
- A quantitative comparison between the results of your model and your experiment.
- Describe a way that you could improve your model. Then comment on whether or not you think the extra work would be worth the effort.

## *Time to Clean Up!*

Please clean up your station according to the Cleanup! Slideshow found on the lab website.

## *Appendix A - Baseball Glossary*

**Batter:** The offensive player trying to generate runs for his team.

**First base:** The first point of safety for a batter after leaving home plate. This is also the first of four stations he must reach in order to score a run.

**Home plate:** The location where batter stands while he is trying to hit the ball thrown by the pitcher. Also the point where a run is scored after a baserunner has advanced around the three bases.

**Inning:** One of nine periods that comprises a regulation baseball game.

**Out:** One of three subdivisions of an offensive team's half inning. After three outs are recorded the teams switch places with offense going to defense and vice versa.

**Outfield fence:** Fence bounding one side of the field of play. If a batted ball goes beyond this fence in the air, the batter has hit a Home Run.

**Pitcher:** The defensive player that throws the ball toward the batter.

**Pitching mound:** The mound (its highest point is 25.4 cm above ground level) a pitcher must stand on while delivering a pitch.

**Run:** The unit of scoring in a game of baseball.

**Strike:** One of three chances that a batter has to hit a pitched baseball into the field of play.

**Strike zone:** The area that horizontally spans from one side to the other of home plate and vertically spans from the batter's knees to his shoulders. If the pitched ball goes past the batter, through the strike zone, and is received by the catcher, it is deemed to be a strike.

## *Appendix B: The Origins of the Magnus Force*

The Magnus force arises in part because of the drag force. As we saw in the Pre-Lab to Free Fall, the drag force on an object increases as the speed of the object increases. Therefore, a baseball moving at 97 mph feels a larger drag force than a baseball moving at 83 mph.

Consider a 90-mph fastball spinning at 800 rpm, shown in Figure 5.

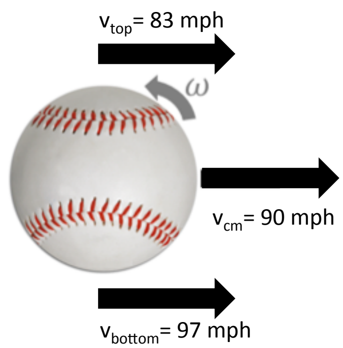



**Figure 5:** A fastball moving toward the plate at 90 mph spinning at 800 rpm. Since the bottom of the ball is moving faster through the air, it experiences a greater drag force than the top of the ball, resulting in an upward force called the Magnus force.

The center of mass of this fastball is moving to the right at 90 mph. However, due to its spin, the bottom of the ball is actually moving forward at 97 mph while the top of the ball is only moving forward at 83 mph. That means that the bottom of the ball feels a greater drag force than the top of the ball. This extra force on the bottom of the ball is the Magnus force.

The Magnus force on a curveball arises for the same reason. But since the curveball is spinning with a different axis, it will feel a push in a different direction.

# *Appendix C: Creating a Video with the Webcam*

Working with the equipment you are given, you might want to create a video that you can analyze in Logger Pro. To acquire such a video, follow these steps:

1. Plug your webcam into one of the USB ports on the back of your computer or in the keyboard.
2. In Logger Pro, under the *Insert* menu, select *Video Capture…*
3. A window titled *Video Capture* will pop up. You will likely see a video of yourself. The default webcam is the one that is built in to the computer. We would rather use the one you just plugged in to the USB port. Click the *Show Settings* button. A new window will pop out of the side of the *Video Capture* window (Figure 6).

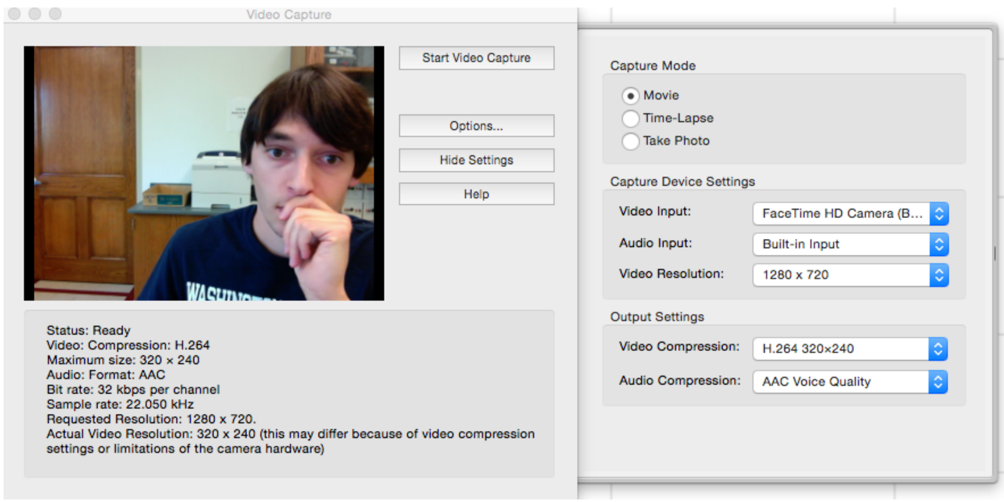



**Figure 6**: Click the *Show Settings* button to select the correct webcam and set the resolution.

4. Click on the "Video Input" drop-down menu and select "Live! Cam Chat HD".
5. Click on the "Video Resolution" drop-down menu and select 640 X 360.
6. Now you can click *Hide Settings*.
7. Make sure that everything is working as it should be. In the *Video Capture* window, click the *Start Video Capture* button. Wait a couple of seconds and click *Stop Video Capture*.
8. A new window should pop up. This is a more-or-less standard video player that will display your new video. The five buttons in the lower left corner of the window have the following functions (from left to right): play, stop, start the video over, go back one frame, go forward one frame. Play around with these buttons until you understand what they do. Then delete this video by clicking on it and pressing the rectangular *delete* key on the keyboard. (For whatever reason, the square *delete* key doesn't work!)
9. At this point you and the camera are ready to record a nice video. Pressing the *Start Video Capture* button in the *Video Capture* window will start the recording. When you are finished recording press the *Stop Video Capture* button.
10. You can track objects in the video just as you did with the Apollo 15 video. You can also track multiple objects in the same video by clicking the icon with the red and green circles and selecting *Add Point Series*.