Give Me a Boost

How Gravity Assists Aid Space Exploration

Lesson Overview

Lesson Summary

This lesson examines how scientists can send a spacecraft to study other planets within economical and technological constraints. When a spacecraft is sent to explore other planets, the mission design team wants to minimize the amount of propellant carried aboard the spacecraft to make trajectory adjustments, because the more the spacecraft weighs, the more expensive it is to lift from the surface of the Earth into space. Many missions today use gravitational interaction with planets to boost the spacecraft's journey after launch. An appreciation of the basic physical conservation laws (energy, momentum, and angular momentum) is needed to understand how the velocity of a spacecraft can be changed when it flies by a planet. In Activity 1, students explore the physical conservation laws by observing the behavior of balls colliding with other objects. In Activity 2, the students use an interactive online simulation tool to explore the various ways in which gravity assists can be used to aid space exploration.

Grade Level
9–12

Duration
Two 45-minute class periods

Essential Question

How can we use basic physical principles to aid our exploration of other worlds in the Solar System?

Lesson 2
of the Grades 9-12
Component of the
Mission Design
Education Module

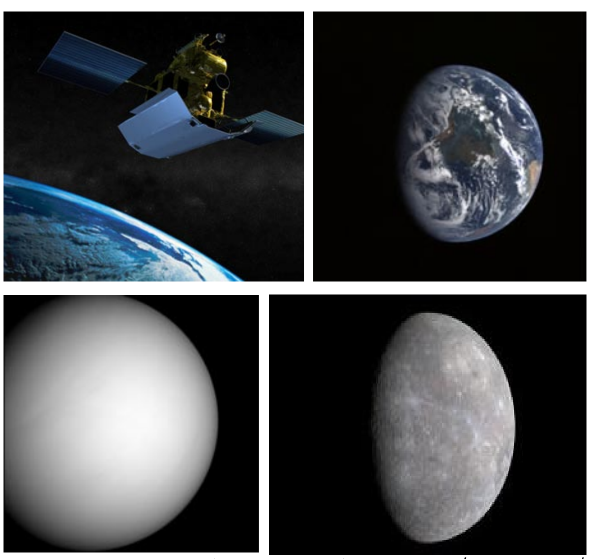


Figure 1. Gravity assists are an important part of spacecraft mission design today. Not only can they speed up the journey to explore distant worlds, but they also make it possible to conduct missions otherwise considered impossible. For example, after the launch of the MESSENGER spacecraft in 2004 (an artist's impression of the spacecraft leaving the Earth; top left), the spacecraft performed gravity-assist maneuvers while flying by (and performing science investigations of) the Earth in 2005 (picture taken by MESSENGER; top right), Venus in 2006 and 2007 (picture of Venus taken by MESSENGER; bottom left), and Mercury in 2008 and 2009 (picture of the previously unseen side of Mercury taken by MESSENGER: bottom right) before going into orbit around the mission's target planet, Mercury, in 2011. (Picture credits: NASA/JHU-APL/CIW; http://messenger.jhuapl.edu/the_mission/artistimpression/images/MessengerEarthDeparture.jpg; http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/twins_lbl_lg.jpg; http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/Venus%202%20Approach%20Image.jpg; http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/Prockter07.jpg)

Objectives

Students will be able to do the following:

- Predict the result of an elastic collision between two objects.
- Explain the laws of the conservation of energy, momentum, and angular momentum.
- Describe how gravity can be used to modify the trajectory of a spacecraft using basic physical conservation laws.

Concepts

- Newton's third law states that when an object exerts a force on another object, the second object also exerts a force on the first object; the reaction force is equal in magnitude but opposite in direction.
- The laws of conservation of momentum and angular momentum state that in a closed system, the total amounts of these basic physical quantities remains constant.
- The law of the conservation of energy states that in a closed system, the total amount of energy remains constant; energy can be converted from one form to another, but it cannot be created or destroyed.
- Spacecraft can utilize the physical conservation laws during gravitational interaction with planets to modify the spacecraft's trajectory.
- Gravity-assist maneuvers are used to make space exploration economically feasible with current technology.

MESSENGER Mission Connection

MESSENGER travels on a complicated path to its target planet, Mercury. The spacecraft flew by the Earth once, Venus twice, and Mercury three times before it finally goes into orbit around Mercury in 2011. Gravity assists from each flyby are used to gradually reduce the difference between the orbits of MESSENGER and Mercury, thereby minimizing the amount of propellant required on the spacecraft's journey. The mission would not be possible at present without the gravity-assist maneuvers.

Standards & Benchmarks

National Science Education Standards

Standard B5: Conservation of energy and the increase in disorder

- ▼ The total energy of the universe is constant. Energy can be transferred by collisions in chemical and nuclear reactions, by light waves and other radiations, and in many other ways. However, it can never be destroyed. As these transfers occur, the matter involved becomes steadily less ordered.

Standard E2: Understandings about science and technology

- ▼ Science often advances with the introduction of new technologies. Solving technological problems often results in new scientific knowledge. New technologies often extend the current levels of scientific understanding and introduce new areas of research.

AAAS Benchmarks for Science Literacy

Benchmark 4E/H1:

- ▼ Although the various forms of energy appear very different, each can be measured in a way that makes it possible to keep track of how much of one form is converted into another. Whenever the amount of energy in one place diminishes, the amount in other places or forms increases by the same amount.

Benchmark 4F/H4:

- ▼ Whenever one thing exerts a force on another, an equal amount of force is exerted back on it.

Benchmark 3A/H1:

- ▼ Technological problems and advances often create a demand for new scientific knowledge, and new technologies make it possible for scientists to extend their research in new ways or to undertake entirely new lines of research. The very availability of new technology itself often sparks scientific advances.

Science Overview

If scientists had unlimited funds to explore space, they could equip spacecraft with enough propellant to fly from one planet to another in as fast and direct route as modern technology would allow. In reality, however, it is important to minimize the amount of propellant carried by spacecraft, because not only are fuel and oxidizer—which together make up the rocket propellant—expensive, but even more cost is incurred lifting them (as well as the spacecraft) from the surface of the Earth to space. For example, the MESSENGER spacecraft heading to Mercury carried a total of 597 kg (1,316 lbs) of propellant at the start of its journey, with a total cost of approximately $48,000, while the cost of lifting the propellant to orbit was $13 million. Therefore, it is important to look for ways to reduce the need for large quantities of propellant aboard a spacecraft as much as possible. One way can be found by examining physical conservation laws and the properties of planetary orbits.

Conservation of Momentum

Some of the most powerful laws of physics are the laws of the conservation of momentum, angular momentum and energy. Momentum (**p**) is a physical quantity that is defined in classical mechanics to be the product of an object's mass (*m*) and velocity (**v**): $\mathbf{p}=m\mathbf{v}$. Note that both momentum and velocity are vector quantities; that is, they have both magnitude and direction (and are marked with bold letters), while mass is a scalar quantity (just magnitude) and is not marked with a bold letter.

The law of the conservation of momentum can be stated as follows: For an interaction (such as an elastic collision) occurring between object 1 and object 2, the total momentum of the two objects before the collision is equal to the total momentum of the objects after the collision. That is,

$$m_1\mathbf{v}_{1i} + m_2\mathbf{v}_{2i} = m_1\mathbf{v}_{1f} + m_2\mathbf{v}_{2f}$$

where m_1 and m_2 are the masses of the two objects, and $\mathbf{v}_{1i}$, $\mathbf{v}_{1f}$ and $\mathbf{v}_{2i}$, $\mathbf{v}_{2f}$ are the initial (i) and final (f) velocities of the objects 1 and 2 (see Fig. 2.) Another way to say this is that the momentum lost (or gained) by object 1 ($m_1(\mathbf{v}_{1i}- \mathbf{v}_{1f})$) is equal to the momentum gained (or lost) by object 2 ($m_2(\mathbf{v}_{2f} -\mathbf{v}_{2i})$). Note that the effect on the objects depends on their masses: for example, if one of the objects is much more massive than the other and is at rest before the collision, the likely result of the interaction is that the large object moves only slightly (if at all) and the small object bounces back with roughly the same magnitude of velocity it had before. The

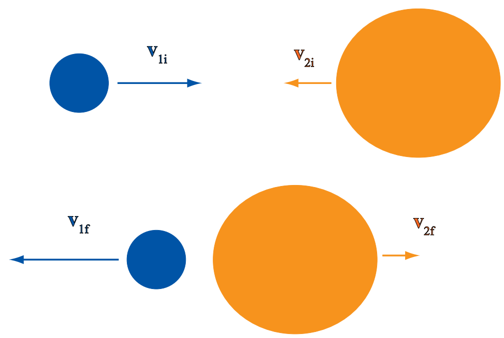


Figure 2. Momentum is conserved in an elastic collision of objects with masses m_1 and m_2. The sum of the mass times the initial velocities ($\mathbf{v}_{1i}$,$\mathbf{v}_{2i}$) of the two objects is equal to the sum of the mass times the final velocities ($\mathbf{v}_{1f}$,$\mathbf{v}_{2f}$) of the objects; that is, momentum is conserved, or $m_1\mathbf{v}_{1i} + m_2\mathbf{v}_{2i} = m_1\mathbf{v}_{1f} + m_2\mathbf{v}_{2f}$.

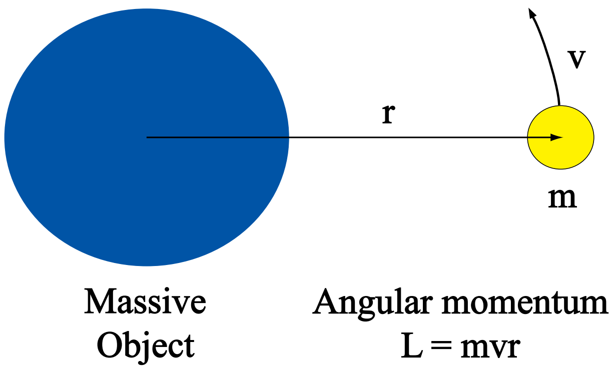


Figure 3: A small mass (m) orbiting a larger massive object at a distance r with a velocity v has an angular momentum of magnitude L = mvr.

law also applies if the objects are moving in the same direction but one overtakes the other: in the resulting collision, momentum is still conserved. The law of the conservation of momentum is a manifestation of Newton's third law, which states that when an object exerts a force on another object (force $\boldsymbol{F} = m\boldsymbol{a}$, where m is the mass and $\boldsymbol{a}$ the acceleration), the second object also exerts a force on the first object; the reaction force is equal in magnitude but opposite in direction. Another way to state this principle is to say that for every action (force) in nature there is an equal and opposite reaction.

Conservation of Angular Momentum

The angular momentum of an object (such as the small object in Fig. 3) about some central point (such as the center of the massive object in Fig. 3) is the product of the object's mass, velocity and distance from the origin. Angular momentum is a vector quantity, meaning that it has both magnitude and direction, but for the present purposes, we can limit our discussion to the magnitude of this quantity. In the simple case of Fig. 3, where a small mass is moving in a uniform circular motion around a massive object, the magnitude of the angular momentum can be expressed as $L = mvr$, where v is the magnitude of the velocity and r the distance from the origin.

The law of the conservation of angular momentum states that in a closed system, the total angular momentum is constant (though it can be transferred between objects interacting within the system.) If we rewrite the expression of angular momentum to the form $v = L/(mr)$ and L is a constant, we notice that the velocity v and the distance r are inversely correlated. This means that the law of the conservation of angular momentum demands that if the distance from the origin r becomes smaller, the velocity v must become larger, and vice versa. An example of this concept is an ice skater who spins faster when her/his arms are drawn in and slower when her/his arms are extended.

Conservation of Energy

The law of the conservation of energy states that the total amount of energy in a closed system remains constant. Energy may come in different forms (kinetic, potential, heat, light), and one form of energy can be converted to another (e.g. potential energy can be converted to kinetic energy) but the total energy (the sum of all energies) within the system is constant. That is, energy may neither be created nor destroyed.

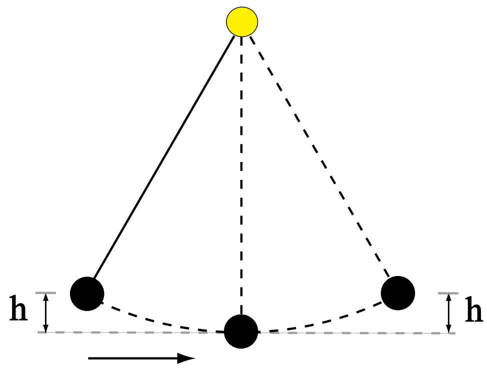


Figure 4. When a pendulum swings back and forth, potential energy changes to kinetic energy and back again, but the total amount of energy remains constant (if no energy is lost due to friction.)

The most commonly used example of this principle is the pendulum (see Fig. 4). The different forms of energy in the swing of the pendulum with a ball of mass m at the end can be written as follows: the (gravitational) potential energy $E_p = mgh$, where m is the mass of the ball, g is the acceleration due to gravity, and h is the height at which the ball starts and ends its swing; and the kinetic energy $E_K = 1/2\ mv^2$, where m is the mass of the ball and v the speed of the ball. When the ball is at its maximum height (h) during the swing of the pendulum, it is not moving (v=0). Therefore, its kinetic energy (E_K) equals zero and its potential energy (E_p) is at its maximum value (mgh). When the ball is at the middle of the swing, it is moving at its greatest velocity and h equals zero. Therefore, E_K is at its maximum value, and E_p equals zero. During the swing, energy is transferred between E_p and E_K. However, the total energy of the system ($E_p + E_K$) remains the same. If there were no outside forces acting on the system, the pendulum would keep swinging forever and no energy would be lost. However, in the real world, some energy is lost due to outside forces such as air drag, and over time the pendulum slows down. But even in this case, if we take into account the energy lost due to the drag (let's call it E_d), the total energy of the pendulum and its surroundings (E_p+E_K+E_d) is constant.

Conservation Laws in Planetary Orbits

The basic physical conservation laws also apply to planetary motions. The conservation of angular momentum helps us understand why planets on orbits closer to the Sun (r is smaller), have larger orbital velocity (v) than planets farther away. For example, the mean orbital velocity of Mercury, the closest planet to the Sun, is, 48 km/s (30 miles/s) while the mean orbital velocity of the Earth is 30 km/s (19 miles/s.) Note, however, that this does not mean that the planets all have the same angular momenta on their orbits around the Sun. For example, Mercury's angular momentum around the Sun is only 0.03 times the Earth's angular momentum around the Sun (9.20×10^{38} kgm^2/s vs. 2.66×10^{40} kgm^2/s.)

Conservation of energy helps us understand why the speed of a planet changes as it orbits the Sun. The planets orbit the Sun on elliptical orbits that are close to but not quite circles. The amount of (gravitational) potential energy of a planet varies from the minimum at its closest approach to the Sun (called perihelion; see Fig. 5) to the maximum at its

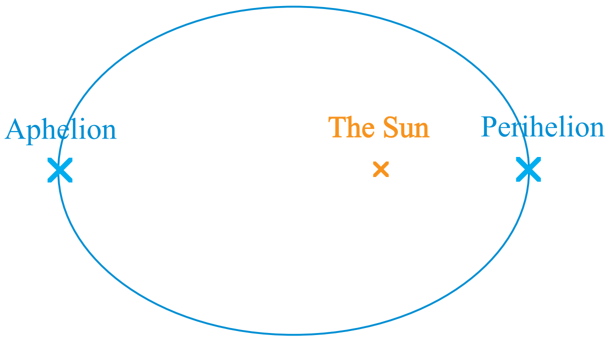


Figure 5. The orbit of a planet around the Sun. During an orbit, the planet's orbital velocity changes from the minimum at aphelion (the furthest point from the Sun) to the maximum at perihelion (the closest point to the Sun), as the potential energy is converted to kinetic energy and back again. The total combined energy remains constant: energy is conserved.

farthest distance from the Sun (called aphelion), while at the same time, the amount of kinetic energy varies from the maximum at perihelion to the minimum at aphelion. As a result, the planet's orbital velocity with respect to the Sun is at the maximum at perihelion, and at the minimum at aphelion. For example, Mercury's minimum orbital velocity is 39 km/s (24 miles/s) and the maximum 59 km/s (37 miles/s); the Earth's orbital velocity varies from 29.29 km/s (18.20 miles/s) to 30.29 km/s (18.82 miles/s.) While the amounts of potential and kinetic energy vary as a planet moves around the orbit, the law of the conservation of energy demands that the sum of the energies remains constant.

Gravity Assists

Gravity assist is a technique used by spacecraft mission designers to change a spacecraft's velocity so that it can reach another planet without using a large amount of fuel. To explain this method, let's start with an analogy. If you were standing on a railroad track (not recommended) and threw a tennis ball at 30 km/h toward a train coming toward you at 50 km/h, the train would "see" the ball hitting it at 80 km/h; that is, the ball's velocity in the train's reference frame is 30 km/h + 50 km/h. Because the collision is elastic and the train is much more massive than the tennis ball, the ball would bounce off the train at 80 km/h in the train's reference frame. However, with regard to the ground, the speed of the ball would be 80 km/h plus the speed of the train (50 km/h); the ball would fly back to you at 130 km/h. You have, therefore, increased the speed of the tennis ball by 100 km/h and changed its direction of motion by using the train's speed and direction of motion. During the exchange, the train also loses some momentum, but since the train is much more massive than the ball, the amount of momentum lost by the train is negligible, while the effect on the ball is significant.

The idea behind a gravity assist is to use a planet's gravity and direction of motion—and the basic conservation laws of physics—to change a spacecraft's speed and direction of motion. Consider the situation depicted in Figure 6. The top image (A) shows a spacecraft flying by a planet in the planet's reference frame. The spacecraft approaches the planet from the bottom of the picture at the inbound velocity $\mathbf{v}_{in}$. When the spacecraft flies closer to the planet, its velocity increases because of the acceleration caused by the planet's gravitational pull. As the spacecraft flies away from the planet, its velocity decreases because of the deceleration caused by the planet's gravitational pull, and the resulting outbound velocity, $\mathbf{v}_{out}$, is the same as the inbound velocity in magnitude, and only the direction of the velocity vector has changed. This is in good accord with the laws of the conservation of energy and angular momentum.

The situation appears slightly different in the Sun's reference frame, however, since the planet is moving along on its orbit around the Sun during the encounter. As a result, the planet's velocity contributes to the spacecraft's velocity in the Sun's reference frame. The situation is depicted in the bottom picture of Fig. 6 (case B). The planet's velocity relative to the Sun is added to the spacecraft's inbound and outbound velocities as a vector sum. As a result, the spacecraft's outbound velocity is *larger* than the inbound velocity in the Sun's reference frame. Because of the conservation laws, a reaction effect acts on the planet, but, because the planet is much more massive than the spacecraft, the effect on its motion is negligible, while the boost to the spacecraft can be significant. So, in the Sun's reference frame, the planet-spacecraft gravitational encounter not only changed the spacecraft's direction but also gave it a velocity boost.

If the geometry of the encounter is different, and the spacecraft passes in front of the planet with respect to its orbital direction during the encounter,

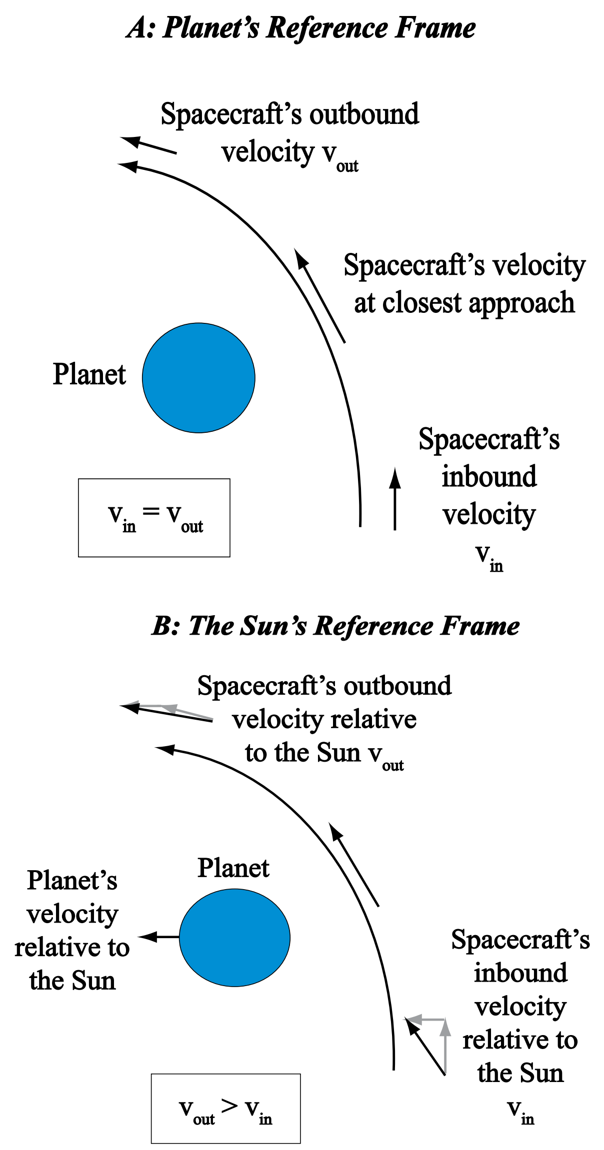


Figure 6. Schematic of the interaction during a gravity-assist maneuver. Case A (top) shows the interaction with respect to the planet. The magnitudes of the inbound and outbound velocities of the spacecraft (v_{in} and v_{out}) are the same (though the direction a little different) relative to the planet However, the situation is different relative to the Sun (case B, bottom), because the planet is moving with respect to the Sun during the encounter. In this reference frame, the planet's velocity is added to the spacecraft's velocity, and the resulting outbound velocity relative to the Sun is different, not only in direction, but also in magnitude.

and not behind it (as in Fig. 6), the flyby results in the opposite result: the spacecraft's velocity is *reduced* with respect to the Sun. As a result, by choosing the geometry of the encounter carefully, it is possible to change the spacecraft's velocity—both direction and magnitude—as desired. Therefore, gravity-assist maneuvers are one of the most useful tools in the Solar System explorer's toolbox.

Examples of current spacecraft missions using gravity assists as an integral part of their mission design are New Horizons and MESSENGER. The New Horizons spacecraft left the Earth in 2006 with the speed of 16 km/s (36,000 mph) relative to the Sun. By flying by Jupiter in 2007, the spacecraft received a gravity-assist boost to its velocity so that its speed rose to 23 km/s (51,000 mph) relative to the Sun. As a result, New Horizons will reach Pluto in 2015, only 9 years after launch. Without the gravity-assist maneuver, the journey would take a lot longer. Meanwhile, the MESSENGER spacecraft, which is scheduled to begin orbiting Mercury in March 2011, uses a complex gravity-assist plan to lower its speed relative to Mercury; that is, to change the magnitude of its two velocity components so that it matches Mercury's high orbital velocity but reduces the sunward velocity component. This is similar to a situation where a stunt performer is trying to jump aboard a speeding train: if the stunt performer stands still and just tries to jump aboard, he or she is likely to fail. The chance of success is much higher if the stunt performer is riding on a truck that matches the speed of the train. Because of these considerations, the MESSENGER spacecraft, launched in 2004, flew by the Earth in 2005, by Venus in 2006 and 2007, and three times by Mercury in 2008 and 2009. While the Earth flyby was a bonus planetary encounter caused by the first Venus flyby in the planned trajectory to Mercury not occurring until 2006, the Venus and Mercury gravity-assist flybys were crucial in positioning MESSENGER so that it can go into a orbit around Mercury in 2011. The maneuvers were important for not only having the spacecraft match the target planet's velocity around the Sun, but also modifying the spacecraft's orbit around the Sun so that it is similar to Mercury's at orbit insertion, especially in terms of inclination, the tilt of Mercury's orbital plane with regard to the Earth's orbit around the Sun. In this case, the gravity-assist trajectory actually increases the travel time (since it takes only a few months to fly directly from the Earth to Mercury), but the requirement to go into an orbit around the target planet makes the additional travel time acceptable.

Gravity Assists in Space Exploration

Gravity assists are essential in modern space exploration. Before the concept of gravity-assist trajectories was conceived, many planetary investigations were thought impossible with the technology available at the time. For example, until the mid-1980s, no one knew how to send a spacecraft to orbit Mercury with current propulsion technology. Scientists and engineers are working on advanced concepts to make it possible for spacecraft to travel faster on their own, but at present the best way to overcome the technological limits is through the concept of gravity assists.

Lesson Plan

Warm-Up & Pre-Assessment

This *Warm-Up* is designed to give students an understanding of Newton's third law: for every action, there is an equal but opposite reaction. It will also help students visualize the concept of conservation of momentum that is explored further in Activity 1.

Materials

Per class:

- 2 rolling chairs

1. Obtain two rolling chairs. Ask two student volunteers to sit in the chairs without touching the ground with their feet. Facilitate a discussion about action and reaction with the class. For example, you can ask the class the following questions:

   What would happen if the students pushed on one another? *(Desired answer: they would move away from each another.)* Why is this the case? *(Desired answer: They are exerting a force on one another.)* If the two chairs move backwards with approximately the same speed, how do the forces directed toward each chair compare? *(Desired answer: They are approximately the same.)* What happens if two students sit on one of the chairs and only one on the other, and then the students in the different chairs push on one another? *(Desired answer: the chair with two students will not move away as fast or as far as the other.)* How do the forces directed toward each chair compare in this case? *(Desired answer: They are still the same. Since the force equals mass times acceleration ($\mathbf{F} = m\mathbf{a}$), the chair with two students has a higher mass but lower acceleration, and the chair with one student has a lower mass but higher acceleration; that is, the forces are the same but because the mass of one of the chairs is higher, its acceleration is lower.)* What would happen if we kept adding students to the chair with the two students? *(Desired answer: The forces directed toward each chair will still be the same in each case—though they may vary between the cases, depending on how hard the students push on each other in each case—but the acceleration for the chair with a large number of students will become smaller until it will hardly move at all.)*

2. Discuss how Newton's third law states that for every action, there is an equal but opposite reaction; in other words, if you exert a force on something, it will exert a force of the same magnitude back to you.

Activity 1: Conservation of Energy and Momentum

In this activity, students will explore elastic collision scenarios by observing the behavior of a ball bouncing off a larger object, which is either held stationary or moving toward or away from the ball during the collision. The students use this information to formulate the laws of the conservation of energy and momentum, and apply these laws in a variety of situations. Students also learn that a third quantity, angular momentum, is conserved in physical processes.

Materials

Per group of 3 or 4:

- Large table, about 1 m × 1 m (3 ft × 3 ft) in size, or an area of the floor cleared for the experiment
- Meter stick
- Small rubber ball (e.g., a SuperBall)
- A piece of wood about the size of a book, or another hard object (such as a paddle from a paddle ball game)

Per student:

- Student Worksheet 1

Preparation

1. Obtain materials for the activity. Each group will need a space that is just less than a meter (3 ft) wide by just greater than a meter (3 ft) long to conduct the experiment. If long tables are not available, move desks aside to create a large enough area on the floor for each group.
2. Make copies of Student Worksheet 1 (one per student).

Procedures

1. Ask the students what happens when you roll two balls toward each other. *(Desired answer: they bounce off each other.)* Let's imagine that one ball is massive (such as a basketball), the other light (such as a tennis ball). What if the basketball is standing still and the tennis ball collides with a slow speed with the basketball; do both of them move? *(Desired answer: usually the tennis ball would bounce back and the basketball would not move.)* Why is this the case? *(Desired answer: the basketball is more massive than the tennis ball so it does not move.)* What if we roll the tennis ball faster toward the basketball; would the basketball ever move after the collision? *(Desired answer: yes; if the tennis ball collides with the basketball with enough speed, both will bounce back.)* So, it appears that the amount each ball bounces back depends on the speed of the balls as well as their masses. Ask the students if they know what the physical quantity where an object's mass is multiplied by its speed is called. *(Desired answer: momentum.)* In a collision such as the one between the basketball and tennis ball, the total combined momentum of the balls is the same before and after the collision, though the momentum of each individual ball may change. We say that the momentum is conserved in the

collision. You can write out the conservation formula on the blackboard:

$$m_b\mathbf{v}_{bi} + m_t\mathbf{v}_{ti} = m_b\mathbf{v}_{bf} + m_t\mathbf{v}_{tf}$$

where m_b and m_t are the masses of the basketball and tennis ball, respectively, and $\mathbf{v}_{bi}$, $\mathbf{v}_{bf}$ and $\mathbf{v}_{ti}$, $\mathbf{v}_{tf}$ are their initial (i) and final (f) velocities. In all closed physical systems, the total momentum is conserved.

2. Ask the students if they know of any other physical quantities that are conserved. Introduce the concept of the conservation of energy. Discuss the case of the pendulum, the different energies involved—potential and kinetic energy—and how they can be measured. Explain that when the pendulum swings, the energy is converted from potential to kinetic energy and back again, but the total energy—the sum of the two energies—remains constant.

3. Explain to the students that they will explore collisions to investigate these conservation laws in action. Divide the class into groups of three or four, and distribute the supplies and Student Worksheet 1.

3. Have the students follow the directions in Student Worksheet 1 to explore elastic collisions.

Discussion & Reflection

- Discuss the results of the experiment and make sure the students understand how the velocity of the ball (a small object) changes as a result of the way it collides with the large object: whether the large object is moving and in which direction with regard to the direction in which the ball is moving.
- Discuss how another important quantity, angular momentum, is also conserved in physical systems. Angular momentum is important for objects that are rotating or orbiting around an origin. You can use the idea of a figure skater extending and pulling in her/his arms during a pirouette as an example. Make sure the students understand that the magnitude of angular momentum of an object depends on its mass, its velocity, and its distance from the origin.
- Discuss planetary orbits and how the conservation laws apply to them (see the *Science Overview* for details.) Make sure the students appreciate the importance of these laws for planetary motion; that way they will have a solid background on which to understand how gravity assists work as they conduct Activity 2.

Activity 2: Give Me a Boost!

Students will use an online simulation tool to explore how spacecraft can change their trajectory via gravitational interaction with planets while flying by them. The students experiment with different flyby configurations to see how the behavior of the spacecraft changes when the input parameters are varied. As a result, the students come to understand how these planetary encounters are similar to the collisions they investigated in Activity 1, and how the basic physical conservation laws are behind the idea of using gravity assists to change the velocity of a spacecraft.

Materials

Per group of 2 or 3:

- Internet access

Per student:

- Student Worksheet 2

Preparation

1. Each group needs to have Internet access to complete the activity. Be sure to book computer time ahead of time.
2. Make copies of Student Worksheet 2 (one per student).

Procedures

1. Students must understand that momentum and energy can be transferred from one object to another as long as the total momentum and energy of the system stays the same. You can use the following examples to help them understand this concept.

   Ask the students to remember what it was like to jump on a moving merry-go-round in the playground when they were younger (the type of merry-go-round that one must push, not the kind that is motorized). Ask the students to imagine that they are standing still and then jump onto a moving merry-go-round. What happens to the speed of the merry-go-round when they jump on? *(Desired answer: The merry-go-round slows down a little.)* What happens to the students when they jump off? *(Desired answer: They keep going in the direction that the merry-go-round was rotating when they jumped off until they hit the ground.)* Why do they think this is the case? *(Desired answer: The merry-go-round has transferred some of its angular momentum to the students, and the students are moving relative to the ground when they jump off the merry-go-round.)* Explain that because angular momentum is conserved, the merry-go-round slows down when the students jump on (the total mass increases, so the velocity has to decrease), and speeds up a bit when the students jump off (the total mass decreases, so the velocity increases.)

2. Discuss with the students how this compares with a spacecraft flying by a planet. Ask the students if they think the same conservation laws apply to the planet-spacecraft system as the other situations the class has discussed. *(Desired answer: yes, the laws are universal.)* Explain to the students they will use an online simulation tool to see what happens when spacecraft with different trajectories fly by a planet.

3. Hand out Student Worksheet 2 and have the students follow the directions to explore gravity assists using the simulation Web site. Note that Part 1 (steps 2-10) of the Worksheet is a simulated version of elastic collisions similar to what the students investigated in Activity 1, but you may want to have the students go through these steps not only to reinforce the concepts learned in Activity 1, but also to investigate one scenario not explored in Activity 1.

Discussion & Reflection

1. Discuss with the students the different types of gravity assists they explored using the online simulation tool and how the same basic method can be used to achieve many different results for the planetary encounter, depending on the needs of the mission.

2. Discuss how the basic physical conservation laws are behind the concept of gravity-assist maneuvers. Ask the students if, during the flyby, some angular momentum is transferred between the planet and the spacecraft? *(Desired answer: Yes.)* In fact, the spacecraft effectively "steals" some of the planet's angular momentum to change its own angular momentum and its velocity with respect to the Sun. Since the planet is much more massive than the spacecraft, the effect is negligible to the planet, but quite significant to the much less massive spacecraft. Ask the students if they can explain why the transfer of angular momentum and energy works in the case of gravity assists, even though the spacecraft and the planet never come into direct physical contact with one another. *(Desired answer: the conservation laws are universal for all physical conditions, and momentum, angular momentum, and energy can be transferred between objects even without physical contact, as long as there is some way to transfer the quantities between the objects. Gravity works well in this respect.)*

Lesson Adaptations

For vision-impaired students, ask one of their team members to describe the set-up and changes in speed for all of the scenarios in Activity 1. For Activity, 2, the online simulation environment includes "long descriptions," which can be accessed by clicking on the "Learn More" tab in the upper right corner of each scenario, and then selecting "D-Link."

Extensions

- Have the students visit the MESSENGER Mission Design Web page (see *Internet Resources & References*) to investigate in detail the spacecraft's complex journey to Mercury.
- Have the students explore other spacecraft missions to see how often the gravity-assist maneuvers are used in space exploration today. The NASA National Space Science Data Center's Chronology of Lunar and Planetary Exploration Web page (see *Internet Resources & References*) contains detailed information on spacecraft missions, including the trajectories and any gravity-assist maneuvers used in the mission.

Curriculum Connections

- *History of science*: Before the idea of a complex trajectory involving multiple gravity assists was conceived, a mission to orbit the planet Mercury was considered unfeasible with current technology. Have the students explore similar instances in the history of science, when a new scientific, mathematical, or technological discovery made it possible to conduct an investigation previously thought impossible.

Closing Discussion

- Discuss with the students the connection between Activity 1 and 2: that the same basic physical principles that govern collisions of balls with hard objects in the classroom can be used to aid our exploration of other worlds in the Solar System.
- Discuss the reason why so many spacecraft missions use gravity-assist maneuvers; they do so in order to meet cost and scheduling requirements. In fact, some missions would not even be possible at present time without gravity assists.
- Hand out to the students copies of the *Mission Information Sheet* and the *Mission Science Goals* located at the end of this lesson, and discuss how the concepts investigated during the lesson relate to the mission.

Assessment

4 points

- Student used logical reasoning to support her or his observations of the properties of the different types of elastic collisions in Student Worksheet 1.
- Student properly explained the connection between the different gravity assist scenarios and elastic collisions (questions 12b and 13c) in Student Worksheet 2.
- Student answered the questions on the Student Worksheets thoughtfully and used reasoning and evidence to support her or his answer.
- Student completed all Worksheets and participated in the lesson.

3 points

- Three of the four criteria above are met.

2 points

- Two of the four criteria above are met.

1 point

- One of the four criteria above is met.

0 points

- No work completed.

Internet Resources & References

MESSENGER Web Site

http://messenger.jhuapl.edu

American Association for the Advancement of Science, Project 2061, Benchmarks for Science Literacy

http://www.project2061.org/tools/benchol/bolframe.htm

National Science Education Standards

http://www.nap.edu/html/nses/

Gravity Assist Discussion at the MESSENGER Web Site

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

Gravity Assist Simulator

http://www.messenger-education.org/Interactives/ANIMATIONS/grav_assist/gravity_assist.html

MESSENGER Mission Design Web Page

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

NASA Glenn Research Center: Conservation of Energy

http://www.grc.nasa.gov/WWW/K-12/airplane/thermo1f.html

NASA Glenn Research Center: Conservation of Momentum

http://www.grc.nasa.gov/WWW/K-12/airplane/conmo.html

NASA Jet Propulsion Laboratory: Interplanetary Trajectories and Gravity Assists

http://www2.jpl.nasa.gov/basics/bsf4-1.php

NASA National Space Science Data Center's Chronology of Lunar and Planetary Exploration

http://nssdc.gsfc.nasa.gov/planetary/chrono.html

New Horizons Web Site

http://pluto.jhuapl.edu/

Acknowledgements

Activity 1 and 2 were adapted from the activity "Invisible Collisions" (http://www.messenger-education.org/Interactives/ANIMATIONS/grav_assist/invisible_collisions_activity_final.pdf).

Elastic Collisions

Name: ______________________________

Date: ______________________________

Materials
- Large table (or a large area of the floor cleared for the experiment)
- Meter stick
- Small rubber ball (e.g., a SuperBall)
- A piece of wood or a paddle

Introduction

Whenever two objects collide (such as when a ball bounces off a wall), there are basic conservation laws of physics in action: the law of the conservation of energy and the law of the conservation of momentum. The law of the conservation of energy states that the total energy of a system is constant: energy may be converted from one form to another, but it cannot be created or destroyed. The law of the conservation of momentum states that the total momentum (which is the velocity of an object multiplied by its mass) of a group of objects in a closed system does not change: it is constant.

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 (unlike, say, in a car crash when the fenders can be crushed.) 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 (such as a rubber ball) and a large object (such as a piece of wood). Be sure to pay close attention to the speeds of the objects during the different scenarios investigated here.

Directions

1. You are going to investigate three different scenarios involving elastic collision between a small ball and a large object. Figure S1 shows you the basic setup of the experiment.
2. For each of the scenarios you will be dropping a ball from the same height, 50 cm. In two scenarios you will also be moving the large object in some direction while the ball is dropping.
3. Read the instructions for each scenario carefully before attempting them.

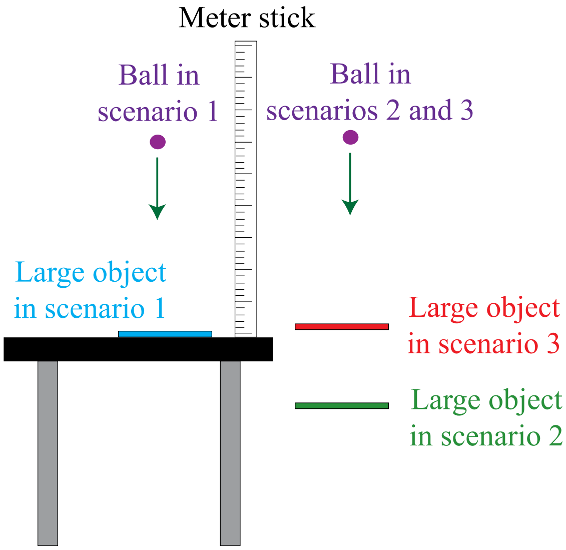


Figure S1. Setup for the experiment. Place a meter stick on the table so that it is standing perpendicular to the surface, close to the edge of the table, and so that the 0 cm mark is at the table's surface (except in scenario 1, where you place the meter stick on top of the large object.) Have one person hold the meter stick in place during the experiments. Place the large object in different places, depending on the scenario investigated. Drop the ball toward the large object from the same height (50 cm) in each scenario, and observe how the ball bounces off the large object.

Scenario 1

In this scenario, you will investigate what happens when the ball collides with a large object that is not moving.

The large object: place the large object flat on the surface of the table.

The meter stick: place the meter stick on top of the large object with the 0 cm mark on the surface.

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

4. Before you begin, predict how you think the interaction between the ball and the large object will change the speed and the height of the bounce of the ball. That is, how will the speed at which the ball will bounce off the large object compare with the speed it will strike it, and how will the height to which the ball will bounce compare with the height from which you will drop it?

____

____

____

____

5. Now perform the activity. Observe how high the ball bounces after colliding with the large object. Try to observe the speed of the ball just before it strikes 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, and then answer the following questions:

a) How does the height from which the ball was dropped compare with the height to which it bounced?

b) How does the speed of the ball when it bounced back from the object compare with the speed it had as it struck the object: was it higher than, lower than, or the same as the initial speed?

Scenario 2

In this scenario you will investigate what happens when the ball and the larger object are moving in opposite directions (that is, toward each another). To do this, you will drop the ball while the large object is moving toward the ball.

The large object: begin with the large object held parallel with the surface of the table, but a little off to the side and below the table surface by about 10 cm (see Fig. S1.) Move the large object up just as the ball approaches so that they collide at about the same height as the bottom of the meter stick at the edge of the table.

The meter stick: place the meter stick perpendicular to the surface of the table near the edge closest to the large object and with the 0 cm mark on the surface (see Fig. S1.)

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

6. Before you begin, predict how you think the interaction between the ball and the large object will change the speed and the height of the bounce of the ball. That is, how will the speed at which the ball will bounce off the large object compare with the speed it will strike it, and how will the height to which the ball will bounce compare with the height from which you will drop it?

7. Now perform the activity. Carefully observe the initial speed of the ball just before it strikes the large object and the final speed right after the collision, as well as the height to which the ball bounces. Try this several times to make sure the ball and the large object collide right at the edge of the table, and not above or below. Then answer the following questions:

a) How does the height from which the ball was dropped compare with the height to which it bounced?

b) How does the speed of the ball when it bounced back from the object compare with the speed it had as it struck the object: was it higher than, lower than, or the same as the initial speed?

Scenario 3

In this scenario you will investigate what happens when the ball and the larger object are moving in the same direction but when the ball is moving faster than the large object, so that the ball overtakes the large object and collides with it. To do this, you will drop the ball while the large object is moving away from the ball.

The large object: begin with the large object held parallel to the surface of the table, but a little off to the side and about 10 cm above the surface (see Fig. S1.) Move the large object down just as the ball approaches so that they collide at about the same height as the bottom of the meter stick at the edge of the table. Make sure the large object is moving slower than the ball so that the ball can overtake the large object.

The meter stick: place the meter stick perpendicular to the surface of the table near the edge of the table closest to the large object and with the 0 cm mark on the surface (see Fig. S1.)

The ball: drop the ball from the height of 50 cm onto the surface of the large object, which will be moving away from it.

8. Before you begin, predict how you think the interaction between the ball and the large object will change the speed and the height of the bounce of the ball. That is, how will the speed at which the ball will bounce off the large object compare with the speed it will strike it, and how will the height

to which the ball will bounce compare with the height from which you will drop it?

9. Now perform the activity. Carefully observe the initial speed of the ball just before it strikes the large object and the final speed right after the collision, as well as the height to which the ball bounces. Try this several times to make sure the ball and the large object collide right at the edge of the table, and not above or below. Then answer the following questions:

a) How does the height from which the ball was dropped compare with the height to which it bounced?

b) How does the speed of the ball when it bounces back from the object compare with the speed it had as it struck the object: was it higher than, lower than, or the same as the initial speed?

10. 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. What are the relationships between the initial and final speeds in these three scenarios?

11. Let's compare just scenario 2 and scenario 3. Recall that in scenario 2 the ball and the large object were moving toward each other; the large object started moving beneath the table surface and was pushed up to collide with the ball. In scenario 3 the ball and the large object were moving in the

same direction; the large object began moving above the table surface and was moving down as it and the ball collided. How did the final speeds of the ball in these two scenarios compare? Why do you think this was the case?

12. We can investigate elastic collisions mathematically. An object's momentum (P) is defined as its mass (m) multiplied by its speed (v). In an elastic collision between two objects the total combined momentum of the objects is the same before and after the collision, though the momentum of each individual object may change. We say that the momentum is conserved in the collision, or, in mathematical terms:

$$P_i = m_1 v_{1i} + m_2 v_{2i} = m_1 v_{1f} + m_2 v_{2f} = P_f$$

where m_1 and m_2 are the masses of the two objects, v_{1i} and v_{2i} their speeds before the collision, v_{1f} and v_{2f} their speeds after the collision, and P_i and P_f the total momenta of the two objects before and after the collision. Answer the following questions:

a) Four billiard balls, each of mass 0.5 kg, are traveling in the same direction on a billiard table, with speeds 2 m/s, 4 m/s, 8 m/s and 10 m/s. What is the total momentum of this system?

b) A ball is moving at 4 m/s and has a momentum of 48 kg m/s. What is the ball's mass?

c) A small ball with a mass of 0.5 kg is moving at a speed of 5 m/s and collides with a stationary ball with a mass of 2 kg. After the collision, the small ball is bouncing back at the speed of 4 m/s. Is the larger ball still stationary? If not, which direction is it moving and at what speed?

Gravity Assist Simulator

Name: ______________________________ **Date:** ______________

Introduction

You will use an online gravity assist simulator to explore how gravity assists can aid space exploration.

Directions

1. Navigate to the Gravity Assist Simulator at

   http://www.messenger-education.org/Interactives/ANIMATIONS/grav_assist/gravity_assist.html

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

Part 1: Elastic Collisions

2. Select Part 1. You will see four possible scenarios across the bottom of the screen. Go through all of the scenarios and answer the questions below. Note that you will be answering some questions *before* observing each of the scenarios.

Scenario 1: Collision with a stationary object

3. ***Before*** observing the scenario, predict how you think the motion of the object will change when it collides with a stationary object and how the final speed will compare with the initial speed. Record your answer here:

____

____

____

4. ***After*** observing the scenario, answer the following questions: how did the motion of the object change and how did the final speed compare with the initial speed? Was this what you predicted?

____

____

____

Scenario 2: Objects moving in opposite directions

5. Proceed to the next scenario by clicking on the Scenario Menu button to the left of the "replay" button in the middle of the screen. ***Before*** observing the scenario, predict how you think the motion of the object will change when it collides with an object moving toward it and how the final speed will compare with the initial speed. Record your answer here:

6. ***After*** observing the scenario, answer the following questions: how did the motion of the object change and how did the final speed compare with the initial speed? Was this what you predicted?

Scenario 3: Small object overtakes large object

7. Proceed to the next scenario by clicking on the Scenario Menu button to the left of the "replay" button in the middle of the screen. ***Before*** observing the scenario, predict how you think the motion of the small object will change when it overtakes and collides with a larger object, and how the final speed will compare with the initial speed. Record your answer here:

8. ***After*** observing the scenario, answer the following questions: how did the motion of the object change and how did the final speed compare with the initial speed? Was this what you predicted?

Scenario 4: Large object overtakes small object

9. Proceed to the next scenario by clicking on the "Scenario Menu" button to the left of the "replay" button in the middle of the screen. ***Before*** observing the scenario, predict how you think the motion of the small object will change when it is overtaken and collided into by a larger object, and how the

final speed will compare with the initial speed. Record your answer here:

10. ***After*** observing the scenario, answer the following questions: how did the motion of the object change and how did the final speed compare with the initial speed? Was this what you predicted?

Part 2: Stationary Planet: Flyby Basics

11. Return to the Main Menu (upper left corner) and select Part 2. In this interactive simulation the planet remains stationary as a spacecraft flies past from three different distances. Observe all three and then answer the following questions:

a) How does the trajectory of the spacecraft differ in the three different cases?

b) What force is acting on the spacecraft to change its motion?

c) In which trajectory (distance from the planet) is the force greatest? How do you know?

Part 3: New Horizons: Jupiter Gravity Assist

The New Horizons spacecraft is the fastest spacecraft ever launched: it left the Earth in 2006 with the speed of 16 km/s (36,000 mph) relative to the Sun. However, it still needs a boost (gravity assist) from Jupiter to reach its target world, the dwarf planet Pluto. Without the gravity assist, New Horizons spacecraft would not reach the Pluto system until at least 2018. By flying by Jupiter in 2007, the spacecraft received a boost so that its speed rose to 23 km/s (51,000 mph) relative to the Sun, and, as a result, it will reach Pluto in 2015. Not only does this save time, but it requires less propellant, which is both heavy and expensive (partially as a result of being heavy, since it, along with the spacecraft, has to be lifted from the surface of the Earth into space at a high cost.)

12. Return to the Main Menu (upper left corner) and select Part 3. In this interactive simulation you can investigate 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. Observe all three and then answer the following questions:

a) Which trajectory changed the speed of the spacecraft the most?

b) Let's relate this to the scenarios you observed previously in Part 1 of this Worksheet. Is the flyby most like scenario 3 (small object overtakes larger object) or like scenario 4 (larger object overtakes small object)? (Note: you can go back to the Main Menu and select "Part 1" to refresh your memory.)

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

Part 4: MESSENGER: Venus Gravity Assist

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?

13. Return to the Main Menu (upper left corner) and select Part 4. In this interactive simulation you can investigate what happens when a spacecraft passes in front of a planet (Venus in this example.) You can choose one distance at a time or all three together. Select "replay" to choose another distance. Observe all three and then answer the following questions:

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

b) Why do you think the speed of the spacecraft changed in this way?

c) Let's relate this to the scenarios you observed in Part 1 of this Worksheet. Is this case most like scenario 3 (small object overtakes larger object) or like scenario 4 (larger object overtakes small object)?

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 into an orbit around the innermost planet in the Solar System. Select the link at the bottom of the page and see the route that the MESSENGER spacecraft has to take to accomplish its mission.

Answer Key

Student Worksheet 1

5. a) In a perfectly elastic collision, the ball would bounce to the same height as from where it was dropped (50 cm). In a more realistic classroom situation, the ball will bounce to a height that is somewhat less than the height from which it was dropped.

   b) The ball should appear to have (roughly) the same initial and final speeds (as long as the observations are made right before and immediately after the collision.)

7. a) The ball should bounce to a height greater than 50 cm; that is, the bounce height is greater than the height from which the ball was dropped.

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

9. a) The ball should bounce to a height less than 50 cm; that is, the bounce height is less than the height from which the ball was dropped.

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

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

    Scenario 2: the final speed was greater than the initial speed.

    Scenario 3: the final speed was less than the initial speed.

11. In scenario 2 the final speed is greater than the initial speed because the large object is moving toward the ball when they collide, and so it gives the ball an additional push. In scenario 3 the large object is moving away from the ball when they collide, so it is not as effective in bouncing back the ball as the other scenarios.

12. a) The momentum of the system is the sum of the parts

    $$P = m_1v_1 + m_2v_2 + m_3v_3 + m_4v_4 = 1 + 2 + 4 + 5 = 12 \text{ kgm/s}.$$

    b) $m = P/v = 12$ kg

    c) Momentum before the collision: $P_i = m_1v_{1i} + m_2v_{2i} = 2.5$ kgm/s.

    Momentum after the collision: $P_f = m_1v_{1f} + m_2v_{2f} = P_i$.

    Therefore, $v_{2f} = (P_f - m_1v_{1f})/m_2 = 0.25$ m/s, so the larger ball is moving away from the smaller ball at a speed of 0.25 m/s.

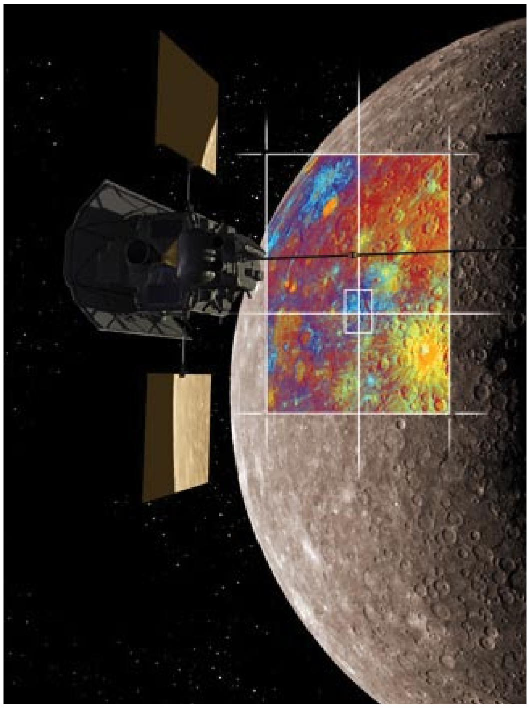
Student Worksheet 2

3. Answers will vary (if the students completed Activity 1, they should be able to predict that the initial and final speeds will be the same.)

4. The initial and final speeds were the same.

5. Answers will vary (if the students completed Activity 1, they should be able to predict that the final speed will be greater.)
6. The final speed is greater than the initial speed.
7. Answers will vary (if the students completed Activity 1, they should be able to predict that the final speed will be less than the initial speed.)
8. The final speed is less than the initial speed.
9. Answers will vary. If the students completed Activity 1, they might think this is the same as the previous scenario, since they did not investigate the differences between which object is overtaking which in Activity 1, and so they could predict that the initial speed is greater than the final speed. This is acceptable, given that they did not do this experiment.)
10. The final speed is greater than the initial speed.
11. a) The closer the spacecraft is to the planet, the higher its speed and the further its trajectory bends as a result of the flyby.
    b) The gravitational force from the planet is acting on the spacecraft to change its motion.
    c) The gravitational force is greater closer 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 changes the most.
12. a) In the closest trajectory (1 million km) the speed of the spacecraft changed the most.
    b) 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 motions of Jupiter and the spacecraft in terms of velocity vectors in the reference frame of the Sun, the large object (Jupiter) is moving faster than the small object (spacecraft) in the horizontal component of the velocity vector, and so it overtakes the spacecraft even though it is the spacecraft whose trajectory we are observing.
13. a) The spacecraft slowed down as a result of its encounter with Venus.
    b) Since the spacecraft passed right in front of the planet, the gravitational force from the planet pulled the planet toward it, and, in the reference frame of the Sun, it slowed down the spacecraft.
    c) This is most like scenario 3 (small object overtakes large object) because the spacecraft (small object) slowed down as a result of the encounter. If you think of the motions of Venus and the spacecraft in terms of velocity vectors in the reference frame of the Sun, the small object (spacecraft) is moving faster than the large object (Venus) in the horizontal component of the velocity vector, and so it overtakes the planet and slows down as the result of the encounter.

MESSENGER Mission Information Sheet



MESSENGER is an unmanned NASA spacecraft that was launched in 2004 and will arrive at the planet Mercury in 2011, though it will not land. Instead, it will make its observations of the planet from orbit. MESSENGER will never return to Earth, but will stay in orbit around Mercury to gather data until at least 2012. MESSENGER is an acronym that stands for "MErcury Surface Space ENvironment, GEochemistry and Ranging," but it is also a reference to the name of the ancient Roman messenger of the gods: Mercury, after whom the planet is named.

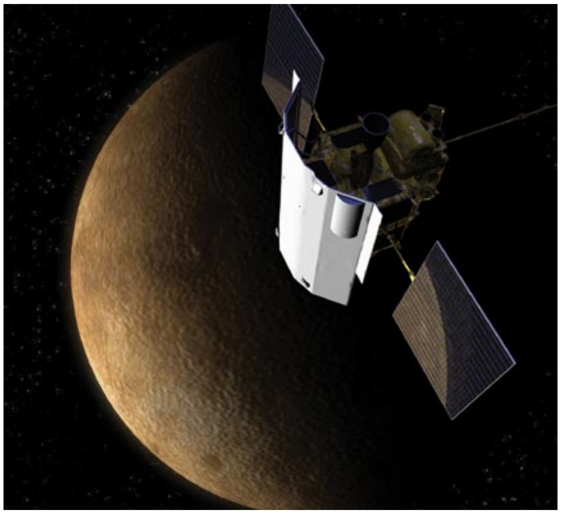
MESSENGER will be only the second spacecraft ever to study Mercury: In 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for one Earth year; its close-up observations will allow us to see the entire surface of the planet in detail for the first time.

Sending a spacecraft to Mercury is complicated. The planet is so close to the Sun that MESSENGER will be exposed to up to 11 times more sunlight than it would in space near Earth. To prevent the intense heat and radiation from having catastrophic consequences, the mission has been planned carefully to make sure the spacecraft can operate reliably in the harsh environment. To rendezvous with Mercury on its orbit around the Sun, MESSENGER uses a complex route: it flew by the Earth once, Venus twice, and Mercury three times before entering into orbit around Mercury.

The MESSENGER spacecraft is built with cutting-edge technology. Its components include a sunshade for protection against direct sunlight, two solar panels for power production, a thruster for trajectory changes, fuel tanks, and radio antennas for communications with the Earth. The instruments aboard MESSENGER will take pictures of Mercury, measure the properties of its magnetic field, investigate the height and depth of features on the planet's surface, determine the composition of the surface, and in general observe the properties of the planet and its space environment in various parts of the electromagnetic spectrum and via particle radiation studies.

During its mission, MESSENGER will attempt to answer many questions about the mysterious planet. How was the planet formed and how has it changed? Mercury is the only rocky planet besides the Earth to have a global magnetic field; what are its properties and origin? Does ice really exist in the permanently shadowed craters near the planet's poles? Answers to these scientific questions are expected to hold keys to many other puzzles, such as the origin and evolution of all rocky planets. As we discover more, we expect that new questions will arise. You could be the one answering these new questions!

MESSENGER Mission Science Goals



The first in-depth investigation of the planet Mercury, MESSENGER is designed to address six broad scientific questions. The answers to these questions will not only increase our knowledge of the planet Mercury, but also help us better understand the whole Solar System.

Why is Mercury so dense? The density of each Earth-like planet reflects the balance between a dense core, and less dense mantle (surrounding the core) and crust (the topmost layer of rock on the planet.) MESSENGER's measurements help determine why Mercury's density is so high that its core appears to be twice as large (relative to the size of the planet) as the Earth's core.

What is Mercury's geologic history? By allowing us to see the whole surface of Mercury for the first time, MESSENGER helps determine what Mercury's surface is like globally and how geologic processes (such as volcanism, tectonism, meteor impacts) have shaped it.

What is the structure of Mercury's core? Earth's magnetic field is thought to be generated by swirling motions in the molten outer portions of our planet's core. MESSENGER's measurements help determine if Mercury's field is generated the same way.

What is the nature of Mercury's magnetic field? Mercury's magnetic field is thought to be a miniature version of the Earth's magnetic field, but not much was known about it before MESSENGER. The new measurements help us understand how Mercury's magnetic field compares with the Earth's field.

What are the unusual materials at Mercury's poles? Earth-based radar observations revealed the presence of unknown bright material in permanently shadowed craters near Mercury's poles. MESSENGER's observations will help determine whether the material is water ice, which is the currently favored explanation for the radar-bright materials.

What volatiles are important at Mercury? MESSENGER will help determine the origin and composition of Mercury's atmosphere, which is so thin that it is really an exosphere. In an exosphere, volatiles (elements and compounds that turn easily to gas) are more likely to wander off into space rather than collide with each other, and so the exosphere must be replenished somehow.

MESSENGER's journey to Mercury — A mission such as MESSENGER used to be considered impossible with present technology, since the change in velocity necessary for a spacecraft to go into orbit around Mercury, the closest planet to the Sun, was thought to be beyond the capability of current propulsion systems. The mission was made possible when a complex journey using multiple gravity assists was conceived in the 1980s. MESSENGER's trajectory had the spacecraft fly by the Earth in August 2005, Venus in October 2006 and June 2007, and Mercury in January 2008, October 2008, and September 2009, before it is able to go into orbit around Mercury in March 2011. Once in orbit, the spacecraft will conduct a year-long comprehensive investigation of the planet to answer the mission's science goals.

For more information on the MESSENGER science goals, including what the spacecraft has discovered so far, visit http://messenger.jhuapl.edu/why_mercury/

MESSENGER