The Physics of Baseball

Learning Goals

By the end of this lab, you should be able to...

- Analyze the flight of a pitched baseball.
- Correctly predict the direction of the Magnus force using a right-hand-rule.
- Find the center of mass of an object using multiple methods.

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, cross products, constant acceleration equations, energy, and center of mass. You will also be introduced to the Magnus force, standing waves, and the center of percussion. Search online if you are not familiar with the game and its rules. The links below will help understanding baseball.
https://en.wikipedia.org/wiki/Baseball

http://mlb.mlb.com/mlb/official_info/index.jsp

Let's discuss a couple of key players.

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 dominant 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.

There are some **optional** videos on the Optional Resources links on the lab module. Two of them demonstrate Randy Johnson's ability to humiliate and destroy. One of these videos demonstrates conservation of momentum at the expense of an unfortunate bird.

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.

The Spin

Surprisingly, the drag force not only affects the distance the ball can travel, but also *the path it follows*. This is the phenomenon connected with the Magnus force.

The Magnus force arises in part because of the drag force. You may have seen videos of dropping basketballs off tall platforms, but giving it backspin before it drops, and the ball sails forward. As we saw in the Free Fall lab, the drag force on an object increases as the speed of the object increases. For reasons you'll learn in lecture, when objects are rotating *and* translating in space, different parts of the object move at different velocities. This difference in speeds, and thus drag forces, is what leads to a net force that can influence the path of the ball.

The math involved in finding the magnitude of this force can be a bit rigorous and highly situational, so for our purposes we will only concern ourselves with the *direction* of the Magnus force. To do this, we need to know two new (but fairly simple) concepts.

First, we need to define the **cross product**. You should be familiar with the dot product at this point, but this product is different in that it *gives a brand new perpendicular vector* from the vectors you start with.

In the figure 1 to the right, you can see the vectors $\vec{A}$ and $\vec{B}$. The cross product $\vec{A} \times \vec{B}$ gives $\vec{C}$. **Note: the order matters here.** We can find the direction via the Right Hand Rule. If you take your right hand, place your thumb along $\vec{A}$(the first vector) and your index finger along $\vec{B}$(the second vector). If you point your middle finger--or palm, if you're feeling shy--along $\vec{C}$,

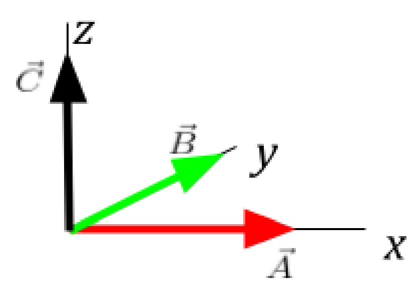


Fig 1: Vectors **A, B,** and **C** on the three-dimensional coordinate system.

you've successfully used the Right Hand Rule!

The shape your hand is in right now will be a great tool for one of the questions in this experiment as well as concepts to follow in lecture, this semester and next. As long as we know the directions of $\vec{A}$ and $\vec{B}$, place our thumb and index finger in the right directions (and right order)**, we'll know the direction of $\vec{C}$.**

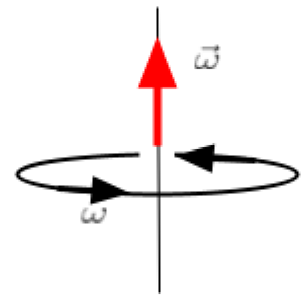


Fig 2: Apply right hand rule to find the direction of angular velocity, $\vec{\omega}$.

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 cross product of angular velocity and linear velocity ($\vec{\omega} \times \vec{v}$).**

What is the direction of $\vec{\omega}$? Similarly, we'll use our right hand! Look to the figure on the right. We see the rotational velocity ω of some object in a counterclockwise (ccw) direction about an axis, with the direction for $\vec{\omega}$ as upward along this axis. Curl your fingers around the axis in the same direction as ω. Then, stick your thumb straight out so it lines up with $\vec{\omega}$. *This* method will let you find the direction of $\vec{\omega}$ for rotating objects (such as a curveball)!

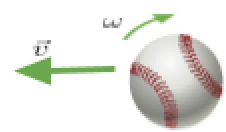


Fig 3: Practice right hand rule to find the direction of Magnus force.

Now, let's practice what you read above. What is the direction of the Magnus force on the baseball shown in figure 3?

Let's start with the 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, we will look at 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 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 on the ball, the pitcher makes use of the Magnus Effect (more on this later) to make the ball's trajectory curve in the direction he chooses.

Q1

Question 1: Analyze Shelby Miller's Fastball and Curveball. All necessary data are shown in the data table below.

Include in the worksheet:

1. Use a kinematic equation to find the time required for the *fastball* and the *curveball* to reach the plate. Show your work. A quadratic equation will have two solutions. Discuss which one is accepted for the actual problem.
2. Optional - If you are curious about the change-up ball time, you can calculate that, too, but not required.
3. Compare the difference in time between the fastball and curveball ($t_{FB} - t_{CB}$) to the typical amount of time a bat is in the hitting zone. Show your work. Is the time difference meaningful? Explain!
4. The direction that the *curveball* curves and a *detailed explanation* of your answer.
5. The distance the *curveball* moves (in each direction x y z, and the total) **due ONLY to the Magnus force** (how far the curveball "curves" as opposed to the same pitch if there were no Magnus force)
6. The magnitude of the Magnus Force.
7. A plausibility statement regarding the distance that the ball curves. (Hint: can the batter still hit the ball at this distance? If your value is not plausible, you should track down and correct your mistake.)

Useful Notes:

1. 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 below.

	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.

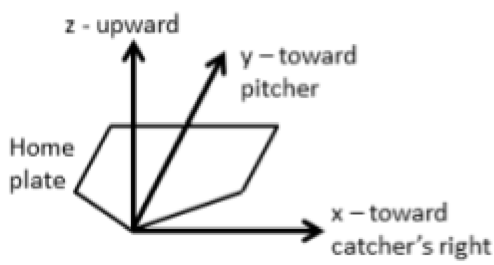
This spreadsheet contains a lot of data, but don't get overwhelmed. Each row corresponds to a single pitch that Shelby Miller threw in this particular game. The first row is his first pitch of the game: a fastball (FB). The second row is his third pitch of the game: a changeup (CH). The final row is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

2. Defining the Coordinate System

Understanding the coordinate system that we will use is absolutely key. Figure 4 defines the coordinate system that we will use in this lab.



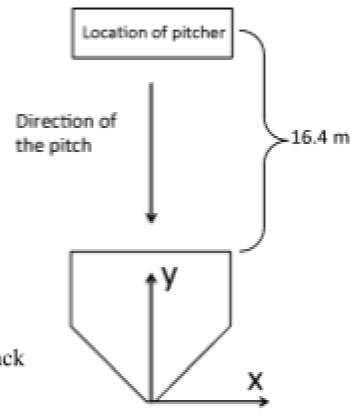


Figure 4: The origin of the coordinate system is at the back of home plate. All data is referenced with respect to this location (left). In a top-down view (right), we see that the pitch is thrown in the negative y-direction, travelling 16.4 m as moves toward the front of home plate.

3. Hints on performing the calculations

Refer to the data table and pay attention to the coordinate system. In addition, recall some of the kinematic equations used to calculate velocity and displacement.

What to do:

a. Fastball

- Calculate the ball time from the pitcher to home plate for this ball. This can be done by using the velocity.

  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.
- The time may also be calculated using the displacement equation.
- The ball begins at $y_i = 16.8\ m$ and ends at $y_f = 0.432\ m$.

b. Curveball

- Calculate the ball time from the pitcher to home plate for this ball.
- The ball begins at $y_i = 16.8\ m$ and ends at $y_f = 0.432\ m$.

- Compare this time with the fastball time.
- Does the difference look meaningful when compared to the time that a bat is in the hitting zone? Remember that a typical Major League hitter's *bat is in the hitting zone for about 0.015 seconds,*
- Calculate the total displacement of the curveball due to Magnus Force.
- Find the direction that the curveball curves. Explain **in detail** how you found the direction. The video of the curveball in the Canvas page and the diagram in Appendix B, Figure 7, are the best references to answer this question. The 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 and is moving away from the viewer.*
- Find the magnitude of the Magnus Force

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.

2. Sweet Spot

Q2

Question 2: Find the sweet spot of the bat.

Include in the Lab Work/Lab Participation document:

1. Diagram of the bat with the measurements marks.
2. Trial measurements and the average.
3. The position of the sweet spot.

Useful Notes:

Equipment

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

Figure 5 shows the important parts of the baseball bat that we will refer to in this lab.

Figure 5: 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.

Application of Physics Knowledge

a. 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 by considering vibrations (waves) that can be created in the bat during the collision and how rotational kinetic energy plays a role.

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.

What to do?

Seeing the vibrations:

- Find and watch the videos of vibrating bats on the In-Lab section of the lab module. There are three short slow-motion videos to watch.

Feeling the vibrations:

- 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.
- Place a piece of masking tape along the length of the 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**.
- Measure and record the length of the bat.
- 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.
- In addition, when Partner B strikes the *handle* of the bat, Partner A should be able to feel the ringing.
- However, there is a point on the bat where Partner A will not feel these strong vibrations when Partner B strikes the bat.
- 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).
- Switch roles to get a second opinion regarding the location of the sweet spot.
- For each of the two locations that your group found, record the distance between the sweet spot and the knob end of the bat.

Hearing the vibrations:

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

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*.

Q3

Question 3: Find the center of percussion of the bat.

Include in the Lab Work/Lab Participation document:

1. Diagram of the bat with the measurements marks.
2. Trial measurements and the average.
3. The position of the center of percussion AND the sweet spot.
4. Best region to hit the bat and explanation of WHY you consider it the best region.

Useful Notes:

Equipment

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

Application of Physics Knowledge

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 the 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.

What to do?

- Hang the bat using the s-hook suspended from the ceiling.
- Strike the bat near the handle. As you strike the bat, pay special attention to the direction that the knob moves as the bat begins to wobble. Make note of it.
- Now let's move to the other end and see what happens when a ball strikes the end of the barrel of the bat.
- Strike the bat very near the end of the barrel. Again, pay special attention to the direction that the knob moves as the bat begins to wobble. Make note of it.

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.

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.

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.

- 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 a smartphone can help you identify the center of percussion more easily and accurately. 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.

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 create and analyze some simple models of the bat using cylinders.

Q4

Question 4: Find the center of mass of the bat and assess the success of your model bat. Your response should contain the following:

Include in the Lab Work/Lab Participation document:

1. A diagram of your models (one-cylinder and two-cylinder) *including all the important dimensions.*
2. Calculations of CoM for both models.
3. The procedure of an experiment to determine the center of mass of the real bat.
4. The result of your experiment.
5. A quantitative comparison (simple difference) of the location of the center of mass *of your models* and your *experimental on*e and a reflection on the comparison.
6. Describe a way that you could improve your model.

Useful Notes

Equipment – bat and drawing tools

Model hints:

- The simplest model of a bat would be a single cylinder. Where is the center of mass of this model? Is the model's prediction likely to be accurate?
- Because of the tapering shape of the bat, one cylinder just isn't going to cut it as a reasonable model. Let's try two cylinders; a little more complicated but still simple enough!
- Draw a picture of your two-cylinder bat. Measure and label all dimensions necessary for calculating the CM of your model bat. Make sure you select a reasonable length for the cylinders. Assuming that the density of the bat is constant, the mass of different parts of the bat (which can't be measured) may be expressed in terms of density and volume.
- Calculate the distance between the CM and the knob end of your model bat. You can organize the data in the Center-of-Mass Calculation template in the lab module.

- You are now ready to assess the accuracy of your model by finding the CM experimentally.
- Devise and perform an experiment to locate the center of mass of the bat.
- Let's consider how we can assess the success of your model.
- What is the distance of the center of mass of your model bat from the experimentally determined center of mass?
- Did your two-cylinder model do better than the single-cylinder model? How much better?

Center of Mass Equation:

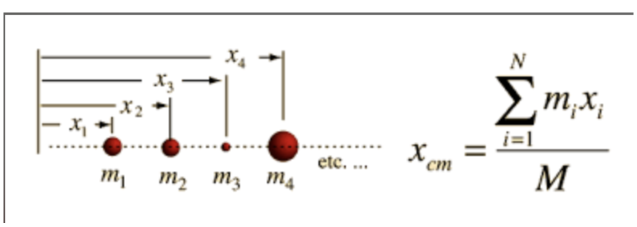
$x_{CoM} = \frac{x_1 m_1 + x_2 m_2 + x_3 + \ldots + x_n m_n.}{m_1 + m_2 + m_3 + \ldots + m_n}$ The system is made up of *n* objects.

x_{CoM} - the distance of the center of mass of the system from a reference point where x=0

$x_1, x_2,\ x_3,\ x_n$ - the distance of the center of mass of each object from the same reference point where x = 0

$m_1, m_2,\ m_3,\ m_n$ - masses of each object of the system. The mass may be expressed as a product of the volume and the density of the object.

Here is another way (see the diagram below) of understanding the Center of Mass of an object made up of some masses (*i* masses in this case). The distance of the Center of Mass of each point/mass is measured from the same point of reference.



Time to Clean Up!

Please clean up your station according to the Cleanup! Slideshow found in the lab module.

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 the 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 introduction, 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 6.

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.

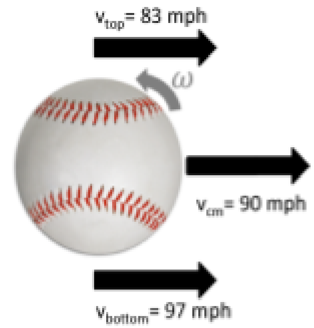


Figure 6: A fastball moving toward the plate at 90 mph spinning at 800 rpm. Since the bottom of the ball is moving faster through the air, it experiences a greater drag force than the top of the ball, resulting in an upward force called the Magnus force.

The 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.

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 $\vec{\omega} \times \vec{v}$.**

Refer to Figure 7 to find the direction of the Magnus force for a fast ball. Is the z-component of that force in the positive or negative direction?

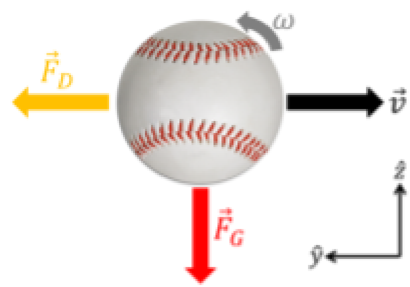


Figure 7: A spinning ball traveling at speed in the direction (toward the plate) and spinning with angular speed in the direction (out of the page, which corresponds to backspin). The Magnus force (not shown) is in the direction.