Invisible Collisions

Overview: This activity relates an elastic collision to the change in a satellite's or spacecraft's speed and direction resulting from a planetary fly-by, often called a "gravity assist" maneuver. Both hands-on and online interactive methods are used to explore these topics.

Target Grade Level: 9-12

Estimated Duration: 2 40-minute sessions

Learning Goals: Students will be able to…

- describe the speed of a ball after it collides elastically with a large object. In particular, compare cases in which the large object is stationary, is moving toward the ball, or is moving away from the ball.
- describe a spacecraft's change of speed and direction as it passes near a planet ("planetary flyby") in terms of an elastic collision with the planet.
- describe the relationship between the distance of a spacecraft's closest approach to a planet and the resulting change in a spacecraft's speed and direction using an online model.

Standards Addressed:

Benchmarks (AAAS, 1993)

The Nature of Science, 1A: The Scientific World View
The Physical Setting, 4G: The Universe

National Science Education Standards (NRC, 1996)

Unifying Concepts and Processes: Evidence, models, and explanation
Physical Science: Motions and forces

Principles and Standards for School Mathematics (NCTM, 2000)

Representation
Algebra

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Background:

We are all familiar with the term "collision" as used in our everyday lives. If you are unlucky enough to be riding in a car that hits something—another car, or perhaps a telephone pole—then you have been in an automobile **collision**. In physics, though, this word is used to describe any situation in which two objects traveling through space meet, interact briefly, and then continue on their way. Typically, their motions after the collision are different from their motions beforehand: they have speeded up, slowed down, or their directions of travel have changed.

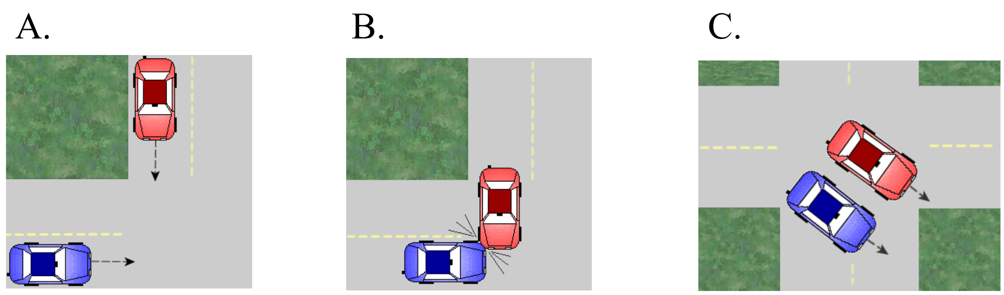


Figure 1. A. Two cars approach an intersection. B. The two cars collide. C. The two cars change both speed and direction as a result of the collision.

Such collisions are all around us. A bat and ball **collide** to produce a hit; the batted ball is traveling in a different direction, and usually at a different speed, than when it was pitched.

Collisions and Kinetic Energy

If two objects collide, what is known about how their motions change? For example, if we know their speeds and directions before the collision, what can we say about their motions afterward? Answering this question depends on many details of the situation, but the matter is greatly simplified if we know—as is the case in a spacecraft flyby—that *kinetic energy is conserved*.

$$K = \tfrac{1}{2}\, m\, v^2$$

Figure 2. Kinetic energy K is proportional to the product of an object's mass m and the square of its speed v.

Kinetic energy is the energy of an object that depends on its speed, as shown above; the greater the speed of an object, the larger the kinetic energy. When two objects collide, we can compare their total kinetic energy (the sum of their individual kinetic energies) before the collision, with their total kinetic energy after the collision. Saying that *kinetic energy is conserved* simply means that these two totals are the same. A collision of this kind is called **elastic,** and in practice this means that no energy is "lost" in processes such as deforming the objects—bent fenders, for example, or skidding tires.

To build our understanding about elastic collisions, let's consider two objects that are moving along the same line, and collide elastically. Imagine that one object overtakes the other so that they strike one another and bounce apart. Then the object that was overtaken speeds up, while the object that was overtaking (i.e., initially faster) slows down or possibly even reverses direction. The amount of slowing down or speeding up depends on the relative masses of the two objects; if one is much more massive than the other, then its motion scarcely experiences any change at all. And if the objects are moving in opposite directions before they collide, and one is more massive then the other, then the lighter object reverses direction as the result of the collision. Such scenarios—with one mass very much larger than the other—are illustrated in Velocities and Collisions part of the Gravity Assist Simulator interactive (http://www.messenger-education.org/students/animations.php).

Connection to the Gravity Assist Maneuvers

How does this help us to understand a spacecraft's *gravity assist maneuver*, such as what took place in July 2007 when the New Horizons spacecraft passed near Jupiter on its way toward Pluto? Although the spacecraft did not hit Jupiter's surface, it passed close enough to feel Jupiter's gravitational pull very strongly. We can say, therefore, that it "collided with" Jupiter even though it did not touch the planet.

This collision had no measurable effect on the motion of Jupiter, since the planet is enormously more massive than the spacecraft. But it had a profound effect on the spacecraft's motion. Jupiter moves rapidly in its orbit about the Sun, at about 13.1 km/s. The spacecraft's motion was at an angle to the planet's orbit—that is, partly perpendicular to the orbit, causing it to move away from the Sun, and partly parallel, moving in the same direction as Jupiter. The velocity associated with this second (parallel) part of the motion was initially smaller than 13.1 km/s. So the spacecraft was overtaken by Jupiter, and was "pulled forward" as it passed behind the planet. As a result, the spacecraft was speeded up by the encounter.

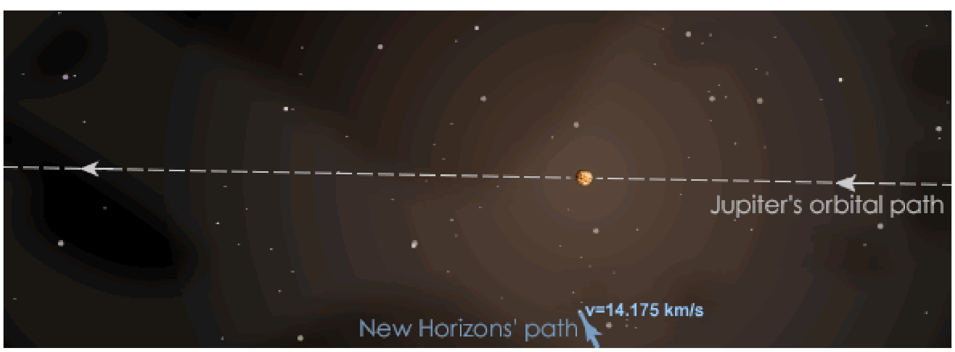


Figure 2. As you can see in this rough simulation, the New Horizons spacecraft's motion is at an angle to Jupiter's orbit as it approaches the July, 2007 flyby. Notice the speed of the spacecraft is about 14 km/s.

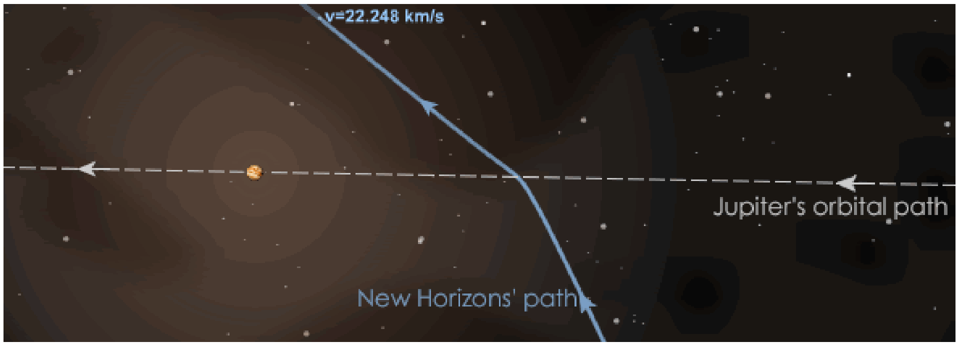


Figure 3. As the New Horizons spacecraft flew past Jupiter, which is traveling from right to left in this image, the spacecraft was pulled toward Jupiter by the planet's gravity. You can see that the path and the speed of the spacecraft were changed by the encounter.

This effect can also be observed in the Gravity Assist Simulator interactive that is a part of this lesson: http://www.messenger-education.org/students/animations.php. Note that in the "Jupiter flyby," both the direction and the speed of the spacecraft are changed in the encounter. Remember that the gravitational attraction between spacecraft and planet is larger the closer the two come to each other. So it should not be surprising that the biggest effect on speed and direction of the spacecraft is observed in the option with the closest distance of approach.

In addition to boosting a spacecraft's speed and helping it reach the outer planets, flybys can be used to modify a spacecraft's trajectory in other ways. For example, the animation includes a "Venus flyby," in which a spacecraft passes in front of a moving planet and is slowed down by the encounter. The MESSENGER spacecraft is currently en route to the planet Mercury, using a complex sequence of flybys involving Earth (once), Venus (twice) and Mercury (three times). Each flyby is carefully configured so that after a journey of six and a half years the MESSENGER spacecraft will be positioned to enter a nearly polar orbit about the innermost planet, using a minimum amount of fuel in the process.

Materials:

- small, dense rubber balls (e.g., superballs) (1 for each group)
- desks or tables (1 area for each group)
- pieces of wood at least the size of a book or other handy very hard objects (NOTE: this object should not have an absorbent/soft layer like a ping pong paddle has) (1 for each group)
- meter sticks (1 per group)
- copies of **Collisions** group data sheet (1 per group)
- copies of **Gravity Assist Simulator** data sheet (1 per person or per group)
- computers with access to the internet for either in-class or homework assignment
- safety goggles (1 pair per student)

Procedure:

Brief overview…

What the teacher will do: The teacher will demonstrate an elastic collisions for the class, then walk around to answer questions while the students are doing the **Collisions** activity in small groups. Then the teacher will distribute the **Gravity Assist Simulator** data sheet for students to complete as they view the online **Gravity Assist Simulator** in class or as homework.

What the students will do: The students will explore different elastic collision scenarios in a hands-on activity followed by an online interactive activity. For the hands-on **Collisions** activity they will drop a ball ("small object") onto a table surface or piece of wood ("large object"). First the large object is held stationary while the ball collides with it. Then it is moving for two different scenarios. Students record their observations of these different elastic collisions in the **Collisions** student data sheet. Then they explore similar collisions and scenarios using an online interactive. While exploring the interactive they record their observations and answer questions using the **Gravity Assist Simulator** data sheet.

Advance Preparation

1. Make copies and gather materials as indicated in the materials section.
2. Arrange for computer time if needed (see 4 under "In-class Procedure").

In-class Procedure

1. Briefly explain to the class that they will be exploring collisions. Arrange the class with the help of the students to facilitate the hands-on elastic collision exploration. You may need to move some desks aside so each group can gather around one desk or table and drop a ball near the edge of that surface. See the **Collisions** group data sheet for more details on how the students set up their hands-on collision exploration. Be sure to emphasize classroom safety rules and use safety goggles with the classroom activity.

2. Assign students to groups of about 3 or 4 students. Provide each group with the following:

   A. 1 copy of the **Collisions** group data sheet

B. the piece of wood/paddle/other large object
C. a small rubber ball (e.g., a superball)
D. a meter stick

3. Students should follow the instructions on the **Collisions** group data sheet by exploring the three elastic collision scenarios (1. ball collides with a stationary large object, 2. ball and large object are moving in opposite directions, 3. ball and large object are moving in the same direction and ball overtakes large object). They should answer the questions on the student data sheet as they proceed through the exploratory. You may wish to demonstrate the first scenario in front of the class, or walk the students through the first trial.

4. Either provide in-class computer time or assign as homework the **Gravity Assist Simulator** student data sheet, in which students answer questions related to the online gravity assist interactive. Note: if providing in-class computer time you may want to assign students to groups of two. ****This data sheet can be used for assessment.****

   URL for the Gravity Assist Simulator interactive: http://www.messenger-education.org/students/animations.php

Extensions and Adaptations:

- For seeing impaired students, ask one of their team members to describe the set-up and changes in speed for all of the scenarios in the hands-on activity. We have included "long descriptions" in the online interactive. Access them by clicking on the "Learn More" tab in the upper right corner of each scenario, and then selecting "D-Link."

References:

From the New Horizons website:

http://pluto.jhuapl.edu/common/content/pdfs/011607_JupiterPressKit.pdf (specifically see pages 2 and 9)

From the MESSENGER website:

http://messenger.jhuapl.edu/the_mission/gravity.html

An advanced explanation:

http://www2.jpl.nasa.gov/basics/grav/primer.html

A basic explanation:

http://science.howstuffworks.com/question102.htm

Standards:

National Science Education Standards (NRC, 1996)

Content Standards: 9-12

Unifying Concepts and Processes, CONTENT STANDARD:

- Evidence, models, and explanation

Physical Science, CONTENT STANDARD:

- Motions and forces

Benchmarks (AAAS, 1993)

Chapter 1. The Nature of Science

1A: The Scientific World View

Grades 9 through 12

- Scientists assume that the universe is a vast single system in which the basic rules are the same everywhere. The rules may range from very simple to extremely complex, but scientists operate on the belief that the rules can be discovered by careful, systematic study.

Chapter 4. The Physical Setting

4G: The Universe

Grades 9 through 12

- Gravitational force is an attraction between masses. The strength of the force is proportional to the masses and weakens rapidly with increasing distance between them.

Principles and Standards for School Mathematics (NCTM, 2000)

Representation

Grades K through 12

- Use representations to model and interpret physical, social, and mathematical phenomena
- Create and use representations to organize, record, and communicate mathematical ideas

Algebra

Grades 9 through 12

- Analyze change in various contexts:
    - approximate and interpret rates of change from graphical and numerical data

Collisions Student Data Sheet

group members:

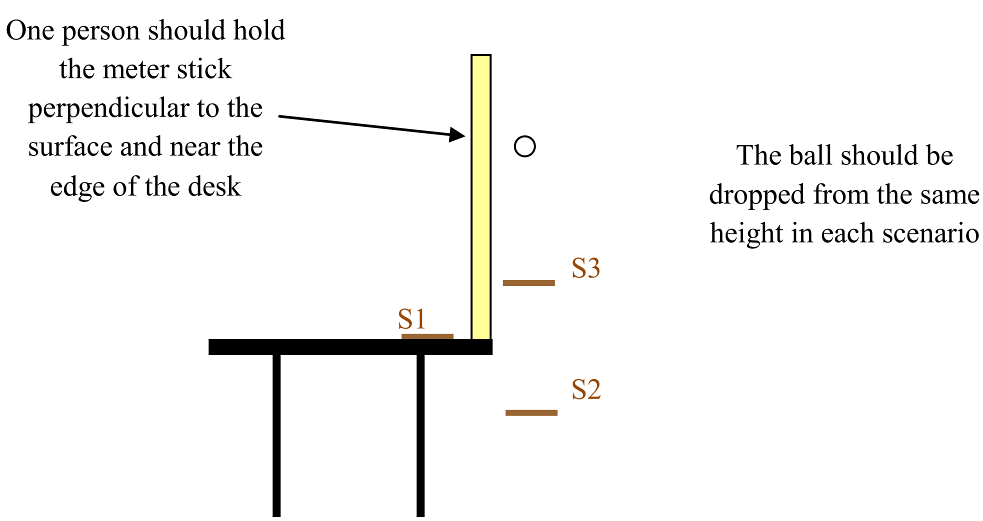
Recall, in an elastic collision the total kinetic energy is the same before the collision as it is afterward. No energy is used to deform the objects permanently in the collision (such as car fenders are bent during an automobile collision). If the total kinetic energy remains the same, can the speed of the objects in the collision change? In the following activity we will explore elastic collisions involving a small object (e.g., a super ball) and a large object (e.g., a piece of wood). Pay close attention to the speeds during the three scenarios below.

Instructions:

1. For each of the following scenarios you will be dropping a ball from the same height, 50 cm. In two of them you will also be moving a large object (e.g., a piece of wood) in some direction while the ball is moving. The meter stick should be placed with 0 m on the surface of the table.

2. Read the instructions for the ball, the meter stick, and the large object before attempting each scenario. Try each scenario a few times and then record your results below.

3. This diagram should help you set up for the activity (note: S1 is for Scenario 1, S2 is for Scenario 2, etc.):



Scenario 1: Here you will investigate what happens when the ball collides with a larger object that is not moving.

The large object: place the large object or piece of wood (labeled with S1 in above diagram) on the surface of the desk and parallel with the surface ("flat").

The meter stick: place the meter stick on top of the large object for this scenario and perpendicular to the surface as in the diagram above.

The ball: drop the ball from 50 cm onto the large object.

Before you begin, predict how you think the interaction between the ball and the large object will change the speed and the bounce height of the ball:

Now perform the activity. Observe how high the ball bounces after colliding with the large object. Try to observe the speed of the ball as it approaches the large object (initial speed), and then immediately after it has hit the large object and is traveling in the opposite direction (final speed). Repeat this several times.

A. How does the height from which it was dropped compare with the height to which it bounced?

B. How does the initial speed of the ball compare with the final speed (smaller than, larger than, or the same as)?

<u>**Scenario 2**</u>: In this scenario you will investigate what happens when the ball and the larger object are moving in opposite directions (i.e., toward one another).

The large object: begin with the large object parallel with the surface of the desk, but off to the side and **below** the desk surface by about 10 cm. (Position "S2" in the diagram above). You will move this object **up** just as the ball approaches so that they collide at about the same height as the bottom of the meter stick (or edge of the desk).

The meter stick: place the meter stick on and perpendicular to the surface of the desk, as in the diagram above. It should be near the edge of the desk closest to the large object.

The ball: Drop the ball from 50 cm onto the surface of the large object, which will be moving toward it.

This time you will drop the ball toward the large object, however the large object will move toward the ball as it approaches.

Before you begin, predict how you think the interaction between the ball and the large object will change the speed and the bounce height of the ball:

Now perform the activity. Again observe the initial speed of the ball as it approaches the large object and the final speed and height after the object and ball have collided. Try this several times and then record your observations:

C. How does the height from which it was dropped compare with the height to which it bounced?

D. How does the initial speed of the ball compare with the final speed of the ball (smaller than, larger than, or the same as)?

<u>Scenario 3</u>: In this scenario you will investigate what happens when the ball overtakes the large object because the ball and the large object are moving in the same direction and the ball is moving faster than the large object.

> **The large object**: begin with the large object above parallel to the surface of the desk, but off to the side and about 10 cm **above** the surface of the desk (position "S3" in the diagram). You will move this object **down** just as the ball approaches so that they collide at about the same height as the bottom of the meter stick (or edge of the desk).
>
> **The meter stick**: place the meter stick on and perpendicular to the surface of the desk, as in the diagram above. It should be near the edge of the desk closest to the large object.
>
> **The ball**: Drop the ball from 50 cm onto the surface of the large object, which will be moving away from it.

Again the large object will be moving, but this time it will be moving away from the ball as it approaches. Note that to achieve this, the large object must be moving slower than the ball.

Before you begin, predict how you think the interaction between the ball and the large object will change the speed and the bounce height of the ball:

Now perform the activity. Observe the initial speed of the ball as it approaches the large object and the final speed and height after the object and ball have collided.

E. How does the height from which it was dropped compare with the height to which it bounced?

F. How does the initial speed of the ball compare with the final speed of the ball (smaller than, larger than, or the same as)?

In **scenario 1** the large object remained stationary during the collision, whereas in the other two scenarios the large object was moving either toward or away from the ball at the point of impact.

G. How did the relationship between the initial and final speeds change in these three scenarios?

Let's compare just **Scenario 2** and **Scenario 3**. (Recall in Scenario 2 the ball and the large object are moving toward each other; the large object began beneath the table surface and was pushed up to collide with the ball. In Scenario 3 the ball and the large object are moving in the same direction; the large object began above the table surface and was moving down as it and the ball collided.)

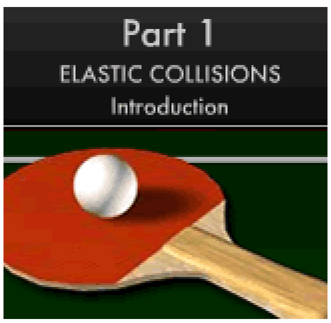
H. How did the final speeds of the ball in these two scenarios compare and **why**?

name:

Directions: Navigate to the Gravity Assist Simulator,

http://www.messenger-education.org/students/animations.php

To navigate within this Simulator, do not use the "back" browser button. Instead, use the navigation within the Simulator, such as "Main Menu" button in the upper left corner or navigations options provided to the left and right of the "Start" button in the middle of the screen.



Directions: After selecting Part 1, you will see four possible scenarios across the bottom of the screen. These scenarios are similar to those from the in-class exploration you completed. Go through all of the scenarios and answer the questions below. Notice that you will be answering some questions BEFORE observing each of the scenarios.

1. BEFORE observing the scenario, predict how you think the motion of the object will change and how the final speed will compare with the initial speed. Record your answer here:

2. AFTER observing the scenario, how did the motion of the object change and how did the final speed compare with the initial speed? Was this what you had predicted?

Note: to proceed to the next scenario click on the "scenario menu" button to the left of the "replay" button in the middle of the screen

3. BEFORE observing the scenario, predict how you think the motion of the object will change and how the final speed will compare with the initial speed. Record your answer here:

4. AFTER observing the scenario, how did the motion of the object change and how did the final speed compare with the initial speed? Was this what you had predicted?

*Again, use the “scenario menu” button

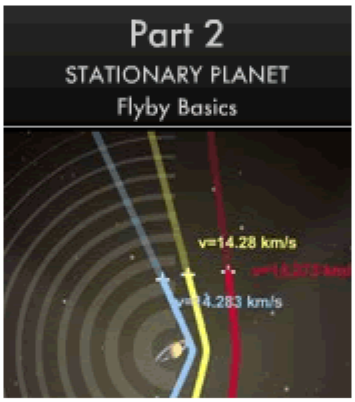
5. BEFORE observing the scenario, predict how you think the motion of the object will change and how the final speed will compare with the initial speed. Record your answer here:

6. AFTER observing the scenario, how did the motion of the object change and how did the final speed compare with the initial speed? Was this what you had predicted?

7. BEFORE observing the scenario, predict how you think the motion of the object will change and how the final speed will compare with the initial speed. Record your answer here:

8. AFTER observing the scenario, how did the motion of the object change and how did the final speed compare with the initial speed? Was this what you had predicted?

9. You did not try a scenario like this one in the hands-on portion of the activity. If you had, you would have placed the large object ABOVE the ball (e.g. at about 60 cm). Then, just as the ball was released, the large object would begin to follow the ball as it dropped. The large object would be moving FASTER than the ball, so it would catch up with the ball and they would collide. If you had performed this scenario, do you think the ball would speed up or slow down as a result of the collision?

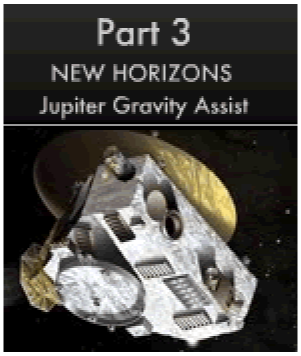


Directions: After returning to the Main Menu (upper left corner) and selecting Part 2, you will see three flyby distances. In this interactive the planet remains stationary as the spacecraft flies past from these three different distances. Observe all three and then answer the questions below.

1. After observing all three scenarios, how does the path or trajectory of the spacecraft differ in the three different trajectories?

2. What force is acting on the spacecraft to change its motion?

3. In which trajectory (i.e. distance from the planet) is the force greatest? How do you know?



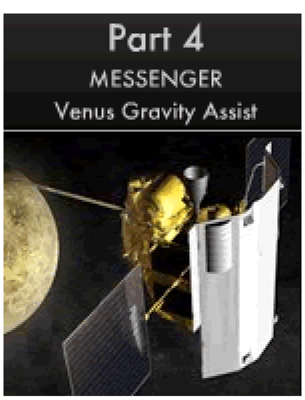
If New Horizons is the fastest spacecraft ever launched, why does it need a boost or "gravity assist" from Jupiter? Pluto is so far away that without the gravity assist from Jupiter, the New Horizons spacecraft wouldn't reach the Pluto system until 2018 at the earliest. Instead, Jupiter's gravity accelerated the spacecraft by an additional 4 kilometers per second (9,000 miles per hour) to pass through the Pluto system in July 2015. Not only does this save precious time, but it requires less fuel, which is both heavy and costly.

Directions: After returning to the Main Menu (upper left corner) and selecting Part 3, you can see what would happen if the New Horizons spacecraft could fly past Jupiter at three different distances. You can choose one distance at a time or all three together. Select "replay" to choose another distance.

1. Which trajectory changed the speed of the spacecraft the most?

2. Let's relate this to the scenarios you observed in Part 1 with the ping-pong ball, previously. Do you conclude this is most like **scenario 3** (small object overtakes larger object) or like **scenario 4** (larger object overtakes small object)? (Note: go back to the "main menu" and select "Part 1" to refresh your memory!)

3. Select the link at the bottom of the page and see the real New Horizons trajectory from Earth to Pluto, with a gravity assist from Jupiter along the way!



In the previous animation (Part 3) you could see that the spacecraft passed just behind Jupiter in its orbit. What would happen if the spacecraft were to pass just in front of the planet?

Directions: After returning to the Main Menu and selecting Part 4, you can see what would happen if a spacecraft were to pass in front of the planet Venus, for example. Again there are three distances that you can watch independently or together. Use "replay" to choose a different distance.

1. In this animation, did the spacecraft speed up or slow down as a result of passing Venus?

2. Why do you think the speed of the spacecraft changed in this way?

3. Let's relate this to the scenarios you observed in Part 1 with the ping pong ball, previously. Do you conclude this is most like **scenario 3** (small object overtakes larger object) or like **scenario 4** (larger object overtakes small object)?

4. The MESSENGER spacecraft is currently en route to the planet Mercury, using a complex sequence of flybys involving Earth (once), Venus (twice) and Mercury (three times). Each flyby is carefully configured so that after a journey of six and a half years the MESSENGER spacecraft will be positioned to enter a nearly polar orbit about the innermost planet.

   Again, select the link at the bottom of the page to see the very complicated trajectory that the MESSENGER spacecraft had to take to enter into orbit around the planet Mercury!

Answer Key for Teachers

Collisions Student Data Sheet:

Scenario 1

A. The ball should appear to have the same or similar initial and final speeds.

B. The ball should bounce to about the height from which it was dropped (about 50 cm).

Scenario 2

C. The ball should be moving faster after the collision; the final speed should be greater than the initial speed.

D. The ball should bounce to a height greater than 50 cm; bounce height greater than dropped height.

Scenario 3

E. The ball should be moving slower after the collision; the final speed should be less than the initial speed.

F. The ball should not bounce as high as 50 cm; bounce height is less than the dropped height.

Comparisons

G. Scenario 1: the initial and final speeds were about the same

Scenario 2: final speed greater than initial speed

Scenario 3: initial speed greater than final speed

H. In scenario 2 the final is greater than the initial because the large object is moving toward the ball when they collide so it pushes the ball (like a ball and a bat). In scenario 3 the large object is moving away from the ball when they collide, so it causes the ball to slow down (like when a catcher pulls the mit back when catching a baseball).

Gravity Assist Simulator

Part 1

1. their predictions will vary; hopefully initial and final speeds will be the same
2. initial and final speeds were the same.

3. prediction: final speed should be greater
4. observe: final speed is greater than the initial speed
5. prediction: initial speed is greater than final speed
6. observe: initial speed is greater than final speed
7. predict: final speed is greater than initial speed
8. observe: final speed is greater than initial speed
9. the ball would speed up as a result of this type of collision.

Part 2

1. the closer the spacecraft is to the planet the more it bends as a result of the flyby
2. The gravitational force from the planet is acting on the spacecraft to change its motion.
3. The gravitational force is greatest closest to the planet, so in the '1 million km' trajectory the force is the greatest. We know this because the speed increases the most in this trajectory and the path is changed the most.

Part 3

1. In the closest trajectory (1 million km) the speed of the spacecraft changed the most.
2. It is most like scenario 4 (larger object overtakes small object) because the spacecraft (small object) speeds up as a result of the encounter. If you think of the motion of the spacecraft in terms of vectors, the large object (Jupiter) is moving faster than the spacecraft in the "left to right" or horizontal component of the vector.

Part 4

1. The spacecraft slowed down as a result of the encounter with Venus.
2. Since the spacecraft passed right in front of the planet, the gravitational force from the planet pulled the planet toward it, thereby slowing the spacecraft down.
3. This is most like scenario 3 (small object overtakes large object). The small object or spacecraft is traveling faster than the planet and passes right in front of it. The larger object (planet) then slows the spacecraft down.