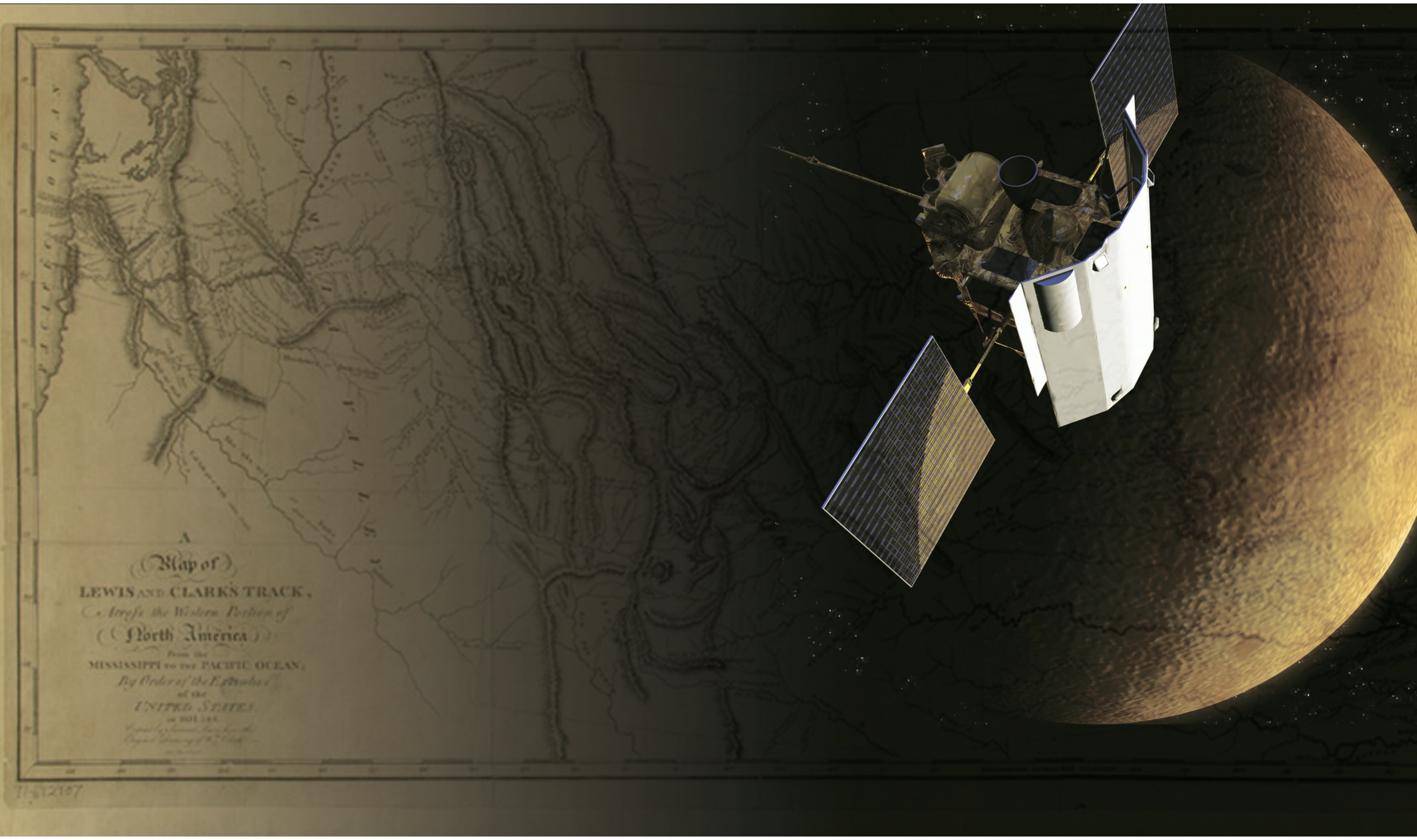
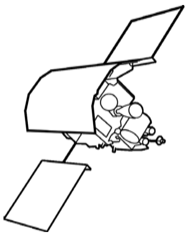
MESSENGER Education Module

MISSION DESIGN





For Grades
5-8 and 9-12

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Mission Design
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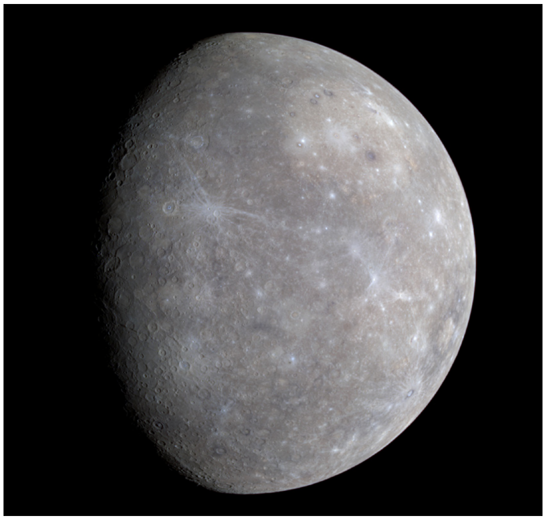
Table of Contents

Mercury - The Elusive Planet



Mercury is the closest planet to the Sun. Since it never strays far in the sky from the Sun's glare, early astronomers had a difficult time viewing it, and considered it a "wandering star" appearing just before sunrise or just after sunset.

Mercury travels around the Sun faster than any other planet. During one Earth year, Mercury makes over four orbits around the Sun. On the other hand, Mercury rotates slowly around its axis—almost 60 times more slowly than the Earth. The amazing outcome is that a single day (for example, from one sunrise to another) on Mercury takes two of its years.

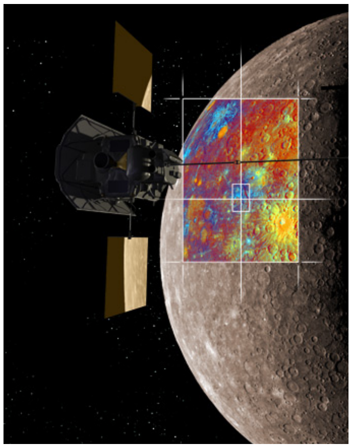
Mercury's orbit around the Sun is much more oval-shaped (eccentric) than the Earth's. This means that unlike the Earth, whose distance from the Sun does not vary much during the year, Mercury's distance from the Sun varies by about 40% during its year. As a result, the size of the Sun seen from Mercury's surface changes by about 40%—and it is always more than twice as big as we see it from Earth!

Mercury is the smallest planet in the Solar System, and not much bigger than our Moon. The surface of Mercury looks like the Moon, covered as it is with craters, while its interior is like the Earth's, with a large core of iron. Mercury has a thin atmosphere, and no moons of its own. It is a world of extreme temperatures in which the surface can heat to over 450°C (850˚F) during the day and cool to –180°C (–300˚F) at night. The huge daily temperature changes take place because Mercury's atmosphere is so tenuous that it is virtually a vacuum and cannot moderate the temperatures like the Earth's atmosphere does. For the same reason, even though much of the atmosphere on Mercury is made of oxygen, you would not be able to breathe there—there just is not enough oxygen to fill your lungs. One breath on Mercury would give you less than one hundred trillionth of the mass of the air you breathe in at sea level on the Earth!

Some Basic Facts About Mercury

Characteristic	Actual value	Compared to Earth
Diameter	4900 km	38% of Earth's diameter
Mass	3.3×10^{23} kg	6% of Earth's mass
Mean density	5400 kg/m^3	About the same as Earth's
Moons	None	One (The Moon)
Orbital period	88 Earth days	1/4 of Earth's
Rotation period (around its axis)	59 Earth days	59 times longer than Earth's
Length of one day (sunrise to sunrise)	176 Earth days	176 times longer than Earth's
Average distance from the Sun	58 million km	0.39 AU (Sun-Earth distance)
Magnetic field	Yes	Weaker than Earth's
Atmosphere	Extremely tenuous	Virtually a vacuum in comparison
Average surface temperature	170ºC (330ºF)	150ºC (270ºF) hotter than Earth's

The MESSENGER Mission to Mercury



MESSENGER is a robotic NASA spacecraft that was launched in 2004 and will arrive at Mercury in 2011. It is only the second spacecraft to study Mercury, and the first since the 1970s, when Mariner 10 rendezvoused with the planet. MESSENGER is the first spacecraft to observe Mercury from orbit and not just fly by the planet. Its observations will allow us to see the entire surface of the planet for the first time.

The acronym MESSENGER stands for MErcury Surface Space ENvironment, GEochemistry and Ranging. The name highlights the scientific topics of the mission, but it is also a reference to the name of the ancient Roman messenger of the gods, Mercury, after whom the planet is named.

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 flies 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, and fuel tanks. The instruments aboard MESSENGER will take pictures of Mercury, measure the properties of its magnetic field, investigate the height and depth of features on Mercury's 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 several questions about Mercury. 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? What is the nature and origin of Mercury's very tenuous atmosphere? Does ice really exist in the permanently shadowed craters near the planet's poles?

MESSENGER Mission Timeline

2004	Aug 3	Launch
2005	Aug 2	Earth Flyby
2006	Oct 24	Venus Flyby I
2007	Jun 5	Venus Flyby II
2008	Jan 14	Mercury Flyby I
2008	Oct 6	Mercury Flyby II
2009	Sep 29	Mercury Flyby III
2011	Mar 18	Enter Mercury Orbit

Mercury is an important subject of study because it is the extreme of the terrestrial planets (Mercury, Venus, Earth, Mars): it is the smallest, one of the densest, it has one of the oldest surfaces and the largest daily variations in surface temperature—but is the least explored. Understanding this "end member" of the terrestrial planets holds unique clues to the questions of the formation of the Solar System, evolution of the planets, magnetic field generation, and magnetospheric physics. Exploring Mercury will help us understand how our own Earth was formed, how it has evolved, and how it interacts with the Sun.

For more information about the MESSENGER mission to Mercury, visit http://messenger.jhuapl.edu/

MESSENGER Education and Public Outreach Program

Introduction

Tonight, if you look up into the sky, you'll see the same bright lights that your ancestors admired, named, and used to find their way when they were lost, or to explain unusual events in their lives. With today's technological imaging, you can better see those galaxies, stars, planets, moons, comets, meteors, asteroids, and now even artificial satellites.

As humans, we have always strived to increase our knowledge about the Universe. For centuries, we explored from the comfort of our own planet, Earth, where we could breathe air, sit on firm land, take notes on stone, paper, or computers, and teach others what we know through our writing and speaking. When we first ventured out into space in the mid-20th century, we had to change the way we gather, store, and share information. Now it would be done with machines that help us "see" in increasingly sophisticated ways, as we explore more deeply away from our home planet.

One of the ways we have learned to gather new information about other planets is to send out data-gathering instruments that are sensitive to a variety of influences. These instruments have to endure the stress of leaving the Earth's comfortable atmosphere atop a rocket, and continue to function under the most hostile conditions imaginable: the cold vacuum of space, the intense heat and radiation from the Sun, and the quick changes between the two as a spacecraft speeds along at thousands of kilometers per hour.

We go into space, to the Moon, and now to planets such as Mercury, even in the face of great risk, to push our problem-solving capabilities beyond current limits, and explore uncharted regions of the Universe. It is the nature of human exploration. We also do this because the potential benefits are too great to ignore. Indeed, it is only if we continue to explore beyond our reach that we will be able to better understand our own world, and address challenges that face us here on Earth.

MESSENGER Education and Public Outreach Program

One of the most recent of our instruments investigating other worlds in the Solar System is MESSENGER, the MErcury Surface, Space ENvironment, GEochemistry and Ranging mission, designed to study the planet Mercury. The spacecraft was launched in 2004; it will enter into orbit around Mercury in 2011 and observe the planet and its space environment for one year.

The goals of the mission not only include gathering massive amounts of information about the mysterious planet Mercury, but to also take the nation along for a thrilling ride of exploration. Indeed, bringing a sense to the general public of how mission planners overcome challenges and achieve triumphs has been taken on as a national responsibility.

The Education and Public Outreach (EPO) team assembled to meet this challenge is an extensive network of individuals from the following organizations: American Association for the Advancement of Science (AAAS); Carnegie Institution of Washington Carnegie Academy for Science Education (CASE); Center for Educational Resources (CERES) at Montana State University (MSU) – Bozeman; National Center for Earth and Space Science Education (NCESSE); Johns Hopkins University Applied Physics Laboratory (JHU/APL); National Air and Space Museum (NASM); Science Systems and Applications, Inc. (SSAI); and Southwest Research Institute (SwRI).

To meet the goal of education and public outreach on a national level, a comprehensive set of activities coordinated with MESSENGER events has been designed to enliven education from kindergarten through college and to excite the general public. These activities include education materials development, teacher training through an educator fellowship program, unique student investigations related to the MESSENGER mission, museum displays, and special outreach to underserved communities and minority students.

A few examples of these exciting initiatives include:

MESSENGER Education Module Development

A set of MESSENGER Education Modules (MEMs) are being produced in connection with the mission. The Modules are standardized presenter's packages that can be used by educators and teacher trainers nationwide in grades pre-K through 12 classrooms. At the core of the MEMs are concept-based, inquiry-driven lessons which address Solar System science, planetary observations through history, and the engineering associated with building and sending a spacecraft to another world. Carnegie Institution of Washington Carnegie Academy for Science Education is overseeing the development of the grade level preK-1 and 2-4 components. The National Center for Earth and Space Science Education is developing the grade level 5-8 and 9-12 components.

The MESSENGER Educator Fellowship Program

The MESSENGER EPO Program sponsors a nationwide teacher training initiative whereby a cadre of Fellows—master science teachers at the elementary, middle, and high school levels—will receive training on the MEMs and conduct educator workshops nationally, training up to 27,000 grade preK-through-12 educators over the mission lifetime. National Center for Earth and Space Science Education is responsible for developing and managing the Fellowship program.

MESSENGER Online

An extensive Web environment has been developed for the MESSENGER EPO Program. Some aspects of the Web site include online science courses and classroom materials for preK-12 teachers. Among other services, the Web site allows download of MEMs by an international audience. View the education Web site at http://messenger-education.org/.

Teaching about the MESSENGER Mission–MESSENGER Educational Pedagogy

For the purposes of teaching about the MESSENGER spacecraft and mission design, and for making that information relevant to the lives of young people today, we have created an educational program, which parallels the 10-year MESSENGER mission. We start from the notion of sending a human-made probe to the closest planet to the Sun, and we ask students to consider the processes and humanpower needed to complete such a mission.

We continue by introducing students to different branches of science that must be studied for an understanding of the data retrieved from the spacecraft. These include astronomy, physics, chemistry, geology, thermodynamics, magnetism, optics, and computer science, to name just a few.

We extend beyond the sciences to make interdisciplinary connections to, e.g., mathematics, technology, social studies, and all aspects of literacy to strengthen students' abilities across the curriculum, helping them discover cultural as well as scientific understandings of the planets, the Sun, and the skies.

We develop students' literacy of science by using appropriate scientific vocabulary and concepts, while also helping them build their literacy through science, as we use inherently fascinating scientific phenomena as a means of promoting reading and writing.

We launch design challenges that motivate students to build systems, design experiments, discover improved ways of doing things, and observe the world around them, in an effort to provide them the required context to best learn the skills they will need throughout life, in all areas.

We approach science education by asking essential questions that drive the quest for knowledge, by giving students ample opportunities to explore situations that embody important scientific ideas, and by encouraging them to express their ideas about what they are exploring. Teachers are then able to choose appropriate ways of helping students test their ideas, to discover which ideas apply more widely and may be more scientifically-derived than what they had previously thought.

We design activities that require first-hand observations as well as in-depth study of existing data. In both cases, students are allowed to develop ideas more fully as they work through their own creative thinking and problem-solving, rather than through rote memorization. It is essential that children change their own misconceptions as a result of what they find themselves, not merely by accepting other ideas they have been told are better than their own.

We encourage creativity and thinking outside the box, while making sure that national science standards are directly addressed in every lesson. Children learn science best through a process that helps them link ideas and develop new concepts. We make full use of science process skills (observing, measuring, hypothesizing, predicting, planning and carrying out investigations, interpreting, inferring, and communicating) to help them make sense of the world around them. In addition to traditional summative evaluations at the end of a lesson, we offer forms of formative assessment throughout the teaching process, so that the teacher is aware of students' evolving ideas and skills. Furthermore, this information is an integral part of effective teaching, since it can significantly change the direction of a given lesson to better address problems or misconceptions that persist.

In general, we provide a context for understanding the significance of scientific ventures and engineering feats such as the MESSENGER mission, and we open the door to students who will both understand and build the future.

MESSENGER Education Themes and MESSENGER Stories

The MESSENGER Education Modules concentrate on the following themes:

- **Comparative Planetology –** Understanding the planets as individual worlds and as part of a larger family by studying their similarities and differences. It is a look at what we know about our family of planets, and what we do not know. It also addresses what is currently known about Solar System formation and evolution. MESSENGER stories relevant to this theme include what Mercury tells us about the family of planets, and how MESSENGER observations are specifically framed to change our view of the Solar System.

- **The Solar System Through History –** How we have come to know what we know about the Solar System, and what future exploration of the Solar System might entail. The student will explore the Solar System through the eyes of, and resources available to, past generations. MESSENGER stories relevant to this theme include different cultures' views of Mercury through history as a case study of planetary observations; and how MESSENGER science and engineering stands on the shoulders of past generations.

- **Framing Pathways to Answers: The Scientific Process in Action –** An exploration of the scientific process as applied to two fundamental types of problems:
  - Solving engineering and design problems within a context of constraints.
  - Exploring a phenomenon of nature by asking a question of that phenomenon, framing

experimental pathways to acquire data, and interpreting that data in the context of a greater body of knowledge.

This theme also places research and exploration in a human context. Relevant stories include solving MESSENGER engineering problems to make the mission possible, and framing experimental pathways to do MESSENGER science.

MESSENGER Education Modules

Each theme defines a MESSENGER Education Module (MEM) that is a story in one to three Units, each like a chapter of a book. Each Unit is associated with its own sub-story told through as many as three Lessons at various grade levels. There are also two overarching MEMs that carry elements of all the themes at the same time. Figures in the next few pages show the overall structure and the contents of the currently available MEMs.

Connections to Science Education Standards and Benchmarks

MESSENGER Educational Modules (MEMs) focus on not only what science is taught but also how science is taught. Many state and local districts use National Science Education Standards and American Association for the Advancement of Science Project 2061 Benchmarks as the foundation for their science curriculum. The MESSENGER Education Modules are mapped to the standards, with a standards matrix found in each Unit. The MEMs emphasize activities that encourage students to ask questions and become deeply involved in work that is based on their own ideas. MEMs stress inquiry-based, process-driven approaches to science education.

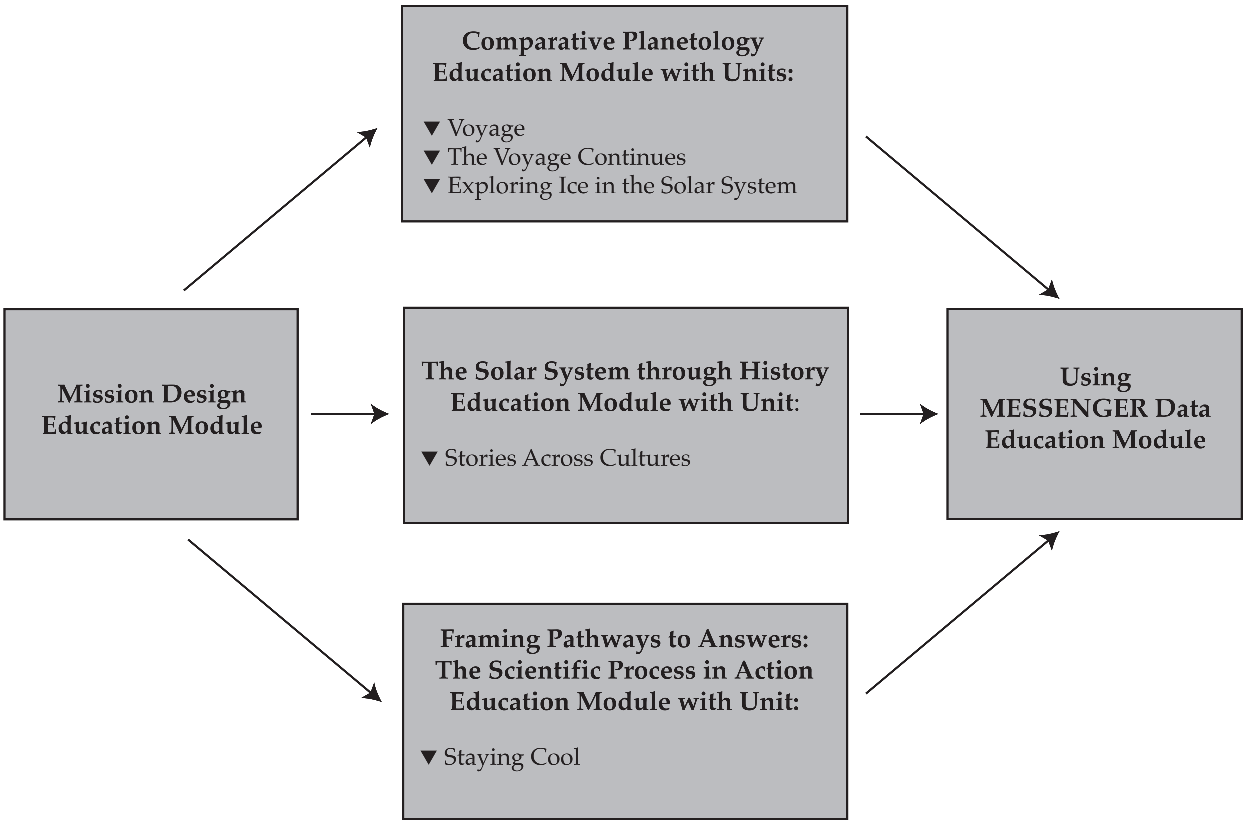


Figure: The complete thematic framework for the MESSENGER Education Modules. Two overarching Modules bookend elements concentrating on each MESSENGER education theme. The Modules connected to individual themes include 1-3 Units that tell the story of the Module.

Currently Available Education Modules and Units

MESSENGER Education Module: Mission Design for Middle and High School

5-8	Exploring Exploring	Mission: Possible – How to Plan an Exploration of Another World	Look But Don't Touch – Exploration with Remote Sensing
9-12	Exploring Solar Systems Across the Universe	Give Me a Boost – How Gravity Assists Aid Space Exploration	Can You Hear Me Now? – Communicating with Spaecraft

MESSENGER Education Module: Comparative Planetology

Unit: *Voyage*: A Journey Through Our Solar System

K-2	Making Models to Understand Our Home	A View of Home from the Front Door and from Space	Taking a *Voyage* Away from Home
3-4	Modeling Patterns and Cycles in Our Lives	Designing a Scale Model of the Solar System	*Voyage* Through the Solar System
5-8	Our Solar System	*Voyage* of Discovery	How Far Is Far?
9-12	A Scale Model Solar System	The *Voyage* Scale Model Solar System	

Unit: The *Voyage* Continues

5-8	Going through a Phase	Round and Round We Go – Exploring Orbits in the Solar System	Where to Look for Life?
	Is There Anyone Out There?	Comets: The Bringers of Life?	Impact Craters – A Look at the Past

MESSENGER Education Module: Comparative Planetology

Unit: Exploring Ice in the Solar System

Pre-K - 5	Inquiry Icebreaker: An Ice Experience			
	Lesson 1: Melting and Freezing	Lesson 2: Ice Has Structure	Lesson 3: Ice Is a Mineral	Lesson 4: Ice Floats
	Lesson 5: Ice Flows	Lesson 6: Snow Is Ice	Lesson 7: Layers of Ice	Lesson 8: Life in Icy Places
	Lesson 9: Ice in Space	Lesson 10: Comets	Lesson 11: Investigating Icy Worlds	Lesson 12: Ice in the Shadows

MESSENGER Education Module: Framing Pathways to Answers: The Scientific Process in Action

Unit: Staying Cool

Pre-K-1	Cooler in the Shadows			Design Challenge: How Can I Keep My Lunchbox Cool?
2-4	Sensing Energy			Design Challenge: How Do You Keep Things from Getting Too Hot?
5-8	Sensing the Invisible – The Herschel Experiment	Snow Goggles and Limiting Sunlight	My Angle on Cooling – Effect of Distance and Inclination	Design Challenge: How to Keep Gelatin from Melting?
9-12	Star Power – Discovering the Power of Sunlight	Dangers of Radiation Exposure	Cooling with Sunshades	Design Challenge: How to Keep Items Cool in Boiling Water?

How to Use a Lesson

Each Lesson within the MESSENGER Education Modules has been instructionally designed with a variety of components, each serving a specific function as a means of delivering a comprehensive and powerful inquiry-based lesson. This document offers teachers an explanation of each section in a Lesson.

Lesson Components:

- *Title and Grade Level of Lesson* – The general theme for the given grade level range.
- *Duration of Lesson* – Anticipated duration of the lesson in the classroom.
- *Lesson Summary* – After reading the summary, the teacher should understand the underlying principles of the lesson, including how it fits into the overall theme of the Module.
- *Essential Question* – This overarching question provides teachers with the main focus of the lesson. Students should be able to answer this question at the completion of the lesson.
- *Objectives* – These objectives are measurable outcomes expected of students.
- *Concepts* – The lesson should provide insight and provoke questions about fundamental concepts.
- *MESSENGER Mission Connection* – Each lesson relates to a specific aspect of the MESSENGER mission to Mercury. This section explains the reason why this lesson is included in the MESSENGER Education Module (MEM).
- *Standards & Benchmarks* – The National Science Education Standards and the American Association for the Advancement of Science Project 2061 Benchmarks are the driving force behind these lessons. Each lesson addresses 1-3 core standards and benchmarks, and may address many more related standards and benchmarks.
- *Science Overview* – This section provides the teacher with background information essential to facilitating the activities in the lesson. Enough information is provided so that answers to most of the questions the teacher (or students) may have can be found in the Science Overview. For a more comprehensive discussion of the topics in the Overview, a science textbook is an appropriate source. The teacher can choose to read or skim as much of this material as they find necessary, which may depend on their personal science background. This section is not intended to be used by the students, although sections may be shared with the students at the discretion of the teacher.

- *Lesson Plan* – The lesson description provides specific instructions for the teacher. It includes everything the teacher requires to carry out the lesson. Teachers are strongly encouraged to adapt the procedures to best meet their needs in their own classroom. (See Lesson Plan description below.)
- *Internet Resources & References* – A list of Web sites that will enhance or clarify the concepts within each Lesson. These include the MESSENGER web site, National Science Education Standards, Benchmarks for Science Literacy, and additional Web sites that may aide in understanding the Science Overview.
- *Student Worksheets* – Worksheets may be copied and given to individual students. They supply the students with everything they need in order to perform the activities. There may be additional worksheets that apply what they have learned from the activity to other concepts within the lesson. Some worksheets are optional or offer challenges for advanced students; these worksheets are clearly marked.
- *Answer Keys* – Includes correct or suggested answers for teachers. Used to aid in assessment.
- *MESSENGER Mission Information Sheet* – Can be copied and handed out to the students to provide them with background information about the MESSENGER mission to Mercury.
- *MESSENGER Mission Science Goals* – Grades 9-12 Lessons include further information on the science goals of the MESSENGER mission and provide a more detailed description how the lesson topic connects to the MESSENGER mission to Mercury.

Each Lesson Plan includes the following:

- *Preparation* – Suggests classroom organization, varied student groupings, set-up strategies, materials distribution, etc.
- *Materials* – Lists the supplies, books, etc., needed by the teacher and students.
- *Warm-up & Pre-assessment* – Strategies for getting students interested and motivated to participate in a lesson. Suggests ways to find out what students already know, including misconceptions they may have. (May occur in warm-up, homework discussions, or separately).

- *Procedures* – Steps to be followed by the teacher to conduct an activity.
- *Discussion & Reflection* – A guide to activities or discussion topics to help students better understand what they have been learning, anchor that new learning into existing knowledge, and to clarify any issues.
- *Lesson Adaptations* (in Special Education, Talented & Gifted, and English as a Second Language Programs) – Offers variations on the Lesson Plan to accommodate the needs of these students. Some lessons may not have adaptations.
- *Extensions* – The extensions allow students to develop higher and more complex levels of understanding concerning concepts and information that they have learned. Some lessons may not have extensions.
- *Curriculum Connections* – Describes the nature of the relationship between the science lesson and other traditional subject areas such as math, history, geography, art, music, English, physical education, technology, foreign languages, etc.
- *Closing Discussion* – Provides strategies for ending a lesson in a meaningful way for the students.
- *Assessment* – Suggests verbal, written or performance-based assessment strategies to verify progress during the lesson or activity.

In addition, *Teaching Tips* appear throughout the Lesson Plan.

MISSION DESIGN: A SHORT OVERVIEW

Introduction

The MESSENGER Education Modules (MEMs) are diverse packages of educational materials developed for the MESSENGER mission to Mercury and connected to the MESSENGER education and public outreach program themes: Comparative Planetology, The Solar System Through History, and Framing Pathways to Answers: The Scientific Process in Action. Each theme defines an Education Module that is a story in one to three Units, each like a chapter of a book. Each Unit is associated with its own sub-story told through as many as three Lessons at various grade levels. There are also two overarching MEMs that carry elements of all themes at the same time. *Mission Design* is one of the overarching MEMs.

The MESSENGER Education Module *Mission Design*

Mission Design provides an overarching framework for discussing exploration in general. The Module places space exploration in the greater context of the history of human exploration, and allows the students to investigate how scientists and engineers today plan missions to study worlds in the Solar System and extend their exploration even further in the Universe. The story of the Module unfolds through investigation of three questions:

- *Why* do we want to explore unknown environments?
- *How* can we plan our exploration?
- *What* do we do during our exploration?

Each grade level component of *Mission Design* consists of three Lessons, each of which addresses one of the essential questions above. For example, the grade 5-8 component begins with the Lesson "Exploring Exploring," in which the students investigate some of the basic reasons why humans have explored unknown environments throughout history, and how the tradition continues in the current era of space exploration. Lesson 2, "Mission: Possible – How Can We Plan an Exploration of Another World?," provides an understanding of how scientists and engineers design a mission to explore an unfamiliar environment, such as another world in the Solar System. In Lesson 3, "Look But Don't Touch – Exploration with Remote Sensing," the students discuss what kind of tools we can use during the exploration, concentrating on the most common tool of planetary exploration, remote sensing.

At both 5-8 and 9-12 grade levels the story is the same, but the lessons chosen explore phenomenology relevant to the specific science standards and benchmarks associated with the grade levels. The content and concepts are far broader than MESSENGER science and engineering, as they should be if these educational materials are to be relevant to the curriculum. The MESSENGER story is used as one vehicle to address a broad curriculum, which includes an understanding of the basic science and engineering concepts required to plan a spacecraft mission to study other worlds in the Solar System.

A Summary of Lessons in the Unit

Grade Level 5-8 Component

The grades 5-8 Lessons address the three basic questions in a broad manner to provide a comprehensive discussion of the Module's basic themes.

▼ *Lesson 1: Exploring Exploring*

The students investigate the concept of exploration through basic reasons that express why humans have always been explorers. They use the Internet to examine the characteristics of past explorers and why they conducted their exploration. The students then examine why current explorers—including the students themselves—want to explore other worlds in the Solar System. They conclude that no matter what or when we explore—past, present, or future—the reasons for exploration are the same; the motivation for exploration is universal.

▼ *Lesson 2: Mission: Possible — How Can We Plan an Exploration of Another World?*

The students explore how scientists and engineers plan missions to explore other worlds in the Solar System. The students will begin by discussing the path of a spacecraft traveling between planets, examining the journey from the Earth to Mars as an example. They will then determine the pros and cons of different ways we can explore another world, either by observing from the Earth or by sending a spacecraft to fly by, orbit, or land on the world. Finally, the students design a mission to explore a world of their choice, from defining the science goals to planning the spacecraft's payload while keeping the total mission budget in mind. By the end of the lesson, the students will understand that what you want to learn about another world determines how you plan the mission, but real-life constraints such as cost and time determine what actually can be accomplished.

▼ *Lesson 3: Look But Don't Touch —Exploration with Remote Sensing*

The students discuss different ways to study other worlds and concentrate on one of the most valuable methods: remote sensing. First, the students study aerial photographs of the Earth to identify geologic features, determine how they differ from one another, and examine the processes involved in their formation. The students then investigate how remote observations of a planetary surface can be used to create geologic maps. By the end of the lesson, students will understand how data gathered by spacecraft can not only be used to investigate the properties of an object, but also how it was formed, how it has evolved over time, and how it is connected to other objects nearby.

<u>Grade Level 9-12 Component</u>

The grades 9-12 Lessons focus on specific aspects of the Module's central questions, in this manner allowing exploration of concepts suitable for high school. If a teacher wishes to have the grades 9-12 students engage in the broader discussion contained in the grades 5-8 Lessons before proceeding to the more in-depth exploration of the relevant high school concepts, the grades 5-8 Lessons can be adapted easily for use at the high school level.

▼ *Lesson 1: Exploring Solar Systems Across the Universe*

The students investigate how exploration of our Solar System provides information on the properties of planetary systems elsewhere in the Universe—and vice versa. The students explore Solar System data to find clues to how our planetary system was formed. They then come to understand that other stars form just like the Sun, and, as a result, many stars could have planets around them. The students examine how scientists can find these extrasolar planets. By observing the behavior of a model star-planet system, the students realize that it is possible to see the effect a planet has on its parent star even if the planet cannot be seen directly. By comparing the properties of our Solar System with other planetary systems, we can gain a deeper understanding of planetary systems across the Universe. This is a great example of how exploration of one object can provide great insight on another; why exploration of two related phenomena can greatly benefit both.

▼ *Lesson 2: Give Me a Boost — How Gravity Assists Aid Space Exploration*

The students investigate how scientists can send a spacecraft to study other worlds 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 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. Therefore, the students will explore physical conservation laws by observing the behavior of balls colliding with other objects, before using an interactive online simulation tool to explore the ways in which gravity assists can be used to aid space exploration.

▼ *Lesson 3: Can You Hear Me Now? — Communicating with Spacecraft*

The students examine the essential role of computers and communications in space exploration: scientists must tell robotic spacecraft how to operate, gather data, and send the data back to the Earth for analysis. The students investigate two examples of how mission design can be improved to maximize the project's science return. They examine how the use of flowcharts can help make computer programs error-free and efficient, in this way making the spacecraft more reliable; and how data can be compressed for transmission over limited bandwidth. By the end of the lesson, the students come to realize that the wealth of data gathered by spacecraft is useless if it cannot be transmitted safely and efficiently to the scientists on the Earth.

Adaptability to Other Missions

While the *Mission Design* Education Module was developed in support of the MESSENGER mission to Mercury, it has been designed to be easily adapted to any mission exploring the Solar System. The goal of the Module is to provide an overarching framework for discussing exploration in the greater context of humans exploring unknown environments, and so the Lessons are designed to discuss concepts relevant to almost any mission of exploration. The only mission-specific components of the Lessons are:

- MESSENGER Mission Connection (on the second page of each Lesson)
- MESSENGER Mission Information Sheet (at the end of each Lesson)
- MESSENGER Mission Science Goals (at the end of each Grades 9-12 Lesson)

By just replacing these sections with content describing another mission, the Lessons can be used in the context of the new mission.

Mission Design

Connections to Standards and Benchmarks

This Education Module has been mapped to the National Science Education Standards (National Research Council, National Academy Press, Washington, D.C., 1996), and to the Benchmarks for Science Literacy (American Association for the Advancement of Science, Project 2061, Oxford University Press, New York, 1993, revised in 2009). A complete explanation of the Standards can be found at: http://www.nap.edu/html/nses/html/. A complete explanation of the Benchmarks can be found at: http://www.project2061.org/tools/benchol/bolintro.htm.

Grades 5-8

	Exploring Exploring	Mission: Possible – How Can We Plan an Exploration of Another World?	Look But Don't Touch – Exploration with Remote Sensing
National Science Education Standards, 5-8			
STANDARD A: SCIENCE AS INQUIRY			
A2: Understandings about scientific inquiry		x	x
STANDARD D: EARTH AND SPACE SCIENCE			
D1: Structure of the Earth system			x
D3: Earth in the Solar System	x		
STANDARD E: SCIENCE AND TECHNOLOGY			
E1: Abilities of technological design		x	
E2: Understandings about science and technology	x	x	
STANDARD G: HISTORY AND NATURE OF SCIENCE			
G3: History of science	x		
AAAS Benchmarks for Science Literacy, 6-8			
BENCHMARK 1: THE NATURE OF SCIENCE			
1C: The scientific enterprise	x		
BENCHMARK 2: THE NATURE OF MATHEMATICS			
2B: Mathematics, science, and technology		x	
BENCHMARK 3: THE NATURE OF TECHNOLOGY			
3A: Technology and science	x		x
3B: Design and systems		x	
BENCHMARK 4: THE PHYSICAL SETTING			
4A: The Universe	x		
4C: Processes that shape the Earth			x

Grades 9-12

	Exploring Solar Systems Across the Universe	Give Me a Boost – How Gravity Assists Aid Space Exploration	Can You Hear Me Now? – Communicating with Spacecraft
National Science Education Standards, 9-12			
STANDARD A: SCIENCE AS INQUIRY			
A1: Abilities necessary to do scientific inquiry			x
A2: Understandings about scientific inquiry			x
STANDARD B: PHYSICAL SCIENCE			
B5: Conservation of energy and increase in disorder		x	
STANDARD D: EARTH AND SPACE SCIENCE			
D3: Origin and evolution of the Earth system	x		
STANDARD E: SCIENCE AND TECHNOLOGY			
E2: Understandings about science and technology	x	x	
STANDARD G: HISTORY AND NATURE OF SCIENCE			
G2: Nature of scientific knowledge	x		
AAAS Benchmarks for Science Literacy, 9-12			
BENCHMARK 1: THE NATURE OF SCIENCE			
1A: The scientific worldview	x		
BENCHMARK 3: THE NATURE OF TECHNOLOGY			
3A: Technology and science		x	
BENCHMARK 4: THE PHYSICAL SETTING			
4A: The Universe	x		
4E: Energy transformations		x	
4F: Motion		x	
BENCHMARK 8: THE DESIGNED WORLD			
8D: Communication			x
8E: Information processing			x

Exploring Exploring

Lesson Overview

Lesson Summary

Students do not always realize that the steps in future exploration are built on a tradition of exploration that is as old as humankind. This lesson introduces the concept of exploration through basic reasons that express why humans have always been explorers; students decide on these reasons through a class discussion. In the first activity, students use the Internet to examine the characteristics of past explorers and why they conducted their exploration. The students then examine why current explorers—including the students themselves—want to explore other worlds in the Solar System. They conclude that no matter what or when we explore—past, present, or future—the reasons for exploration are the same; the motivation for exploration is universal.

Grade Level
5–8

Duration
Two 45-minute class periods

Essential Question

Why do we explore unknown environments?

Lesson 1
of the Grades 5-8
Component of the
Mission Design
Education Module

Figure 1. Exploration has always been an integral part of human history, from the exploration of the Earth across the oceans (modern-day replica of an ancient Polynesian voyaging canoe; top left) and over land (a map of the Lewis and Clark expedition over the Louisiana Purchase territory; top right), to exploration of the sky (photograph of the Wright Flyer; bottom right) and space (an artist's impression of the MESSENGER spacecraft investigating Mercury; bottom left.) (Picture credits: http://www.coris.noaa.gov/about/eco_essays/nwhi/media/voyaging_canoe400.jpg; http://www.loc.gov/exhibits/treasures/images/872m.jpg; http://www.grc.nasa.gov/WWW/K-12/aerosim/LessonHS97/WRIGHT.GIF; NASA/JHU-APL/CIW; http://messenger.jhuapl.edu/the_mission/artistimpression/artists_impression.html)

Objectives

Students will be able to do the following:

- Identify characteristics common to all explorers.
- State some of the basic reasons why people explore.
- Explain why humans should explore worlds outside of the Earth.

Concepts

- Explorers can be very different, but they share some common characteristics.
- The desire to explore is part of human nature, and it holds its foundation in our past.
- Space exploration has opened up a whole new area about which to ask questions and seek answers.

MESSENGER Mission Connection

The MESSENGER spacecraft is heading to Mercury so that humans can explore that world. Unveiling the mysteries of Mercury will not only provide a lot of information on this poorly known planet, but also help scientists learn more about the properties of other planets, including the Earth, and even provide clues to the formation of the Solar System. The reasons for exploring Mercury are the same reasons that have motivated explorers throughout human history.

Standards & Benchmarks

National Science Education Standards

Standard D3: Earth in the solar system

- The earth is the third planet from the sun in a system that includes the moon, the sun, eight other planets* and their moons, and smaller objects, such as asteroids and comets. The sun, an average star, is the central and largest body in the solar system.

Standard E2: Understanding about science and technology

- Many different people in different cultures have made and continue to make contributions to science and technology.

Standard G3: History of science

- Many individuals have contributed to the traditions of science. Studying some of these individuals provides further understanding of scientific inquiry, science as a human endeavor, the nature of science, and the relationships between science and society.

American Association for the Advancement of Science, Project 2061

Benchmark 1C/M1:

- Important contributions to the advancement of science, mathematics, and technology have been made by different kinds of people, in different cultures, at different times.

Benchmark 3A/M2:

- Technology is essential to science for such purposes as access to outer space and other remote locations, sample collection and treatment, measurement, data collection and storage, computation, and communication of information.

Benchmark 4A/M3:

- Nine planets* of very different size, composition, and surface features move around the sun in nearly circular orbits. Some planets have a variety of moons and even flat rings of rock and ice particles orbiting around them. Some of these planets and moons show evidence of geologic activity. The earth is orbited by one moon, many artificial satellites, and debris.

**Since the time these standards were written, the International Astronomical Union decided that there are only eight major planets in the Solar System. The former ninth planet, Pluto, is considered a dwarf planet.*

Science Overview

Humans have always had the desire to know, "What is out there?" It is easy to imagine our earliest ancestors being curious as to what was over the next hill, what was on the other side of this lake or over that mountain. However, in many cases, little is known about the early explorations since few records remain of them, except in stories that were handed down from one generation to the next. There are some human remains and tools that have been found around the Earth, so it is possible to track where the people lived and where they went. Cave drawings indicate what animals were hunted, and some of their bones have also been found in old human habitats. In addition to being curious, the early people tended to follow the source of their food (animals) in order to survive. Following the animals sometimes led the nomadic people to new areas that also contained other resources, such as better shelter or a source of water. In this way, the explorations also provided future generations a better place to live. Examples of human exploration throughout history show that even though the methods and tools of exploration may have changed, many of the basic reasons for exploration remain the same. Please note that human history offers stories of exploration too numerous to be described in detail here, and so the following paragraphs include just a handful of highlights of past and present exploration.

Figure 2. A view from the surface of Mars recorded by the robotic Spirit rover. What is on the other side of this hill? The question is an example of the kind of curiosity that has motivated explorers throughout history. (Picture credit: NASA/JPL-Caltech; http://marsrovers.jpl.nasa.gov/gallery/press/spirit/20060505a/Sol810A_P2536_L257F-A810R1_br2.jpg)

Ancient Explorers

One important reason for exploration has been to establish trade to improve the local economy. A good example is a group of people called the Minoans. They lived on the island of Crete off the coast of Greece in the Aegean Sea, with their civilization at its height from about 2600 to 1450 BCE. Since the Minoans lived on an island, they became great seafarers and established a trade network across the Mediterranean. Their explorations reached as far as mainland Greece, Cyprus, Egypt, and even Spain, to trade for supplies. The Minoans spoke a language that little is known about, and they wrote in a script that has not been deciphered. Therefore, many aspects of the Minoan culture remain unknown today and provide opportunities for archaeologists to make future discoveries.

The famous Norwegian explorer Thor Heyerdahl thought that people from South America could have settled Polynesia in the south Pacific in ancient times. He was curious to know if Stone Age people could have made the long trip across the ocean with the technology and the materials they had available. Heyerdahl gathered a small team and traveled to Peru to explore this possibility. The team constructed a balsawood raft in a style based on the illustrations made by Spanish conquistadors of old Incan rafts. Calling the raft Kon-Tiki, the team sailed for 101 days over 6,900 km (4,300 miles) across the Pacific Ocean before arriving at the Tuamotu Islands on August 7, 1947. While the exploration team had modern equipment such as a radio, as well as food and fresh water, they also were able to catch fish from the sea, as the raft attracted lots of marine life. As a result, in addition to showing that there were no technological constraints for the people of South America to make the journey across the Pacific, along the way, the exploration provided a lot of information about life in the sea. Even though modern linguistic, physical and genetic evidence suggests that the Polynesian islands were settled from South Asia instead of from South America, Heyerdahl's journey is an important example of modern exploration into ancient cultures by showing that the stone age people with limited technology could have made the long trip over open oceans of the South Pacific.

Perhaps because of the large distances between the islands on which they lived, Polynesians became excellent seafarers and used canoes (see Fig. 3) to journey across open seas hundreds of years ago. The people within the Polynesian triangle, cornered by Hawaii, Rapa Nui (Easter Islands) and Aotearoa (New Zealand), traveled frequently across the vastness of oceans with the help of skilled canoe crews. Of particular importance for these journeys were the navigators, who used their knowledge of the oceans, winds, and astronomy to guide the canoes safely even at times when the shoreline was no longer visible. In other parts of the world, gathering the courage to travel across open seas took centuries longer. In addition to basic curiosity, the journeys were driven by a desire to find more resources and new lands on which to settle. Frequent ocean journeys were later performed for commerce between the islands, and sometimes for conquering islands from earlier settlers.

Figure 3. A modern-day replica of an ancient Polynesian voyaging canoe. Polynesian voyagers used canoes to travel across the open oceans of the southern Pacific, reaching all the way to Hawaii. (Picture credit: http://www.coris.noaa.gov/about/eco_essays/nwhi/media/voyaging_canoe400.jpg)

Another group of great early explorers are the Vikings, who roamed the oceans of the North Atlantic from the late 8th century to the 11th century. While the Vikings usually are thought of only as the people who raided the coasts of Europe (and especially the British Isles), they were also merchants. They traveled from their native Scandinavian lands all around Europe, all the way to Northern Africa and the Middle East. They also ventured out to open seas, traveling to the islands across the North Atlantic, establishing a settlement in Greenland, and even to North America. Leif Erikson is the first European known to have traveled to North America, reaching Newfoundland in around the year 1000. The Vikings originally thought of settling into the area, which they called Vinland, but the idea was later abandoned, perhaps because of conflicts with the Native Americans living in the area already.

The Dawn of the Age of Discovery

Christopher Columbus is one of the best-known explorers of all time. He was instrumental in ushering in the so-called Age of Discovery, which was a period from the early 15th century to the early 17th century, during which European ships traveled around the world. They were exploring with an economic purpose in mind—to find new ways to reach desired trade destinations, as well as discover new trade partners—but along the way, the explorers discovered many new places and people. Columbus was an Italian explorer who, funded by Spanish monarchs, sailed across the Atlantic Ocean in 1492, hoping to find a new route to India and China to trade for goods such as silk and spices. Finding a new route was an important goal at the time to solve the problems that had arisen with the old land route called the Silk Road. Columbus made four trips to the Caribbean and South America during the years 1492-1504. He visited the Bahamas, Cuba, Central America, South America, and Hispaniola (now Dominican Republic) though not the North American mainland; he never found the route to India. However, he met new people and visited new places, and helped bring about a new era of exploration by opening a whole continent for European exploration, and, unfortunately, also for exploitation. Some of the other major explorers during the Age of Discovery include Vasco da Gama, who was the first person to sail directly from Europe to India by sailing around the southernmost point of Africa; Giovanni Caboto (also known as John Cabot), who was the first modern European to have arrived at the North American mainland; Yermak Timofeyevich, who explored Siberia; Ferdinand Magellan, who led the first expedition to sail around the world; and Willem Janszoon, who is thought to be the first European to have seen the coast of Australia.

The Lewis and Clark Expedition

After the lay of the lands and the continents on the face of the Earth was discovered, much remained to be learned about the interior of the continents. A good example of this type of exploration is the expansion of the Unites States in the early 19th century.

After the United States purchased the Louisiana Territory from France in 1803, President Thomas Jefferson was curious to know more of the new land west of the Mississippi River. He also thought that if there was a waterway from the Mississippi to the Pacific Ocean (called "the Northwest Passage"), whoever controlled it would control trade across the continent. Captain Meriwether Lewis and William Clark were chosen to lead an expedition to explore the new territory and to search for the waterway. The expedition was to keep a detailed diary of the people, plant life, animals, minerals, and the geography of the explored areas. Lewis and Clark spent months planning the expedition, since limited information about what they could expect on the journey made it difficult to decide what kind of supplies to bring along. The 33-member team left St. Louis, MO, in May 1804 for the journey and returned in September 1806 after reaching the Pacific Ocean. One of the key members of the expedition was Sacagawea, a Shoshone woman who joined the group in North Dakota and accompanied the team to the Pacific Ocean and back. She acted as a guide and an interpreter as the expedition traveled among the Native American tribes, located crucial resources when the team crossed the Rocky Mountains, and even rescued the expedition's journals, which had fallen into a river from a capsized boat. Even her

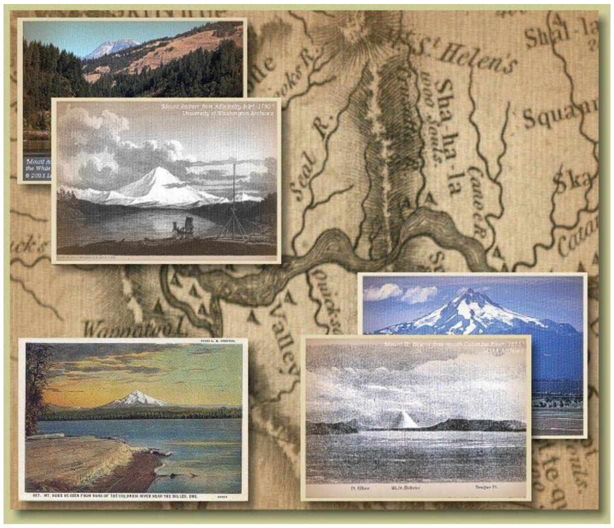


Figure 4. Pictures of some of the volcanoes encountered during the Lewis and Clark expedition over the Louisiana Purchase territory overlain on a map drawn during the journey. Expeditions over land and water were the main way of exploring unknown environments until the development of aircraft. (Picture credit: http://vulcan.wr.usgs.gov/LivingWith/Historical/LewisClark/SiteImages/beginning_image.jpg)

mere presence in the team was important to the success of the expedition: it conveyed to the tribes the expedition encountered that the travelers did not have hostile intentions, but were on a peaceful journey of exploration, instead. While the Lewis and Clark expedition did not find the Northwest Passage waterway to the Pacific Ocean, it returned with a wealth of information about the new lands west of the Mississippi River.

Exploration of Ocean Depths

Some of the areas of the Earth that are the least explored today are the depths of the Earth's oceans. While mapping out the sea floor in 1951, a British survey ship Challenger II located a deep depression at the bottom of the Pacific Ocean now known as the Mariana Trench, just east of the Mariana Islands. The bottom of the feature is about 11 km (7 miles) below sea level. What was at the bottom of the Mariana Trench? In 1960, the famous French underwater explorer, Jacques Piccard, and U.S. Navy Lt. Donald Walsh descended in the U.S. Navy bathyscaphe (a type of deep-sea exploration vehicle) Trieste to find out. The water pressure at the bottom of the trench is enormous, over 1000 times the standard atmospheric pressure at sea level. To their surprise they found organisms that could live at that depth. What was originally a curiosity about the shape of the sea floor led to the discovery of a deep trench, and curiosity about the new feature led to the discovery of organisms in a place where none was expected. Scientists now know that there is a lot of life at the depths of the oceans, and continued explorations of strange environments such as hydrothermal vents reveal many strange life forms in places scientists once thought no living beings could exist.

Exploration of Flight

One of the greatest achievements of human technological exploration is the first successful flight with a powered aircraft. On December 17, 1903, Wilbur and Orville Wright made four brief flights at Kitty Hawk, NC, with the aircraft they had designed (Fig. 5.) Even though these flights were short (the longest covering 262 meters, or 859 feet), they started the journey toward the development of modern airplanes.

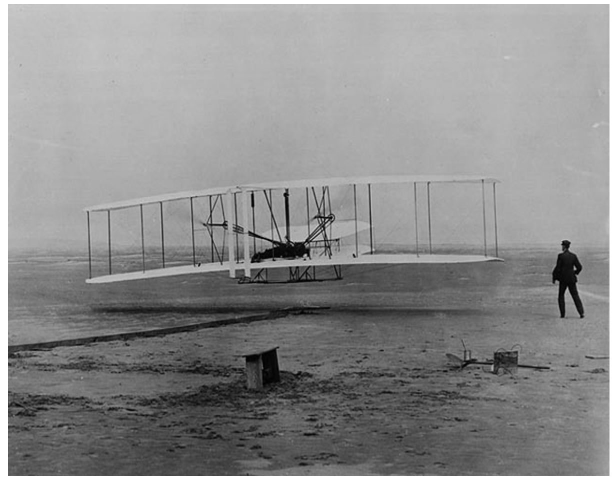


Figure 5. The Wright Flyer was the first modern airplane. Built by the brothers Wilbur and Orville Wright, the Flyer became the first heavier-than-air machine to fly a powered and controlled flight on December 17, 1903. (Picture credit: http://www.grc.nasa.gov/WWW/K-12/aerosim/LessonHS97/WRIGHT.GIF)

Another important aviation milestone was reached when Charles Lindbergh made the first solo non-stop flight across the Atlantic Ocean with the Spirit of St. Louis aircraft, flying from New York to Paris on May 20-21, 1927. The first flight across the Atlantic by a heavier-than-air aircraft had been performed earlier by the crew of the NC-4 in May 1919, but they made their journey in stages, and it took the crew 19 days to cross the Atlantic Ocean.

Amelia Earhart's name became a household word in 1932 when she became the first woman (and the second person ever) to fly solo across the Atlantic, on the fifth anniversary of Charles Lindbergh's feat, flying a Lockheed Vega from Harbor Grace, Newfoundland to Londonderry, Ireland. On June 1, 1937, she and Fred Noonan, her navigator, took off on an attempt to fly around the world starting from

Miami, FL. After numerous stops in South America, Africa, the Indian Subcontinent and Southeast Asia, they arrived at Lae, New Guinea on June 29. About 35,000 km (22,000 miles) of the journey had been completed. On July 2, 1937, Earhart and Noonan took off from Lae. Their intended destination was Howland Island, a tiny piece of land a few kilometers long, 6 meters (20 ft) high, and 4,113 km (2,556 miles) away. They never reached the island. A coordinated search by the Navy and Coast Guard was organized, but no physical evidence of the flyers or their plane was ever found.

On October 14, 1947, the Bell X-1 became the first airplane to fly faster than the speed of sound. Piloted by U.S. Air Force Capt. Charles E. "Chuck" Yeager, the X-1 reached a speed of 1,127 kilometers (700 miles) per hour, Mach 1.06, at an altitude of 13,000 meters (43,000 feet).

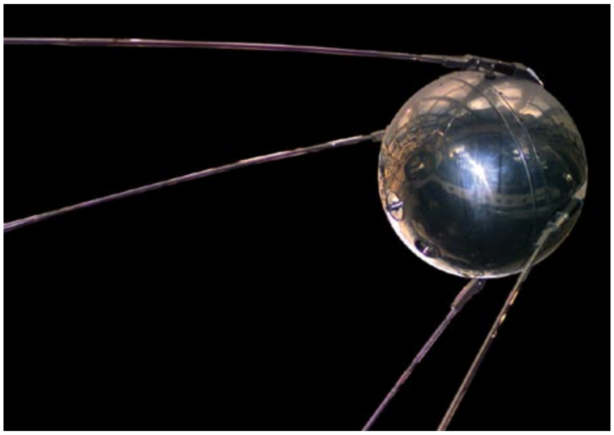


Figure 6. Sputnik 1 became the first human-made object to orbit the Earth in October 1957. (Picture credit: NASA Space Science Data Center; http://nssdc.gsfc.nasa.gov/planetary/image/sputnik_asm.jpg)

Exploration of Space

In October 1957 the Soviet Union announced the landmark launch of the satellite Sputnik (Fig. 6) into orbit around the Earth. The satellite was small—only 58 cm (23 inches) in diameter and weighed about 84 kg (185 lbs)—but powerful enough to transmit signals back to Earth, announcing to the whole world that the first human-made object had been sent to space. In this manner, Sputnik 1 opened a brand new frontier for human exploration. The first spacecraft launch was soon followed by others, including the first successful satellite launch by the United States in 1958.

Because the Sputnik launch occurred at the height of the Cold War, the American public became concerned about the Soviet space program. Politicians feared that Soviet superiority in space could threaten American national security. In response, the U.S. government formed the National Aeronautics and Space Administration (NASA) in 1958 to conduct all U.S. nonmilitary exploration of space. In October 1958, within its first week, NASA announced Project Mercury, its first manned space program. However, the Soviet Union also won this chapter of the so-called space race. In 1961, Yuri Gagarin became the first human to travel into space, as well as orbit the Earth, a few months before Alan Shepard, Jr., became the first American in space, and John Glenn the first American to orbit the Earth. The first woman in space was the Soviet cosmonaut Valentina Vladimirovna Tereshkova on the Vostok 5 mission in 1963. The first American woman in space was Sally Ride in 1983.

After the first human ventures into space, landing the first person on the Moon became the prized goal of both Soviet and U.S. space exploration. In 1961, President John F. Kennedy announced that the United States was planning a mission to land the first human beings on the Moon before the decade was over. This extraordinary milestone in human exploration took place on July 20, 1969, when Neil Armstrong and Buzz Aldrin landed safely on the surface of the Moon (see Fig. 7.) This historic moment forever changed the way humans look at the Universe. For the first time, a human being had set foot on a world other than our own!

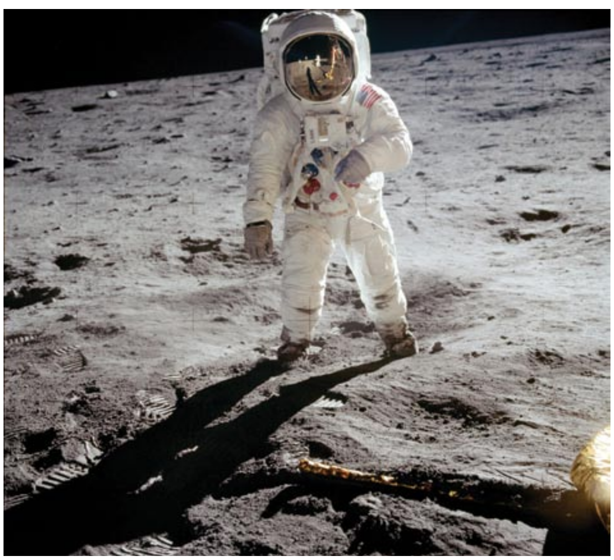


Figure 7. Picture of the lunar module pilot Buzz Aldrin taken by the Apollo 11 commander Neil Armstrong (whose reflection can be seen on Aldrin's helmet visor.) Armstrong and Aldrin became the first human beings to set foot on another world in the Solar System besides the Earth on July 20, 1969. (Picture credit: NASA Project Apollo Archive/Apollo Image Gallery, scanned by Kipp Teague, AS11-40-5903; http://www.apolloarchive.com/apollo_gallery.html)

NASA's Space Shuttle, officially called Space Transportation System (STS), has been the U.S. government's launch vehicle for human spaceflight since the 1980s. The winged Shuttle orbiter is launched strapped to an external fuel tank, carrying between five and eight astronauts into low Earth orbit, to a height of 185-643 kilometers (115-400 miles) from the Earth's surface. After completing its mission, the Shuttle re-enters the atmosphere and makes an unpowered gliding horizontal landing. During the program's history there have been five Shuttles used in the program. Two have been destroyed in accidents: Challenger, seconds after liftoff in 1986, and Columbia during reentry to the Earth's atmosphere in 2003. After each incident, Shuttle flights were suspended for about 2.5 years to investigate the disasters and fix the problems found, in order to avoid losing additional lives in future flights. The exhaustive investigations and the resumption of Shuttle flights after the disasters demonstrate NASA's dedication to human spaceflight. The remaining Shuttles—Atlantis, Discovery, and Endeavour—have been used mainly to construct and supply the International Space Station (ISS.) The fleet will be retired in 2011, after which NASA will rely on Russian spacecraft to carry astronauts to the ISS. NASA is planning to develop new spacecraft to carry humans even farther into space, but the state of these plans is uncertain at this time (June 2010.)

Robotic Exploration of Space

While human exploration of space is exciting because it involves actual human beings traveling to space, the space environment makes this mode of exploration challenging, dangerous, and expensive. As a result, humans have only traveled as far as the Moon and not any farther into space. Instead, robotic spacecraft have become invaluable in the exploration of the Solar System, providing us with information on our cosmic backyard. The history of the robotic exploration of the Solar System is long and full of interesting stories and discoveries, but instead of describing every milestone, the following paragraphs discuss just a handful of recent spacecraft missions.

A great example of current exploration of the inner Solar System is NASA's MESSENGER mission to Mercury (Fig. 8.) The spacecraft was launched in 2004 and after three flybys of its target planet in 2008 and 2009, it will go into orbit around Mercury in 2011. MESSENGER is only the second spacecraft ever to visit, and the first to orbit, the innermost planet of the Solar System. MESSENGER will provide a lot of information about the properties of the planet, the space environment near Mercury, and even the Sun. Its results will provide answers to a wide range of science questions, from the origin and evolution of Mercury to the formation of the Solar System and the properties of other planets, including the Earth.

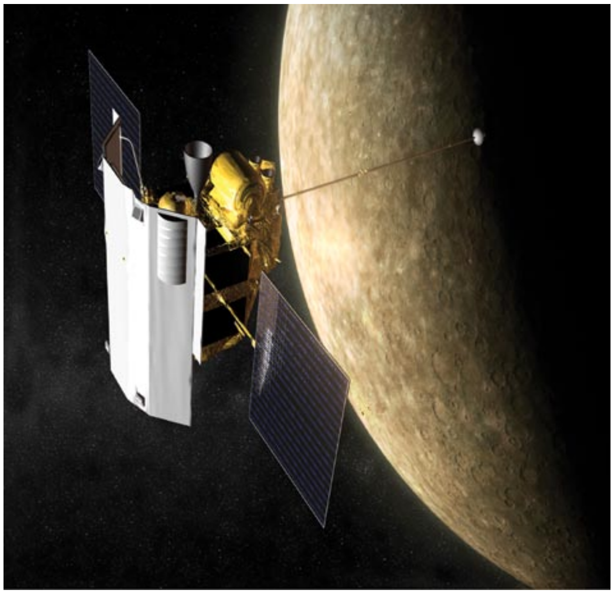


Figure 8. An artist's impression of the MESSENGER spacecraft exploring Mercury. MESSENGER is the first spacecraft to explore the innermost planet in the Solar System since the 1970s, and the first spacecraft ever to investigate the planet from orbit. (Picture credit: http://messenger.jhuapl.edu/the_mission/artistimpression/artists_impression.html)

Two robotic rovers (Spirit and Opportunity; known together as Mars Exploration Rovers) landed on Mars in January 2004. One of their main goals was to look for evidence of liquid water on the surface of Mars in the past. Finding signs of water is important, since one of the basic requirements for life as we know it is liquid water. If Mars had water on its surface in the past, perhaps it could have supported life at some point. Currently, Mars is a dry planet with only a very thin atmosphere consisting of mainly carbon dioxide. While previous spacecraft exploring the planet had shown that there used to be rivers on the Martian surface, the rovers were the first to find evidence showing that in the past Mars had lots of liquid water on its surface, in the form of lakes and oceans. Where did the water go? Why did the Martian environment change so that the surface featuring lakes and oceans became the dry wasteland we see today? While scientists are still trying to find answers to these questions, one possible answer to where the water vanished was provided by the spacecraft 2001 Mars Odyssey, which discovered that there is water frozen underneath the Martian surface near its south pole. Could there be life on the ice? That seems like a strange possibility to even consider. However, there are some microorganisms on Earth that can survive in ice by extruding a chemical that melts just enough ice around them to allow them to live. There are other forms of bacteria that survive in ice by going into a suspended state and being revived when the ice melts. To answer the questions of the history of water on Mars, and the possible presence of life there in the past or in the present, there are plans to send several other robotic missions to Mars in the next several years, including a mission that will return samples of the Martian soil to the Earth.

The Cassini-Huygens spacecraft mission is a joint project by NASA and the European Space Agency (ESA.) Since its arrival at Saturn in 2004, the spacecraft has been exploring the Saturn system, providing a wealth of new information about the planet, as well as its rings, magnetosphere, and moons. One of the central parts of the Cassini mission was the delivery of the Huygens probe to Saturn's moon Titan. Huygens entered Titan's atmosphere on January 14, 2005, and sent back pictures and other data for about three hours as it descended and landed on the surface. The probe provided an unprecedented look at Titan's surface, which had been previously hidden by the thick atmosphere's haze and clouds. The surface seems to be geologically active, and appears to have liquids flowing at least occasionally on its surface, though instead of water, the flowing liquid on the cold moon is methane. Titan, which has an atmosphere that in many ways resembles that of the early Earth, could be a possible host for life, if it was not so cold that no living beings that we know of could survive on its surface. As it is, it is unlikely any living beings ever could have survived on the surface of Titan.

The New Horizons spacecraft was launched by NASA in January 2006 to explore the outer reaches of the Solar System. It will be the first spacecraft ever to visit Pluto, when it flies by this small world in 2015. At present, we do not know much about Pluto, and the mission will reveal a lot of information about it and its three moons. After flying by Pluto, the robotic spacecraft will continue its exploration further out in the Solar System, where many icy worlds similar to Pluto reside. These worlds, the first of which was discovered in

1992, now include more than 1,000 known objects, and there are probably thousands more awaiting discovery. Most of these objects are smaller than Pluto, but a world called Eris, discovered in 2003, is a little larger than Pluto. This discovery led to the new classification of Solar System objects in 2006, when the International Astronomical Union (IAU) passed a resolution that Pluto, Eris, and other Solar System objects that are large enough to be spherical in shape but do not meet all the criteria of an actual planet belong to a class of objects called dwarf planets. Most of the objects in the region of the Solar System beyond the orbit of Pluto are not large enough to be called dwarf planets; they are just large chunks of ice and rock orbiting the Sun in the far reaches of the Solar System. Until the IAU resolution, Pluto had been known as the ninth planet, and many people were upset over what some saw as a demotion of Pluto. However, the initial furor has passed, and it appears that Pluto will be known as a dwarf planet from now on, unless some new discovery requires changes in the classification of Solar System objects again.

In addition to planets and their moons, as well as the newly classified dwarf planets, there are other objects in the Solar System that are interesting targets of exploration. One example of robotic space missions to these kinds of objects is NASA's Stardust mission to Comet Wild 2. The spacecraft flew by the comet in 2004, coming within 250 km (155 miles) of the nucleus of the comet at closest approach. The spacecraft took images of the nucleus and captured samples of comet material. The collected samples were returned to the Earth in 2006. Understanding the composition of different kinds of comets, which are thought to be leftovers from the formation of the Solar System, provide important clues to what the conditions in the Solar System were like during its formation, and how they have changed during its history.

Exploration of the Universe

Human curiosity and the desire to explore have always reached beyond the bounds of Earth. Even in ancient times, people wondered what lay beyond the Earth, but it has only been in the last few centuries, and especially in the last few decades, that technology has provided proper tools for our investigations. One of the great milestones in this process was the development of the telescope, which took place in about 1608. There is some dispute as to exactly who made the first telescope, but the feat is usually attributed to Hans Lippershey. However, there is little dispute about who was the first person to use the telescope for significant astronomical discoveries. Though other people may have used the new instrument to look at the sky, Galileo Galilei not only used (and improved) the telescope in the early 17th century to observe celestial objects no human had ever seen in such detail before, but also reported on his discoveries. In so doing, Galileo started the era of detailed astronomical observations not possible with the unaided eye.

Telescopes are the basic tool of observational astronomy, and they have become ever more accurate in modern times, when new ways to use this venerable tool have been developed. In 1923, German scientist Hermann Oberth suggested using a rocket to carry a telescope to space, and in 1946, the American astrophysicist Lyman Spitzer, Jr., wrote a detailed paper proposing a space observatory. He proposed placing a large telescope into space where it would be able to observe objects in space without having to deal with the blurring effects of the Earth's atmosphere. In 1975 NASA, along with the European Space Agency, began the development of the telescope that would later be known as the Hubble Space Telescope (HST). The telescope was named after the American astronomer Edwin Hubble, who is considered the founder of modern cosmology. In 1990 HST was placed into orbit around the Earth by the Space Shuttle. While it wasn't the first space telescope, the hundreds of thousands of pictures of more than 25,000 astronomical targets it has taken has made HST possibly the most important telescope in the history of astronomy. To honor the contributions of Lyman Spitzer, Jr., to the development of space telescopes, NASA named an infrared space telescope launched in 2003 after him; the Hubble and Spitzer Space Telescopes are part of NASA's Great Observatories program.

One of the technological advances that has made space telescopes possible is a camera that does not use film. Instead, space telescope use electronic devices known as Charge Coupled Devices (CCDs). These detectors can see objects that are a billion times fainter than what the unaided eye can see. These devices are also at the heart of every digital camera; while commercial digital cameras are built differently, they use the same CCD technology. This is a great example of how the desire to explore the Universe benefits from (and in return can influence the work of engineers working on more Earthly problems). The information captured by the HST's cameras are sent to the control centers on Earth (at Goddard Space Flight Center in Greenbelt, MD, and the Space Telescope Science Institute in Baltimore, MD) where computers are used to actually form the pictures we see on Web sites and in newspapers.

Learning More about Explorations in the Past

The paragraphs above offer just a brief glimpse into the history of exploration, and they cannot cover all the details, or even mention all the important stories from our history. Fortunately, finding out information on past explorations is easy with the help of the Internet. However, it is good to remember that even though the Internet has become an invaluable method of sharing information, sometimes the information may not be accurate. Anyone can publish a Web page discussing a topic of their choice, and it is entirely possible that the contents of the Web page are biased or inaccurate. As a result, it is important to consider the source of the information when doing

Internet research. The best sources of information on the Internet are usually government agencies, universities and affiliated research institutions, or well-known encyclopedias, though even they are not always 100% accurate.

When reporting on Internet research, it is important to cite as much of the information on the Web site as possible, including:

- The name of the author or editor
- The name of the Web site
- The posting date
- The name of the Web site publisher
- The date you accessed the material
- URL (Uniform Resource Locator); the standard way to describe Web page addresses.

using the format:

Editor, author, or compiler name. *Name of the Site.* Posting date. Name of Web site publisher. Date of access. URL.

Note that not every Web site includes all the information, but it is always advisable to include as much information as possible. For example, if you are referring to information published on January 10, 2010, on the NASA home page that you read on January 12, 2010, you would give the citation as:

Editor, author, or compiler name. *NASA Home Page.* January 10, 2010. NASA. Accessed on January 12, 2010. http://www.nasa.gov.

By documenting the source of information, anyone questioning the accuracy of the report can check the source themselves.

Exploration in the Future

As a child grows up and begins to crawl, the desire to investigate things (usually by putting new things into his or her mouth) begins. The method of investigation changes with age, but the basic curiosity is still there. After we learn that the lights in the sky are the Moon, planets, and stars, we begin to wonder what they are like. In this manner, the growth of the child follows the pattern the human race has taken. Humans were first curious about their immediate surroundings, traveling by land and by sea to explore their neighborhood. The first steps of exploration led humans to travel across the Earth and to investigate our home planet as a whole. In recent decades, human exploration has reached beyond the bounds of Earth into space. Humans have observed objects in space with telescopes, sent robotic spacecraft to explore different environments of the Solar System, and even landed humans on the Moon (a total of six times in 1969-1972.) There is little doubt that the human journey of exploration will continue in the future. Exploration is an essential part of human nature, and as far as the technological advances will allow, the human race will push the boundaries of exploration to see what the other neighborhoods in the Universe are like, and how they compare with our own neck of the woods.

Lesson Plan

Warm-Up & Pre-Assessment

1. Ask the students to think about past explorers. You can ask them to name a few past explorers and what they explored. Ask the students why they think these people wanted to explore. Write down the answers on the chalkboard or overhead projector. Stop when the list includes seven entries. The students may come up with many more reasons, but stop at seven, so that there are as many entries as letters in the word "explore" used in Step 3 below.

2. Ask the students to name a few present-day explorers, or careers that modern-day explorers may have (e.g., astronauts, historians, engineers, scientists.) Ask students to look at the list they made in Step 1; do the entries in the list apply to present-day explorers, as well? Make sure students understand that the reasons for past explorations are usually the same as the motivations for present explorations. Students may want to amend the list in light of thinking about exploration in general rather than just past exploration. Combine some of the reasons, if necessary, to keep the list at seven entries.

3. Divide the students into seven teams and hand out a piece of poster board and a set of markers to each team. Assign each of the teams one of the seven reasons they have come up with, as well as one letter from the word "EXPLORE." Instruct the teams to come up with an inspirational slogan to describe their reason for exploration that begins with their assigned letter. (The team assigned to "X" can make their letter the second or third letter in their slogan, as there are not many words that begin with the letter X.) Ask the students to design a poster based on their slogan. Advise the students to write their letter on top and then design the rest of the poster.

4. Tape the teams' posters on the wall, and discuss as a class the contents of the posters, the slogans and the underlying reason for exploration.

Materials

Per class:

- Roll of masking tape
- 7 sheets of poster board (1 sheet per team)
- 7 sets of markers (1 set per team)

ACTIVITY 1: FAMOUS EXPLORERS

In this activity, students will investigate different explorers and examine the driving questions behind their explorations. Students will choose an explorer that they are interested in studying, and conduct an Internet investigation on that explorer. Teachers will be advised as to the best ways for students to conduct this research, and students will learn how to conduct an effective Internet research project using credible sources. Students will answer questions about their explorer as to why he or she wanted to explore. As a group, the students will be able to add or subtract from the list of reasons for exploration that they had come up with in the warm-up section.

Materials

Per student:

- Internet access
- *Student Internet Resources*
- Student Worksheet 1

PREPARATION

- Make copies of Student Worksheet 1 and *Student Internet Resources* list located in the back of the lesson.

PROCEDURES

1. Ask the students to brainstorm a list of famous explorers. Possible answers include Columbus, Magellan, Lewis and Clark, Leif Erikson, Yuri Gagarin, John Glenn, Neil Armstrong, Amelia Earhart, Sally Ride, etc.
2. Have the students choose one of the explorers on the list—or another explorer that they are interested in learning about—to research.

Teaching Tips

Make sure that the students get an opportunity to research one of their favorite explorers, since it is important to research something in which the students are interested. However, also try to make sure also that there is a variety of explorers being researched in terms of historical times, subjects of exploration, and the personal characteristics of the explorers.

3. Hand out copies of *Student Internet Resources*. Have the students complete the questions on Student Worksheet 1 by visiting the Web sites listed, or finding other appropriate Web sites. Make sure that the students cite appropriately the sources of their information.

Teaching Tips

- Take this opportunity to review with the students what to look for in a reliable Web site. Point out that basically anyone can set up a Web page where they portray their opinions as facts. Make sure the students understand that having reputable sources is essential in good Internet research. Review how to cite Internet resources properly. See the *Science Overview* for further information.

4. Have the students prepare a poster or a short presentation about their explorer and his or her reasons for exploring.

Discussion & Reflection

1. Have the students briefly present the explorer he or she researched, either in front of the whole class or in small groups.
2. Ask the students to compare the explorers and their reasons for exploring. Were there any similarities? Were there any differences?
3. Discuss how the students learned that explorers can be very different in many ways, but all share some common characteristics. Refer back to the reasons for explorations the class discussed during the Warm-Up. Discuss whether the students themselves share those characteristics and are also explorers, questioning and learning new things about their environment.

Activity 2: Exploring the Solar System

Students will break into groups, and each group will receive a short write-up about a planet or another world in the Solar System. After reading the information, the groups will come up with an explanation why humans would want to explore that world, using the reasons they have explored in Activity 1 and the Warm-Up. They will create a poster or an electronic presentation (e.g., PowerPoint, Web page) which includes a proposal to NASA about why we would want to build a spacecraft to explore this particular world.

Materials

Per class:

- Audiovisual materials, depending on type of presentation (e.g., LCD projector, screen; place to hang posters.)

Per group of 2 or 3:

- *Space Exploration Card* (one card per group)
- Presentation materials (if presented electronically, students will need access to computers with appropriate presentation software; if with a poster, students will need access to poster board, markers, etc.)
- Student Worksheet 2

Preparation

- Make copies of Student Worksheet 2. Make copies of the *Space Exploration Cards* located in the back of the lesson so that each team will have one card.
- Remind students (or teach them) how to use PowerPoint or a similar presentation program, or how to make a simple Web page. Be sure to get all of the audiovisual needs taken care of before class.

Procedures

1. Remind students of the Warm-Up and Activity 1 as to why people explore. Ask them how the reasons relate to space exploration.
2. Have a discussion about why people want to explore space and ways in which they can do so (e.g. human spaceflight versus robotic missions, sending spacecraft to other planets, moons, asteroids, comets, etc.) Ask the students what they know about space missions that have taken place in the past, ones that are underway right now, and missions that are planned in the future.
3. Divide the students into groups of two or three.
4. Assign each group (or have each group choose) one of the worlds described on the *Space Exploration Cards*. Give each group the card pertaining to their world.
5. Hand out Student Worksheet 2. The Worksheet will guide students through the process of investigating why their world might be worth exploring.

Teaching Tip

Be sure to point out that even though each *Space Exploration Card* mentions the likelihood of life existing on the different worlds, the search for life is by no means the only, or in many cases even a very important, reason to explore these worlds. There are open science questions about all worlds discussed in the *Cards*, making them well worth exploring. Challenge the students to find basic science questions about the properties of the worlds based on their description; these questions are not spelled out in detail in the *Cards* themselves so that the students can come up with their own questions.

Discussion & Reflection

After the students present their planned missions, have each group give a "closing argument" as to why NASA should fund their mission. Make sure the groups focus on *why* they want to explore this world, and why others should want to explore it, too.

Teaching Tip

Have the students vote anonymously which mission they would choose—with the restriction that they cannot vote for their own mission. You may want to give a reward for the winning team.

Lesson Adaptations

- This lesson provides Web sites that the students can use for their research. However, you may want to take some time before the lesson to do your own research to find additional Web sites that are appropriate for your students' abilities and needs.

Extensions

- Enlist a local scientist to come to your class to talk about his/her explorations. Universities, university extension services, NASA centers, federal land management agencies, and private industries are good resources for locating scientists.
- Have the students locate an explorer in their community and write a short biography about that person, highlighting why the person is an explorer and what motivates him or her.

Curriculum Connections

- *History*: Have the students examine the role of explorers in shaping human history. We often focus on how wars and politics have shaped history, but what effect have new discoveries made by explorers had? How have explorations in the past been connected to other events taking place at the same time, such as armed conflicts, or societal and political concerns?
- *Language Arts*: Have the students read a novel or a short story about exploration, either real or imaginary. Have the students write a book report, focusing on the reasons the characters in the novel or the story explored.
- *Language Arts*: Have the students write a story of explorations hundreds of years from now. Will human desire for exploration continue? Where will these explorations take us?
- *History of Science*: In discussing exploration, we tend to concentrate on success stories. However, even a failed experiment or expedition may teach us a lot about the Universe around us. Have the students investigate cases where a failure or an accident has advanced our knowledge.

Closing Discussion

1. Discuss with the students how it is human nature to explore: babies crawl, kids survey the playground, teenagers question, and adults often find themselves in a new situation where they may have to explore previously unknown courses of action. We are all explorers. Exploration can lead the students to an exciting career that greatly enriches their lives and benefits society.
2. Lead a discussion about how exploring the worlds in the Solar System can help us understand our own world better. Students will find that the reasons for exploring a familiar place are the same reasons humans want to explore unknown environments and other worlds.
3. Discuss how our current explorations build on the work of previous explorers, who charted the face of the Earth, explored the depths of the oceans, reached into the sky, and now have taken the furthest reaches of exploration into space.
4. Discuss with the students how technology helps exploration. The explorations of today have been made possible by advances in our ability to create new tools to aid our exploration of the unknown.
5. The students should understand that no matter what we explore, whether it is a new city we have moved to, a new place on the Earth never seen by humans before, or another world in

the Solar System or in the rest of the Universe, the basic reasons we explore are the same; the motivation for exploration is universal.

6. Hand out copies of the *Mission Information Sheet* located at the back of the lesson. Discuss with the students how the mission builds on the rich history of exploration.

Assessment

4 points

- ▼ Student described the reasons for exploration for the explorer of his or her choice in Student Worksheet 1.
- ▼ Student used reasoning to explain why his or her group's assigned world is worth exploring in Student Worksheet 2.
- ▼ Student participated in the presentation of his or her group's proposal to explore their assigned world and used evidence and reasoning to support their proposal.
- ▼ Student completed both Worksheets.

3 points

- ▼ Three of the four above criteria were met.

2 points

- ▼ Two of the four above criteria were met.

1 point

- ▼ One of the four above criteria was 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/publications/bsl/online/bolintro.htm

National Science Education Standards

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

BBC Space Exploration Timeline

http://www.bbc.co.uk/science/space/exploration/missiontimeline/

Enchanted Learning Zoom Explorers

http://www.enchantedlearning.com/explorers/

The Explorers Club

http://www.explorers.org/

Mariana Trench

http://www.marianatrench.com/

The Mariner's Museum: Exploration through the Ages

http://ww2.mariner.org/exploration/index.php

NASA 50th Anniversary

http://www.nasa.gov/50th/home/

NASA Apollo Program

http://spaceflight1.nasa.gov/history/apollo/

NASA Cassini Mission

http://saturn.jpl.nasa.gov /

NASA Exploration: "Why We Explore"

http://www.nasa.gov/exploration/whyweexplore/why_we_explore_main.html

NASA History Division: Sputnik

http://www.hq.nasa.gov/office/pao/History/sputnik/

NASA Hubble Space Telescope

http://hubblesite.org/

NASA Mars Exploration Rovers

http://marsrovers.jpl.nasa.gov/home/

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

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

NASA New Horizons Mission

http://pluto.jhuapl.edu/

NASA Solar System Exploration

http://solarsystem.nasa.gov/

NASA Solar System Exploration: Dwarf Planets

http://solarsystem.nasa.gov/planets/profile.cfm?Object=Dwarf

NASA Space Shuttle

http://www.nasa.gov/mission_pages/shuttle/main/

NASA Spitzer Space Telescope: Lyman Spitzer, Jr.

http://www.spitzer.caltech.edu/about/spitzer.shtml

NASA Stardust Mission

http://stardust.jpl.nasa.gov/home/

National Geographic Lewis and Clark Web Site

http://www.nationalgeographic.com/lewisandclark/

The Nine Planets Web Site

http://www.nineplanets.org/

PBS: Polynesians Voyagers

http://www.pbs.org/wayfinders/polynesian.html

Polynesian Voyaging Society

http://pvs.kcc.hawaii.edu/

Smithsonian Institution National Air and Space Museum Space Race Exhibition

http://www.nasm.si.edu/exhibitions/gal114/gal114.htm

Smithsonian Institution National Museum of Natural History Viking Exhibition

http://www.mnh.si.edu/vikings/

Technical University Eindhoven Discoverers Web

http://www.win.tue.nl/~engels/discovery/

The University of Calgary: Christopher Columbus

http://www.ucalgary.ca/applied_history/tutor/eurvoya/columbus.html

U.S. Centennial of Flight Web Site

http://www.centennialofflight.gov/

Student Internet Resources

If the explorer of your choice is listed here, you may want to use the Web sites listed below to find information on the explorer. If he or she is not listed, you can use Internet search engines to find information on the explorer on other Web sites.

Explorers in General

http://www.win.tue.nl/~engels/discovery/

http://ww2.mariner.org/exploration/index.php

http://edtech.kennesaw.edu/web/explorer.html

http://www.enchantedlearning.com/explorers/

Apollo 11 Astronauts

http://www.nasa.gov/mission_pages(apollo)/apollo11_40th.html

http://www.hq.nasa.gov/office/pao/History/ap11ann/astrobios.htm

http://starchild.gsfc.nasa.gov/docs/StarChild/space_level2/apollo11.html

Christopher Columbus

http://ww2.mariner.org/exploration/index.php?type=explorer&id=12

http://www.ibiblio.org/expo/1492.exhibit/c-Columbus/columbus.html

http://www.ucalgary.ca/applied_history/tutor/eurvoya/columbus.html

Amelia Earhart

http://www.ameliaearhart.com/

http://www.acepilots.com/earhart.html

http://www.centennialofflight.gov/essay/Explorers_Record_Setters_and_Daredevils/earhart/EX29.htm

Leif Erikson

http://ww2.mariner.org/exploration/index.php?type=explorer&id=10

http://www.enchantedlearning.com/explorers/america.shtml

http://www.bbc.co.uk/history/historic_figures/erikson_leif.shtml

Yuri Gagarin

http://www.centennialofflight.gov/essay/Dictionary/GAGARIN/DI169.htm

http://starchild.gsfc.nasa.gov/docs/StarChild/whos_who_level2/gagarin.html

http://www.astronautix.com/astros/gagarin.htm

Galileo Galilei

http://galileo.rice.edu/

http://brunelleschi.imss.fi.it/museum/esim.asp?c=300251

http://www.pbs.org/wgbh/nova/galileo/

John Glenn

http://www.jsc.nasa.gov/Bios/htmlbios/glenn-j.html

http://www.johnglennhome.org/john_glenn.shtml

http://history.nasa.gov/40thmerc7/glenn.htm

Thor Heyerdahl

http://news.bbc.co.uk/1/hi/world/europe/1938294.stm

http://www.blueworldexplorer.co.uk/explorers/heyerdahl.htm

http://www.mnsu.edu/emuseum/information/biography/fghij/heyerdahl_thor.html

Lewis and Clark Expedition

http://www.nationalgeographic.com/lewisandclark/

http://www.pbs.org/lewisandclark/

http://www.nps.gov/lecl/historyculture/index.htm

Charles Lindberg

http://www.lindberghfoundation.org/charles_a._lindbergh/ charles_a._lindbergh-biography.html

http://www.charleslindbergh.com/

http://www.uh.edu/engines/epi1062.htm

Ferdinand Magellan

http://ww2.mariner.org/exploration/index.php?type=explorer&id=8

http://www.nmm.ac.uk/magellan/

http://www.bbc.co.uk/history/historic_figures/magellan_ferdinand.shtml

Sally Ride

http://www.jsc.nasa.gov/Bios/htmlbios/ride-sk.html

http://quest.arc.nasa.gov/people/bios/women/sr.html

http://www.greatwomen.org/women.php?action=viewone&id=125

Valentina Tereshkova

http://starchild.gsfc.nasa.gov/docs/StarChild/whos_who_level2/tereshkova.html

http://www.astronautix.com/astros/terhkova.htm

http://www.enchantedlearning.com/explorers/page/t/tereshkova.shtml

Orville and Wilbur Wright

http://www.pbs.org/kcet/chasingthesun/innovators/owwright.html

http://www.centennialofflight.gov/wbh/index.htm

http://wright.nasa.gov/index.htm

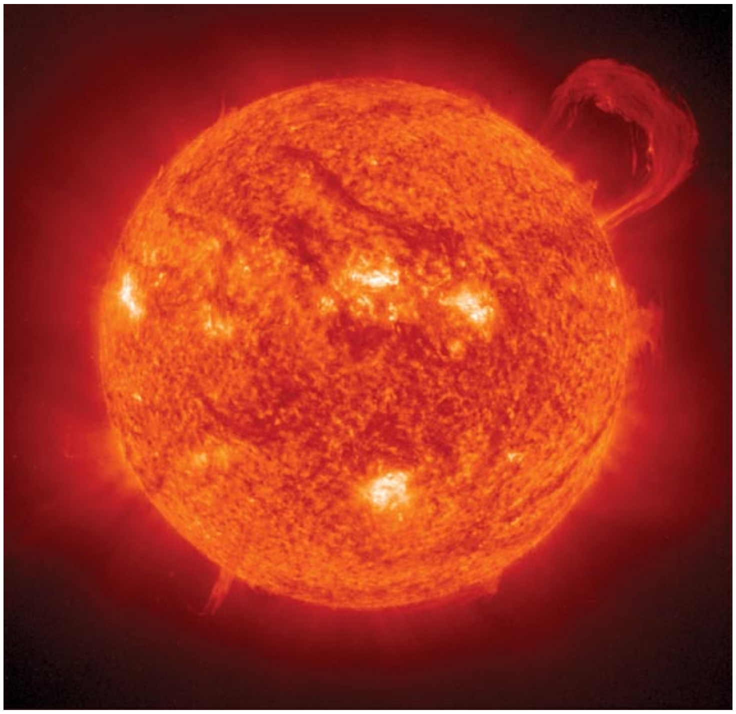
Charles E. "Chuck" Yeager

http://www.af.mil/information/bios/bio.asp?bioID=7680

http://www.aiaa.org/content.cfm?pageid=469

http://www.acepilots.com/usaaf_yeager.html

The Sun



The Sun is the star at the center of our Solar System. It is a fairly typical star, just one of over 200 billion stars in the Milky Way galaxy. It is not among the brightest or the faintest stars. Even though it is more massive than most of the stars in the Milky Way, there are still billions of stars more massive than the Sun. The reason it looks so big and bright as compared with the stars in the night sky is that it is very close to the Earth. The Sun's diameter is about 109 times the diameter of the Earth. The mass of the Sun is about 333,000 times the Earth's mass. The Sun's role as the center of the planetary system comes from its high mass; it has 99.8% of the mass in the Solar System and, therefore, guides the movement of the other objects in the Solar System via gravitational forces. The Sun is made up entirely of gas, mostly of hydrogen and helium, with heavier elements such as oxygen, carbon, neon, and nitrogen mixed in. The Sun is powered by nuclear fusion occurring at its center; in this process, hydrogen atoms are converted into helium, with energy released as a by-product. While the Sun is too bright to look into directly without damaging the eyes, special instruments can be used to observe the surface of the Sun. The surface is very active: on top of the basic granular surface appearance of the Sun, striking visible features include sunspots (relatively cool, darker regions,) prominences (cool, dense plasma extending outward from the surface,) and flares (great explosions on the Sun—the most violent eruptions in the Solar System.) The light emitted by the Sun brings energy to the rest of the Solar System and largely dictates the temperatures on the planets. Without the Sun, no life could exist on the Earth.

A Few Basic Facts About the Sun

Average distance from the Earth	150 million kilometers
Diameter	1.4 million kilometers
Mass	333,000 Earth masses
Rotation period (around its axis)	26-36 Earth days (varies from the equator to the poles)
Composition: main components	Hydrogen, helium
Temperature at the center	15.7 million ºC (28 million ºF)
Temperature on the visible surface	5,500ºC (10,000ºF)

For more information on the Sun, visit the NASA Solar System Exploration pagehttp://solarsystem.nasa.gov/planets/profile.cfm?Object=Sun

(Picture credit: Courtesy of SOHO/Extreme Ultraviolet Imaging Telescope (EIT) consortium. SOHO is a project of international cooperation between ESA and NASA; http://solarsystem.nasa.gov/multimedia/gallery/PIA03149.jpg)

Mercury

Mercury is the closest planet to the Sun. Its diameter is only a little more than a third of the Earth's, and it is smaller than some of the moons of the other planets (Jupiter's Ganymede and Saturn's Titan.) It has a very tenuous atmosphere, which is only a little more substantial than a vacuum. Sunlight heats up the surface of the planet to high temperatures during the day, up to 450ºC (840ºF). At night, the surface cools off rapidly, and the temperatures can drop down to –180ºC (–300ºF). This daily temperature variation is the largest of all of the planets. Mercury orbits the Sun once every 88 Earth days. Mercury's day is much longer than the Earth's. It rotates once around its axis every 59 Earth days; the slow rotation rate, combined with the planet's fast orbital period around the Sun, makes the the length of one day on Mercury is equal to 176 Earth days; that is, the time from one sunrise to another is 176 Earth days. There is no liquid water on Mercury, although it is possible that water ice could exist in the permanently shadowed craters near Mercury's poles. Mercury is a planet with a very large iron core and a thin mantle compared with the Earth. Mercury is bombarded by intense solar radiation since its atmosphere is not sufficiently thick to provide much protection (unlike the atmosphere of the Earth), and it is so close to the Sun. It is unlikely that any life could survive on Mercury, and it would be very inhospitable for any human explorers in the future. The first spacecraft to visit Mercury was Mariner 10, which flew by the planet three times in 1974 and 1975 and took images of about half of the planet's surface. Since Mercury is too close to the Sun to be safely imaged by the Hubble Space Telescope, the planet has remained largely unknown until recently. The robotic MESSENGER spacecraft flew by Mercury three times in 2008 and 2009, taking pictures of much of the unseen parts of the planet. In 2011 the spacecraft will go into orbit around Mercury to conduct a comprehensive study of the planet.

A Few Basic Facts About Mercury

Average distance from the Sun	0.387 AU[1]
Diameter	4,880 kilometers
Mass	0.055 Earth masses
Orbital period (length of one year)	88 Earth days
Rotation period (around its axis)	59 Earth days
Length of one day (sunrise to sunrise)	176 Earth days[2]
Main composition	Rock
Atmosphere	Virtually a vacuum
Average surface temperature	170ºC (330ºF)
Moons	None

[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*
[2]*The length of one day can be quite different from the rotation period for a slowly rotating planet like Mercury.*

For more information on Mercury, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Mercury

(Picture credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington; http://solarsystem.nasa.gov/multimedia/gallery/messenger_new_big.jpg)

Venus

A Few Basic Facts About Venus

Average distance from the Sun	0.723 AU[1]
Diameter	12,100 kilometers
Mass	0.815 Earth masses
Orbital period (length of one year)	225 Earth days
Rotation period (around its axis)	244 Earth days[2]
Length of one day (sunrise to sunrise)	117 Earth days[3]
Main composition	Rock
Atmosphere: main component	Carbon dioxide
Average surface temperature	462ºC (864ºF)
Moons	None

[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*
[2]*Venus rotates around its axis clockwise as seen from the north pole of the Sun, and not counterclockwise, as most other planets do; it is said to rotate in retrograde direction.*
[3]*The length of one day can be quite different from the rotation period for a slowly rotating planet like Venus.*

Venus is the second planet from the Sun and the brightest object in the Earth's sky after the Sun and the Moon. Venus is a near twin in size to the Earth but is otherwise very different. Venus's rotates around its axis very slowly, once every 244 Earth days. The slow rotation rate, combined with the planet's orbital period around the Sun—226 Earth days—makes the length of one day on Venus equal to 117 Earth days; that is, the time from one sunrise to another is 117 Earth days. In addition, Venus rotates in a clockwise direction when viewed from above the north pole of the Sun; this is opposite to the rotation of the Earth and most other planets. Venus has a very thick carbon dioxide atmosphere that traps heat from the Sun during the day and does not let the surface cool at night. As a result, the temperatures on the surface of Venus are over 464ºC (867ºF). Similar greenhouse effect operates also on the Earth, but on Venus the process went to extremes and raised the temperature to the high value seen today. To make the planet even more inhospitable, the atmospheric ressure on the surface of Venus is about 90 times as high as the air pressure at sea level on Earth. Any water that might have existed on the surface of Venus in the past has long since evaporated, and finding life on the planet is not likely (though not entirely impossible.) We may learn a lot about Earth by learning why Venus, in so many ways similar to the Earth, turned out so differently. The first spacecraft to visit Venus was Mariner 2, which flew by the planet in 1962. The planet has been subsequently visited by many other robotic spacecraft, including Venera 7, which in 1970 became the first human-made object to return data from the surface of another planet. In the 1990s the Magellan spacecraft used radar to peer through the thick atmosphere of Venus to map 98% of the planet's surface. The high temperature and unbreathable thick atmosphere makes the planet a hostile place for any explorers.

For more information on Venus, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Venus

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Venus_Clouds.jpg)

The Moon

A Few Basic Facts About the Moon

Average distance from the Earth	384,000 kilometers
Diameter	3,475 kilometers
Mass	0.0123 Earth masses
Orbital period (once around the Earth)	27.3 Earth days
Rotation period (once around its axis)	27.3 Earth days[1]
Length of one day (sunrise to sunrise)	29.5 Earth days[2]
Main composition	Rock
Atmosphere	Virtually a vacuum
Temperature range on the surface	–233 to +123ºC (–387 to +253 ºF)

[1]Because the Moon's rotation period around its axis and orbital period around the Earth are the same, the same side of the Moon always faces the Earth.
[2]The length of one day can be different from the rotation period for a slowly rotating object like the Moon.

The Moon is Earth's celestial neighbor. It is about 384,000 km (239,000 miles) from the Earth, and its diameter is about one quarter of the Earth's. It takes the Moon 27 1/3 days to go once around the Earth. The Moon's composition is very similar to those of the Earth and the other rocky, Earth-like planets in the Solar System. In fact, its similar composition to the Earth's crust material was a crucial clue in developing an understanding of its origin. The Moon is thought to have formed when a Mars-sized object smashed into the forming Earth billions of years ago. Material was blasted into orbit around Earth by this collision and later collected together to become the Moon. The surface of the Moon is heavily cratered as a result of meteoroid bombardment in the past. There are two main types of terrain on the Moon: the old, light-colored, heavily cratered highlands, and the younger, dark, smooth areas called maria. Many robotic spacecraft have explored the Moon throughout the history of space exploration, and the Moon has the unique privilege of being the only heavenly body that humans have ever visited. Between 1969 and 1972, six Apollo spacecraft landed on the Moon. The Apollo missions brought back a total amount of 382 kg (842 lbs) of rock samples from the surface of the Moon. Studies of these samples in laboratories here on the Earth have revealed lots of information about the composition, the structure, and the history of the Moon. There are currently plans to send humans back to the Moon and even establish a permanent colony there.

For more information on the Moon, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Moon

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/PIA00405.jpg)

Mars

A Few Basic Facts About Mars

Average distance from the Sun	1.524 AU[1]
Diameter	6,790 kilometers
Mass	0.107 Earth masses
Orbital period (length of one year)	687 Earth days
Rotation period (around its axis)	24 hours 37 min
Main composition	Rock
Atmosphere: main component	Carbon dioxide
Average surface temperature	–63ºC (–81ºF)
Moons	2

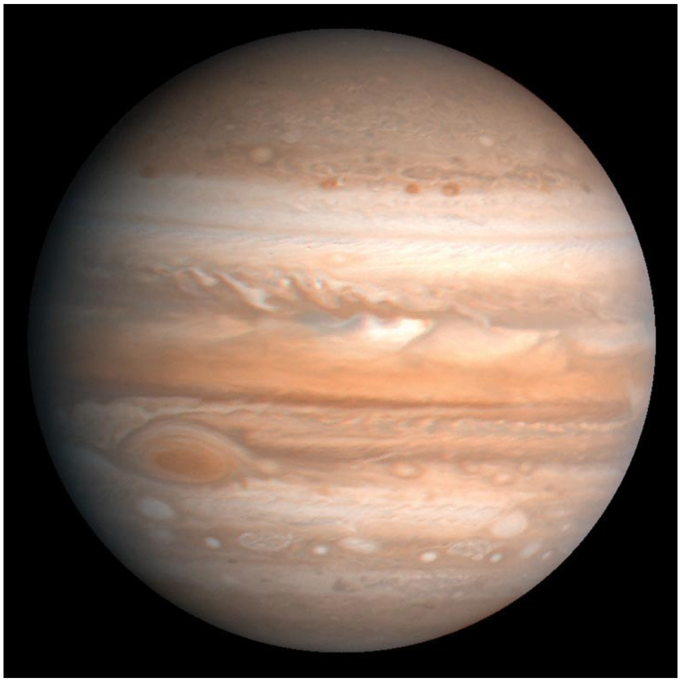
[1] *Astronomical Unit (AU) is the average distance from the Earth to the Sun.*

Mars is the fourth planet from the Sun. It is about half the size of the Earth in diameter. This makes the surface of Mars equal in area to all the land area on the Earth. The Martian day is about 43 minutes longer than the Earth day, and its year is 686 Earth days. Mars has a carbon dioxide atmosphere, but it is extremely thin, only about 1/100 as thick as the Earth's atmosphere. The thin air does not retain heat well, and surface temperatures range from a frigid –130ºC (–200ºF) on a winter night to 27ºC (80ºF) at the equator on a summer day. Mars appears red because iron contained in the rocks and the sand on its surface has combined with oxygen in the atmosphere through the same process that produces rust on the Earth. Mars occasionally has dust storms that cover the whole planet for months. Mars has polar ice caps made of carbon dioxide ice ("dry ice") and water ice. The size of the polar ice caps changes significantly during the planet's seasons. The first spacecraft to visit Mars was Mariner 4, which flew by the planet in 1965. Many robotic spacecraft have explored the planet since then. Two robotic rovers, Spirit and Opportunity, which have been roaming the surface of Mars since 2004, confirmed earlier suspicions that there used to be lots of liquid water on the surface of Mars in the past, in the form of rivers and seas. If there was plenty of water on the planet in the past, perhaps living beings could have existed there. Or, perhaps there are simple life forms still on Mars similar to bacteria on Earth that can survive in frigid conditions by creating anti-freeze chemicals that keep the water in their cells from freezing. In any case, Mars looks like the likeliest place for life to exist outside of the Earth. As a result, there are plans to send many other robotic spacecraft to Mars to explore the planet further, and even to return samples of Martian soil to Earth. Over the next few decades, Mars will probably become the second body in the Solar System after the Moon to host human visitors, and eventually to host the first colony of humans on another planet.

For more information on Mars, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Mars

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Hubble_Mars.jpg)

Jupiter



A Few Basic Facts About Jupiter

Average distance from the Sun	5.204 AU[1]
Diameter	143,000 kilometers
Mass	318 Earth masses
Orbital period (length of one year)	11.9 Earth years
Rotation period (around its axis)	9 hours 56 min
Main composition	Gas
Atmosphere: main components	Hydrogen, helium
Average temperature at cloudtops	–161ºC (–258ºF)
Moons	At least 63

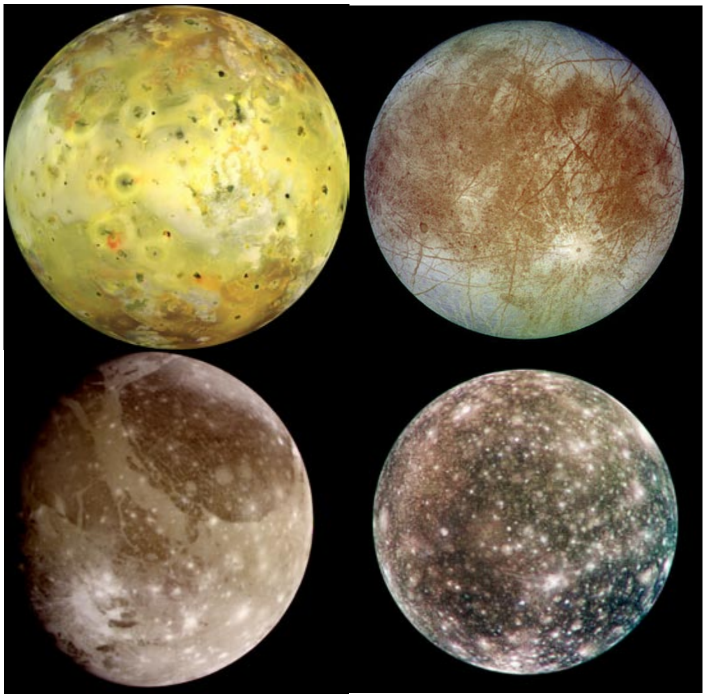
[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*

Jupiter is the fifth planet from the Sun and the largest planet in the Solar System. Its mass is 318 times the mass of the Earth, and over 1,300 Earths could fit inside of it. Jupiter is a gas giant mostly made of hydrogen and helium. Jupiter has no solid surface that we can see, and the apparent visible surface is just the top layers of clouds in its massive atmosphere. These upper layers of the atmosphere show complicated wind patterns. The winds blow in opposite directions in the light-colored zones and dark belts. Perhaps the most recognizable feature on Jupiter's visible surface is the Great Red Spot, a huge storm, more than twice the diameter of the Earth, which has been seen by observers on the Earth for more than 300 years. Deeper in the atmosphere, the gases become thicker until they eventually turn into a liquid. At its center, Jupiter may have a solid, rocky core a few times the size of the Earth, though based on current data, it is also possible that it does not have a solid core at all. Jupiter has at least 63 moons and a faint ring system. The ring system is much fainter than the rings of Saturn and was not discovered until the Voyager 1 and 2 spacecraft flew by the planet in 1979. Jupiter's day is about 10 hours long, and its year is about 12 Earth years. Jupiter radiates more energy into space than it receives from the Sun. This excess energy, produced by the planet being compressed under its own gravity, is thought to be ultimately responsible for the complex motions in Jupiter's atmosphere. The first spacecraft to visit Jupiter was Pioneer 10, which flew by the planet in 1973. The planet has since then been visited by several other spacecraft. It is unlikely that any life forms could live on the planet, and the lack of a solid surface on which humans could land on, as well as the high atmospheric pressure and high-energy radiation environment, make the planet a most challenging environment for any possible human visitors.

For more information on Jupiter, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Jupiter

(Picture credit: NASA; http://nssdc.gsfc.nasa.gov/imgcat/hires/vg2_usgs_1990.jpg)

Galilean Moons
Io, Europa, Ganymede, Callisto



The four largest moons of Jupiter (pictured in the left) are known as the Galilean moons, since they were discovered by Galileo Galilei in 1610. Jupiter's immense gravity exerts strong tidal forces on the moons. The tides bend and flex the rock of the crust and core of the moons, creating heat. The level of this tidal heating depends on the moons' distances from Jupiter, and the moons are quite different in their properties. Io (top left) is the innermost of the Galilean moons. The tidal forces from Jupiter generate enough heat to produce volcanoes and evaporate any ice and water the moon may have once had. With at least 180—and possibly as many as 400—active volcanoes, Io is the most volcanically active object in the Solar System, with a surface covered by sulfur, giving it the bright color. Europa (top right), the smallest of the Galilean moons, slightly smaller than the Earth's Moon, has a very smooth surface with few craters. The moon is covered by water ice that is probably a few kilometers thick, and underneath the ice there probably is a liquid water ocean. Ganymede (bottom left) is the largest moon in the Solar System, larger than the planet Mercury. It is the only moon known to have an internal magnetic field, possibly created the same way as the magnetic field of the Earth. Ganymede is thought to have an underground ocean, though the evidence is not quite clear as for Europa. Callisto (bottom right) is the second largest of the Galilean moons, and the third largest moon in the Solar System (after Ganymede and Saturn's Titan). Its surface is heavily cratered and ancient, and it does not appear to experience as much tidal heating as the other moons. However, it still may have a liquid water ocean under the surface. Since liquid water is thought to be one of the requirements for living beings, could life exist in the underground oceans? This question remains currently unanswered, but the Galilean moons will undoubtedly see new robotic spacecraft missions exploring this possibility in the future. The frigid temperatues at this distance from the Sun (–200ºC; –390ºF) and the dangerous high-energy radiation from Jupiter make the moons very uncomfortable places for any future human explorers.

A Few Basic Facts About the Galilean Moons

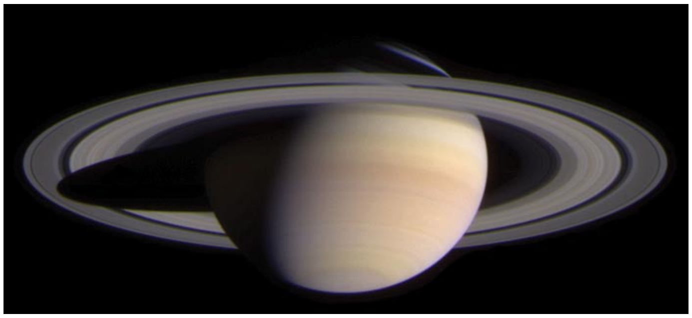
	Io	Europa	Ganymede	Callisto
Average distance from Jupiter	421,600 kilometers	670,900 kilometers	1,070,400 kilometers	1,882,700 kilometers
Diameter	3,640 kilometers	3,120 kilometers	5,260 kilometers	4,820 kilometers
Mass	0.015 Earth masses	0.008 Earth masses	0.025 Earth masses	0.018 Earth masses
Orbital period (around Jupiter)[1]	1.8 Earth days	3.6 Earth days	7.2 Earth days	16.7 Earth days

[1]*Because the rotation period around the axis and the orbital period around Jupiter are the same for these moons, their same side always faces Jupiter.*

For more information on the Galilean moons, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Display=Moons&Object=Jupiter

(Picture credits: Io: NASA/JPL/University of Arizona, http://photojournal.jpl.nasa.gov/catalog/PIA02308; Europa: NASA, http://nssdc.gsfc.nasa.gov/imgcat/hires/gal_p48040.jpg; Ganymede: NASA/JPL, http://photojournal.jpl.nasa.gov/catalog/PIA00716; Callisto: NASA/JPL/DLR, http://photojournal.jpl.nasa.gov/catalog/PIA03456)

Saturn



A Few Basic Facts About Saturn

Average distance from the Sun	9.582 AU[1]
Diameter	120,500 kilometers
Mass	95.2 Earth masses
Orbital period (length of one year)	29.5 Earth years
Rotation period (around its axis)	10 hours 39 min
Main composition	Gas
Atmosphere: main components	Hydrogen, helium
Average temperature at cloudtops	–189ºC (–308ºF)
Moons	At least 61

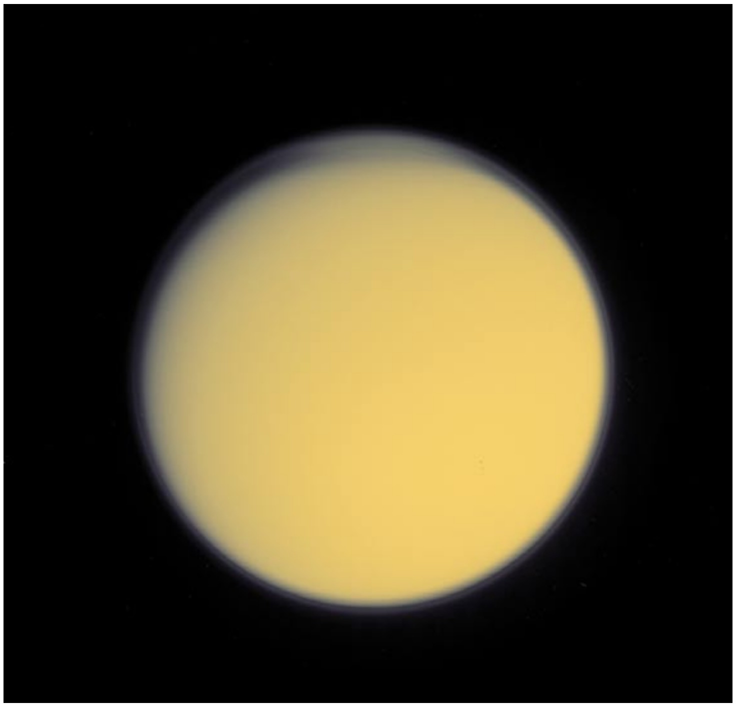
[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*

Saturn is the sixth planet from the Sun and the second largest planet in the Solar System after Jupiter. Its diameter is about 85% of Jupiter's but it is a lot lighter: its mass is about a third of Jupiter's. This means that it has a very low density. In fact, its density is the lowest of all the planets and less than the density of water. This leads to the popular description that in a planet-size bathtub filled with water, Saturn would float. Still, in composition and internal structure, the planet is thought to be fairly similar to its larger sibling, Jupiter. Like Jupiter, Saturn is a gas giant mostly made of hydrogen and helium gas. Saturn has no solid surface we can see, and the apparent visible surface is just the top layers of clouds in its atmosphere. These outer layers of the atmosphere have light-colored zones and dark belts, where the winds blow in opposite directions, but the bands are not as prominent as on Jupiter. Deeper in the atmosphere, the gases get thicker, until finally they turn into a liquid. At its center Saturn may have a solid core a few times the size of Earth, though based on current data, it is also possible that it does not have a solid core at all. Saturn's day is about 10.5 hours long, and its year is about 29.5 Earth years. Saturn has at least 61 moons, and perhaps many more that are yet to be discovered. Saturn's most striking property may be its exquisite ring system. All giant planets in the Solar System are surrounded by a complex ring system, but Saturn's ring system is, by far, the most extensive. The rings are surprisingly thin: they are 250,000 km (155,000 miles) in diameter, but their thickness is typically less than 10 meters (30 feet), though this varies somewhat within the ring system depending on the location and the size of the ring particles. Even though the rings look solid when viewed from the Earth, they are actually composed of millions of small icy particles varying in size from a centimeter (less than an inch) to a few meters (yards), and perhaps even to a size of a kilometer (half a mile). Scientists are still trying to determine the origin of the ring particles; the most commonly accepted suggestions are that they are particles blown off the planets' moons by asteroid or meteoroid impacts, or leftovers from the breakup of larger moons. Saturn radiates more energy into space than it receives from the Sun. Some of the excess energy comes from the planet being compressed under its own gravity, but some may come from other sources, such as helium gas condensing in Saturn's atmosphere into droplets and raining down deeper into the planet. The first spacecraft to visit Saturn was Pioneer 11, which flew by the planet in 1979. It has since then been visited by a handful of other spacecraft, most recently by the Cassini-Huygens spacecraft, which arrived at Saturn in 2004. It is unlikely that any life forms could live on Saturn, and the lack of solid surface on which humans could land on and the high atmospheric pressure make the planet an unlikely destination for human visitors.

For more information on Saturn, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Saturn

(Picture credit: NASA/JPL/Space Science Institute; http://solarsystem.nasa.gov/multimedia/gallery/Saturn_Approach.jpg)

Titan



A Few Basic Facts About Titan

Average distance from Saturn	1,221,800 kilometers
Diameter	5,150 kilometers
Mass	0.0225 Earth masses
Orbital period (once around Saturn)	15.9 Earth days
Rotation period (around its axis)	15.9 Earth days[1]
Atmosphere: main components	Nitrogen, methane
Average temperature at surface	–180ºC (–290ºF)

[1]Because Titan's rotation period around its axis and orbital period around Saturn are the same, the same side of Titan always faces Saturn.

Titan is one of the 61 known moons of Saturn, and the second largest moon in the Solar System (after Jupiter's Ganymede.) It is 1.5 as large in diameter as the Earth's Moon, and even larger in diameter than the planet Mercury. Titan's most interesting feature is that it is the only moon in to Solar System to have a significant atmosphere. At Titan's surface, the atmospheric pressure is 1.5 times that of the Earth's at sea level. The atmosphere is composed primarily of molecular nitrogen with a little argon and methane mixed in. In many ways, Titan's atmosphere is similar to the conditions on the Earth early in its history when life first emerged on our planet. But it is this thick hazy atmosphere that makes it so hard to see Titan's surface. Titan has been recently studied in detail by the robotic Cassini-Huygens spacecraft, which has been studying the Saturn system since 2004, and by the Huygens probe, which in 2005 flew through the moon's thick atmosphere and landed on the surface. The images taken by the spacecraft revealed an active surface with flowing liquids (composed of methane, rather than water) and many meteorological and geologic processes in action. Titan could have been a possible host for life, if it were not so cold—the temperature on the surface of Titan is frigid –180ºC (–290ºF)—that no living beings that we know of could survive on its surface. As a result, it is unlikely any living beings could have ever survived on the surface of Titan, and the moon would not be a comfortable environment for human visitors to explore.

For more information on Saturn, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Saturn&Display=Moons

(Picture credit: NASA/JPL/Space Science Institute; http://photojournal.jpl.nasa.gov/tiff/PIA06122.tif)

Uranus

A Few Basic Facts About Uranus

Average distance from the Sun	19.201 AU[1]
Diameter	51,100 kilometers
Mass	14.4 Earth masses
Orbital period (length of one year)	84.0 Earth years
Rotation period (around its axis)	17 hours 14 min[2]
Main composition	Gas, icy and rocky materials
Atmosphere: main components	Hydrogen, helium, methane
Average temperature at cloudtops	–220ºC (–364ºF)
Moons	At least 27

[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*
[2]*Uranus rotates around its axis clockwise as seen from the Sun's north pole, and not counterclockwise, as most other planets do; it is said to rotate in retrograde direction*

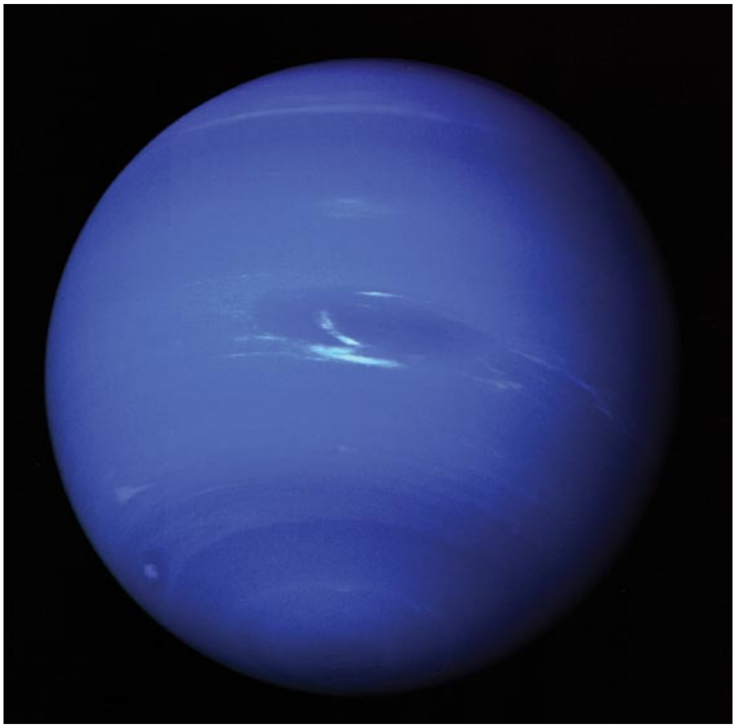
Uranus is the seventh planet from the Sun. It is smaller than Jupiter and Saturn, but similar to Neptune in size. Uranus's composition is a little different from Jupiter and Saturn in the sense that it seems to be made of mostly of a mixture of rocky and icy materials, and even though it has an extensive atmosphere by the Earth's standards, it is not as large a component of the planet as it is on Jupiter and Saturn. As a result, Uranus (as well as Neptune) is sometimes called an "ice giant" instead of a gas giant. Uranus has no solid surface that we can see, and the apparent visible surface is just the top layers of clouds in its atmosphere. These outer layers of the atmosphere have light and dark bands where the winds blow in opposite directions, but they are very faint and not visible in images taken of the planet without extensive image enhancements. However, it may be that the visibility of the bands changes according to the planet's seasons. Underneath Uranus's atmosphere, the mixture of icy and rocky materials is probably distributed uniformly, and the planet may not have a solid core at all. Uranus's day is about 17 hours long, and its year is about 84 Earth years. Uranus has at least 27 moons (and perhaps many more yet to be discovered.) Like the other giant planets, Uranus has a ring system, though it is much fainter than the rings of Saturn. Uranus's unique feature is that it appears to have been knocked over sometime in the past. Most planets orbit around the Sun spinning upright; that is, their rotational axes are almost perpendicular with respect to their orbit (with small deviations, like the Earth's 23.5º tilt). Uranus's rotation axis is almost lying within its orbital plane. The cause of this unique feature is not certain, but it may have been caused by an impact of a large object, such as an asteroid or a moon. Giant impacts like this were common during the early history of the Solar System; a similar impact is thought to have created the Earth's Moon. Unlike the other giant planets, Uranus does not appear to have an internal heat source. Why this is the case is not certain. The only spacecraft to have visited Uranus is Voyager 2, which flew by the planet in 1986. It is unlikely that any life forms could live on Uranus, and the lack of solid surface on which humans could land on, as well as the high atmospheric pressure make the planet a very difficult environment for humans to explore.

For more information on Uranus, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Uranus

(Picture credit: NASA and Heidi Hammel / Massachusetts Institute of Technology; http://photojournal.jpl.nasa.gov/tiff/PIA00032.tif)

MESSENGER
Mission to Mercury

Neptune



Neptune is the eighth planet from the Sun. It is smaller than Jupiter and Saturn, but similar to Uranus in size. Neptune's composition is a little different from Jupiter and Saturn in the sense that it seems to be made of mostly of a mixture of rocky and icy materials, and even though it has an extensive atmosphere by the Earth's standards, it is not as large a component of the planet as it is on Jupiter and Saturn. As a result, Neptune (as well as Uranus) is sometimes called an "ice giant" as opposed to a gas giant. We cannot see Neptune's solid surface, and the apparent visible surface is just the top layers of clouds in its atmosphere. Giant storm centers can be seen on its visible surface, similar to those on the other giant planets. Also, like on the other giant planets, the atmosphere has great wind patterns creating bands on the atmosphere where winds blow in different directions. In fact, the winds on Neptune are the fastest in the Solar System, reaching speeds of 2,000 km/hour (or 1,200 miles/hour) relative to the planet's interior rotation rate. Underneath the atmosphere, the mixture of icy and rocky materials making up the bulk of the planet is probably uniformly mixed, though there may be a solid core about the mass of the Earth at the planet's center. Neptune's day is about 17 hours long, and its year is about 165 Earth years. It has at least 13 moons; probably many more are yet to be discovered. Like the other giant planets, Neptune has a ring system, though it is much fainter than the rings of Saturn. The only spacecraft to have visited Neptune is Voyager 2, which flew by the planet in 1989. It is unlikely that any life forms could live on Neptune, and the high atmospheric pressure would make the planet quite inhospitable for human visitors.

A Few Basic Facts About Neptune

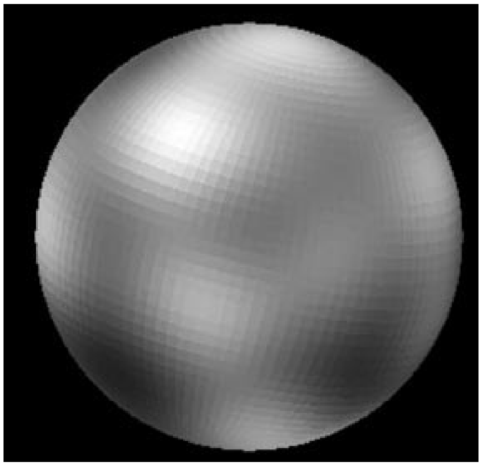
Average distance from the Sun	30.047 AU[1]
Diameter	49,500 kilometers
Mass	17.1 Earth masses
Orbital period (length of one year)	165 Earth years
Rotation period (around its axis)	16 hours 7 min
Main composition	Gas and icy materials
Atmosphere: main components	Hydrogen, helium, methane
Average temperature at cloudtops	–218ºC (–360ºF)
Moons	At least 13

[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*

For more information on Neptune, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Neptune

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Neptune_Full.jpg)

Pluto



A Few Basic Facts About Pluto

Average distance from the Sun	39.482 AU[1]
Diameter	2,390 kilometers
Mass	0.0021 Earth masses
Orbital period (length of one year)	248 Earth years
Rotation period (around its axis)	6.4 Earth days[2]
Moons	3
Main composition	Ice and rock
Atmosphere: main components	Methane, nitrogen
Average surface temperature	–223ºC (–369ºF)

[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*
[2]*Pluto rotates around its axis clockwise as seen from the north pole of the Sun, and not counterclockwise, as most major planets do; it is said to rotate in retrograde direction.*

Pluto used to be known as the ninth planet, but it always seemed a bit odd when compared with the other eight planets. Like the terrestrial planets (Mercury, Venus, the Earth, and Mars), it is small, but, because it is a mixture of rock and ice, its density is low, and it is not located in the same part of the Solar System as the terrestrial planets. Instead, it is located in the outer part of the planetary realm of the Solar System, where the giant planets reside, but it certainly is not a gas or an ice giant, either. Instead, Pluto appears to be more closely related to the hundreds of objects astronomers have discovered beyond Neptune's orbit in recent years. When one of these so-called Kuiper Belt Objects was discovered to be larger than Pluto, the International Astronomical Union decided in 2006 that Pluto cannot be considered a major planet any more, and instead belongs to a new class of objects called dwarf planets. As a result, there are now only eight major planets in the Solar System, and Pluto is an example of the new group of objects called dwarf planets. There are probably many more dwarf planets in the outer regions of the Solar System yet to be discovered. Pluto has three moons, but this is not unusual for smaller Solar System objects: many dwarf planets, Kuiper Belt Objects, and asteroids have moons. Pluto's day is about 6.4 Earth days long, and its year is about 248 Earth years. Pluto was discovered in 1930 by a fortunate accident. When scientists in the 19th and 20th centuries observed the orbits of Uranus and Neptune around the Sun, they noticed that the planets did not quite follow the predicted path in the sky. They deduced that there must be another planet-size object further out in the Solar System disturbing the orbits of these planets. Scientists started scanning the skies for planets in the places where the calculations suggested the planet (sometimes called "Planet X") would be, and in 1930 Pluto was discovered. However, it later turned out that Pluto's mass is much too small to cause the effects seen in the orbits of Uranus and Neptune. Eventually it was found out that the apparent problem with these observed orbits was not caused by a yet-to-be-discovered planet but by the fact that Neptune's mass was not known well at the time of the orbital calculations. We now know that no massive planet further out in the Solar System is needed to explain the orbits of Uranus and Neptune. Instead, Pluto's discovery turned out to be just fortunate happenstance. No spacecraft has ever visited Pluto. This will change soon, when the robotic spacecraft New Horizons, launched in 2006, will arrive at Pluto in 2015. The frigidly cold temperatures—the temperature on the surface of Pluto is thought to be –223ºC (–369ºF)—make it unlikely for any living beings to live on the dwarf planet, and they certainly make Pluto very inhospitable for any possible future human explorers.

For more information on Pluto, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Pluto

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/nssdc_hst_pr96_09a.jpg)

Asteroids

Asteroids are small rocky objects that can be found in different regions of the Solar System. They orbit the Sun like planets, but they are a lot smaller. Ceres used to be known as the largest asteroid; it is about 950 km (590 miles) in diameter. However, Ceres is now classified as a "dwarf planet", a new category of objects in the Solar System defined by the International Astronomical Union in 2006 to include objects like Ceres and Pluto, which are too small to be considered major planets, but resemble them in many other ways. Ceres is still associated with asteroids, since it is located in the same part of the Solar System as the vast majority of asteroids—the Asteroid Belt, a region between the orbits of Mars and Jupiter. The largest asteroids are Pallas, Vesta and Hygiea, which are between 400 km (249 miles) and 525 km (326 miles) in diameter. There are hundreds of thousands of known asteroids. Astronomers probably have seen almost all of the asteroids larger than 100 km, and about half of those with diameters in the 10-100 km range. But there are probably millions of asteroids with sizes in the 1 km range that have never been seen. Some of the moons of planets, such as the two moons of Mars and the outer moons of Jupiter and Saturn, are similar to asteroids, and they may be captured asteroids rather than having formed in the same way around the planet as other moons. Asteroids are thought to be remnants of the formation of the Solar System that did not accrete into the planets. There have been about a half-dozen spacecraft that have flown by asteroids, sometimes on their way to other destinations. The first spacecraft to take close-up pictures of an asteroid was Galileo, which flew by the asteroids Gaspra (in 1991), and Ida, as well as its moon Dactyl (in 1993), before heading to study Jupiter. The first spacecraft specifically designed to explore an asteroid was the Near-Earth Asteroid Rendezvous – Shoemaker spacecraft, which explored the asteroids Mathilde and Eros, and eventually landed on the surface of Eros in 2001. The spacecraft Dawn, launched in 2007, is planned to fly by Ceres and Vesta in 2011-2015. Because asteroids are small, they are unlikely to host living beings. However, they might be good sources of raw materials for future space explorers.

A Few Basic Facts About Asteroids

Range of average distances from the Sun	Most between 1.1-3.0 AU[1], some up to 14 AU
Diameters	1-960 kilometers
Masses	Up to 0.0002 Earth masses
Orbital periods (around the Sun)	Most between 1.1 and 5.2, some up to 51 Earth years
Rotation periods (around their axis)	2.3 to 418 hours
Main composition	Rock
Moons	Some asteroids have moons

[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*

For more information on asteroids, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Asteroids

(Pictured above: Asteroid Gaspra; picture credit: NASA/JPL; http://photojournal.jpl.nasa.gov/tiff/PIA00118.tif)

Comets

A Few Basic Facts About Comets

Range of average distances from the Sun	2.2 – 1,170 AU[1]; perhaps up to 50,000 AU
Diameters	A few to up to 20 kilometers
Masses	1-10 trillionth of Earth mass
Orbital periods (around the Sun)	3.3 –40,000 Earth years; even more for more distant comets
Rotation periods (around their axes)	3 – 70 hours
Main composition	Ice and rock

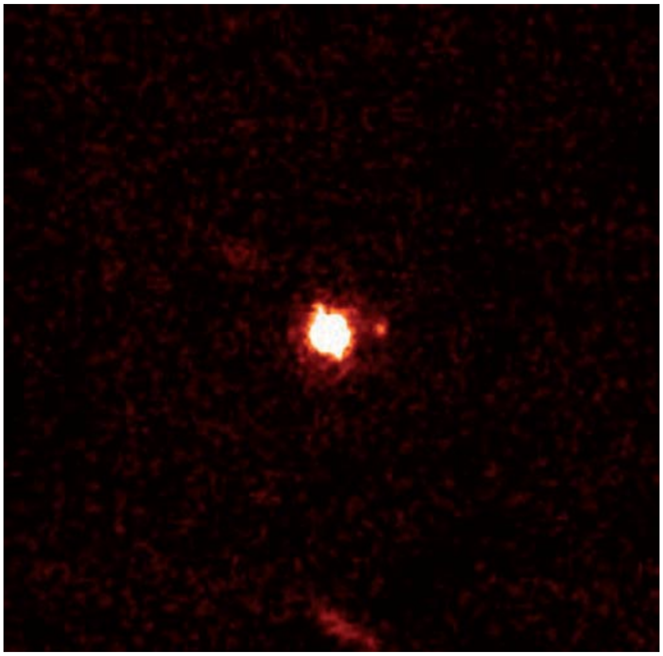
[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*

Comets reside in the outer regions of the Solar System. They are basically dirty ice balls composed of ices (water ice, as well as other kinds of ices, such as carbon dioxide, ammonia, and methane ices), rock, and dust. They are thought to be remnants of or the actual building blocks of (at least the outer) planets, and, therefore, are a subject of great interest for researchers interested in understanding the early history of the Solar System. Comets spend most of their time in the outer reaches of the Solar System and are not visible to observers on the Earth. There, the comet consists of only its solid body, the nucleus, which is only a few kilometers across and darker than charcoal. It is only when a comet's orbit takes it to the inner parts of the Solar System that a comet becomes observable. The Sun heats the frozen body of the comet, and causes ices on the comet's surface to sublimate—change directly from solid to gas. The gases blown off the nucleus, as well as specks of dust caught in the outflow, form a large cloud of gas and dust particles around the nucleus, called the coma, which can be over 1.6 million km (1 million miles) in size. Sunlight pushes against the dust particles in the coma, while the solar wind—fast outflow of electrically charged particles from the Sun—interacts with the gas. As a result, gas in the coma is pushed away from the nucleus, forming a very long tail stretching away from the comet pointed away from the Sun. It is not unusual for the tails of comets to extend tens of millions of kilometers. The dust that is forced off the coma forms a second tail that is curved away from the comet's direction of motion. If comets venture close to the Earth, they can be some of the most striking objects in the sky. There have been about a dozen robotic spacecraft that have explored comets, sometimes on the way to (or after flying by and exploring) other objects in the Solar System. The most famous comet-exploring spacecraft are perhaps Deep Impact, which released a probe that smashed into the comet Tempel 1 in 2005, and Stardust, which collected material from the coma of comet Wild 2 in 2004 and returned the captured samples to the Earth in 2006. Because comets are small, because they are located in the far reaches of the Solar System during much of their orbit and because they have very unstable surfaces when they get close to the Sun, they are unlikely to host living beings. However, they might be good sources of raw materials for future space explorers.

For more information on comets, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=Comets

(Pictured above: Comet C/2001 Q4 – NEAT; picture credit: T. Rector (University of Alaska Anchorage), Z. Levay and L. Frattare (Space Telescope Science Institute) and National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation; http://solarsystem.nasa.gov/multimedia/gallery/Comet_NEAT.jpg)

Kuiper Belt Objects



A Few Basic Facts About Kuiper Belt Objects

Range of average distances from the Sun	30 – 50 AU[1]; maybe up to 135 AU
Diameters	37 – 200, maybe up to 2,400 kilometers
Masses	Varies, up to slightly more than 0.00021 Earth masses
Orbital periods (around the Sun)	200 – 300, maybe up to 770 Earth years
Rotation periods (around their axis)	3 hours to a few Earth days
Main composition	Ice and rock
Moons	Some Kuiper Belt Objects have moons

[1]*Astronomical Unit (AU) is the average distance from the Earth to the Sun.*

Since 1992, astronomers have found hundreds of objects similar to Pluto beyond Neptune's orbit. These objects are all small icy worlds most commonly called Kuiper Belt Objects (KBO), after the astronomer Gerard Kuiper, though they are sometimes also called trans-Neptunian objects, because they reside in space beyond the orbit of Neptune. The Kuiper Belt region, located at a distance of 30 to 50 times as far from the Sun as the Earth, may have 35,000 objects with diameters larger than 100 km (60 miles). These objects are similar to Pluto: small objects made of a mixture of rock and ice. Most of the Kuiper Belt Objects discovered to date are smaller than Pluto, but detailed observations of an object named Eris, first discovered in 2003, revealed that it is larger than Pluto. This led the International Astronomical Union to decide in 2006 that Pluto (as well as Eris) belongs to a new class of objects called dwarf planets. There probably are more dwarf planets, in addition to smaller KBOs, yet to be discovered in the Kuiper Belt. Because the objects there are so far away from the Sun and are so small, they are hard to discover without powerful telescopes and advanced observation techniques. No spacecraft has ever visited any Kuiper Belt Object, though this may change in a few years, since the robotic spacecraft New Horizons, launched in 2006, is scheduled to fly by one or more Kuiper Belt Objects after flying by Pluto in 2015. The frigidly cold temperatures in the Kuiper Belt—the temperatures on the surfaces of KBOs are not thought to reach much above –230ºC (–450ºF)—make it unlikely for any living beings to live there, and these harsh conditions certainly make the objects very inhospitable destinations for human explorers.

For more information on Kuiper Belt Objects, visit the NASA Solar System Exploration page http://solarsystem.nasa.gov/planets/profile.cfm?Object=KBOs

(Pictured above: Dwarf planet Eris; picture credit: Courtesy W. M. Keck Observatory; https://www.keckobservatory.org/images/gallery_pictures/4_73.jpg)

Famous Explorers

Name: ______________________________ **Date:** ______________________

Directions: Choose an explorer to research. Using the Internet, answer the questions below. If the explorer of your choice is included in *Student Internet Resources*, you may want to use the Web sites given there. If not, you can use Internet search engines or Web sites provided by your teacher to find information. After answering the questions, create a way to present your explorer to the class, either by making a poster or a short presentation.

Name of the Explorer: ____

1. What was he or she exploring?

____

____

____

2. What experiences did the explorer have in his or her life that led to a passion to explore this area?

____

____

____

3. What questions do you think the explorer had when he or she began the exploration? Explain.

____

____

____

4. Did the explorer answer his or her questions, or are these ongoing explorations? Describe the results of the exploration.

____

____

____

5. What was the fundamental reason why he or she explored?

____

____

____

6. List the sources of information for your research.

____

____

____

MESSENGER
Mission to Mercury

Exploring the Solar System

Your team: ______________________________

____

____

Date: ______________________________

Directions: Read the *Space Exploration Card* describing the world you are going to investigate, and answer the questions below. After answering the questions, prepare a presentation on your world and why you would want to explore it. When preparing your presentation, follow the instructions given by your teacher.

The name of the world you are going to investigate: ______________________________

1. Why would you want to explore this world?

2. What do you hope to learn about the world in your exploration?

3. How would you want to explore this world? Would you like to send humans to do the exploration? Would you like to send a robotic spacecraft? Explain.

4. How do you think your exploration builds on what previous explorations of this world have discovered already?

5. Do you think exploring this world will help us understand other worlds in the Solar System better? Explain.

6. Does your exploration need any special technology? Pay special attention to the environment in which the exploration will take place (For example: Is it hot? Cold? Will the exploration be done by humans or robotic equipment needing special protection from the environment?)

Based on your answers, write a proposal to NASA explaining in detail why you think NASA should fund a mission to explore your world. Use the following page for your proposal.

Proposal

World to be explored: ______________________________

Proposal Team/Principal Investigators: ______________________________

____

____

Organization/School: ______________________________

Proposal to investigate the target world:

ANSWER KEY

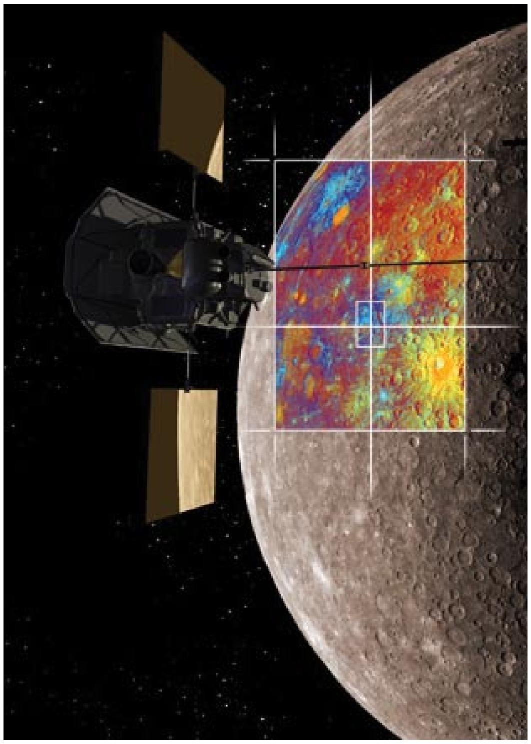
Student Worksheet 1

Answers will vary. Be sure the answers include careful thought into what motivated the explorer to undertake their exploration. You may also want to make sure the answers include topics discussed during the Warm-Up.

Student Worksheet 2

Answers will vary. Make sure the students explain the reasons for exploring their world, as well as how the exploration of their world connects with exploration in general.

MESSENGER Mission Information Sheet

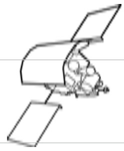


MESSENGER is an unmanned NASA spacecraft that was launched in 2004 to study the planet Mercury. After three flybys of its target planet in 2008 and 2009, the spacecraft will go into orbit around Mercury in 2011. It will not land but will make detailed observations from orbit. MESSENGER will never return to the 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, who, it was said, wore winged sandals and was somewhat of a trickster.

MESSENGER will be 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 about one Earth year, during which time it will make close-up and long-term observations, allowing us to see the whole planet in detail for the first time.

During its mission, MESSENGER will attempt to answer several questions about Mercury. 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? What is the nature and origin of Mercury's very tenuous atmosphere? Does ice really exist in the permanently shadowed craters near the planet's poles? Mercury is an important subject of study because it is the extreme of the terrestrial planets (Mercury, Venus, Earth, Mars): it is the smallest, one of the densest, it has one of the oldest surfaces and the largest daily variations in surface temperature—but is the least explored. Understanding this "end member" of the terrestrial planets holds unique clues to the questions of the formation of the Solar System, evolution of the planets, magnetic field generation, and magnetospheric physics. Exploring Mercury will help us understand how our own Earth was formed, how it has evolved, and how it interacts with the Sun.



Mission: Possible

How Can We Plan an Exploration of Another World?

Lesson Overview

Grade Level
5–8

Duration
Three 45-minute class periods

Essential Question

How can we plan an exploration of another world?

Lesson 2
of the Grades 5-8
Component of the
Mission Design
Education Module

Lesson Summary

The goal of the lesson is to have the students understand how to plan a mission to explore another world in the Solar System. The students will begin by discussing the path of a spacecraft traveling between planets, examining the journey from the Earth to Mars as an example. In Activity 1, students will determine the pros and cons for different ways we can explore another world, either by observing from the Earth or by sending a spacecraft to fly by, orbit, or land on the world. In Activity 2, the students will plan for a mission to explore another world in the Solar System. They will come to understand that what scientists want to learn about an object determines how they plan the mission, but real-life constraints such as cost and time determine what actually can be accomplished.

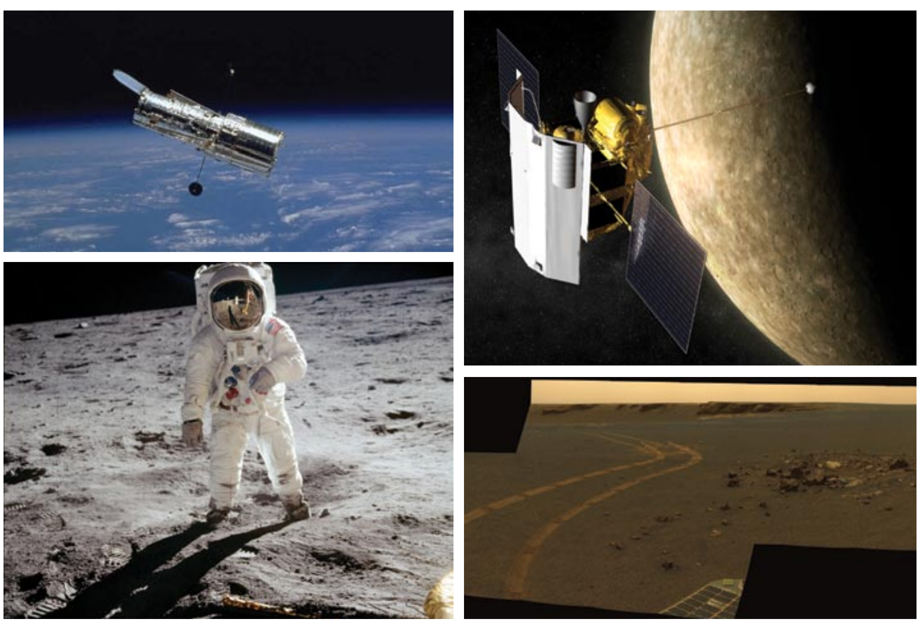


Figure 1. How do we explore other worlds in the Solar System? Depending on the goals and the constraints of the mission, the exploration can be done through observations with telescopes on (or near) the Earth (e.g., Hubble Space Telescope, top left), by having robotic spacecraft making remote measurements by flying by or orbiting the world (e.g., MESSENGER mission to Mercury, top right), landing on the target world (e.g., Martian rovers, which took photographs of the surface of Mars including its own tracks across the landscape, bottom right), or by sending humans to do the exploration (e.g., Apollo missions to the Moon, bottom left.) (Picture credits: NASA; http://hubblesite.org/gallery/spacecraft/06/;NASA/JHU-APL/CIW; http://messenger.jhuapl.edu/the_mission/artistimpression/atmercury_br.html; NASA Project Apollo Archive/Apollo Image Gallery, scanned by Kipp Teague, AS11-40-5903; http://www.apolloarchive.com/apollo_gallery.html; NASA/JPL-Caltech/Cornell University; http://photojournal.jpl.nasa.gov/catalog/PIA10213)

This lesson was developed by the National Center for Earth and Space Science Education (http://ncesse.org).

Objectives

Students will be able to do the following:

- Describe the relationship between the locations of planets as they move around the Sun.
- Make multi-sensory observations.
- Gather data.
- Demonstrate an understanding of real-life constraints on spacecraft missions.

Concepts

- There are many ways to study other worlds in the Solar System.
- There can be more than one solution to a problem.
- Real-life constraints such as cost and time determine how much can be learned about another world.

MESSENGER Mission Connection

The MESSENGER spacecraft is one of NASA's Discovery missions, which are meant to do a lot of science within a limited budget. Even with a relatively inexpensive mission, the mission team was able to create an orbiting spacecraft that will tell us more about Mercury than we knew from the only previous mission to Mercury (Mariner 10) and all ground-based observations combined.

Standards & Benchmarks

National Science Education Standards

Standard A2: Understandings about scientific inquiry

- Different kinds of questions suggest different kinds of scientific investigations. Some investigations involve observing and describing objects, organisms, or events; some involve collecting specimens; some involve experiments; some involve seeking more information; some involve discovery of new objects and phenomena; and some involve making models.
- Mathematics is important in all aspects of scientific inquiry.
- Scientific investigations sometimes result in new ideas and phenomena for study, generate new methods or procedures for an investigation, or develop new technologies to improve the collection of data. All of these results can lead to new investigations.

Standard E1: Abilities of technological design

- Students should make and compare different proposals in the light of the criteria they have selected. They must consider constraints—such as cost, time, trade-offs, and materials needed—and communicate ideas with drawings and simple models.

Standard E2: Understandings about science and technology

- Perfectly designed solutions do not exist. All technological solutions have trade-offs, such as safety, cost, efficiency, and appearance. Engineers often build in back-up systems to provide safety. Risk is part of living in a highly technological world. Reducing risk often results in new technology.

AAAS Benchmarks for Science Literacy

Benchmark 3B/M1:

- Design usually requires taking into account not only physical and biological constraints, but also economic, political, social, ethical, and aesthetic ones.

Benchmark 2B/M1:

- Mathematics is helpful in almost every kind of human endeavor—from laying bricks to prescribing medicine or drawing a face.

Science Overview

Before any travel, it is good to plan the trip carefully. What is the best way to get to your destination? What will you do once you reach the destination? What kind of supplies might you need? How much is the trip going to cost? The same is true when planning for an exploration, and especially when planning for space travel to investigate another world in the Solar System. Careful planning makes the mission more likely to succeed.

When planning an exploration of another world, scientists need to consider what kind of information they want to gather. They need to formulate the scientific goals of the mission, and then figure out what is the best way to meet the goals within their budget. If the study cannot be conducted with ground-based observations or telescopes located near the Earth in space, they must consider the extra cost of sending a spacecraft to explore the world by flying by, orbiting, or landing on the target world. The exploration gets more complex and expensive as you progress from ground-based observations to a flyby, an orbital, and a landing spacecraft mission. Most often, the final mission is a compromise between what the scientists want to find out about their target, and what real-world constraints allow.

Observations from the Earth

Scientists explored the Universe for thousands of years by using just their unaided eyes to observe phenomena in the sky. While much can be learned about the positions and behavior of the objects in the sky without additional equipment, it is difficult to come to a deeper understanding of the basic nature of the observed phenomena with eyes alone. A significant breakthrough in this regard occurred in about 1608, when the first telescope was constructed; there is some dispute as to exactly who made the first telescope, but the feat is usually attributed to Hans Lippershey. The new tool was soon used by Galileo Galilei to observe objects in the sky no human had ever seen in such great detail before; in effect, this was the beginning of the era of detailed astronomical observations.

Over the last few centuries, astronomical observations have become more advanced not only in the way telescopes are constructed, but also in the way the actual observations are made. At the time of Galileo, astronomers jotted down their observations in notebooks, and the data was only as good as the observer's notes. The development of photographic plates, and, in more recent times, the introduction of advanced image capturing and enhancement technologies, have made ever more complex observations possible. As a result, the last hundred years has revolutionized our understanding of the Universe, and our place in it. Today, ground-based telescopes are still the most commonly used tools in observational astronomy, because they are less expensive to build, maintain, and use when compared with the other options disussed below. Telescope designers race to make new techniques to build, maintain and use ever bigger telescopes. The largest telescopes in the world today use mirrors of about 10 m (394 inches) in size. For example, the Keck Observatory (Fig. 2) on Mauna Kea, Hawaii, has two 10-meter telescopes that can be used either separately or together to enhance the observations even further. The total cost of the Keck telescopes was $231 million to design and build; this includes $48 million for instrumentation (camera systems, etc.) that are mounted on the telescope to make the actual observations. There are plans to build telescopes that have mirrors as big as 30 m (1,181 inches) in diameter over the next decade or so.

There are limits to the effectiveness of ground-based observations, however. Because the telescopes must see through the Earth's atmosphere, which is in constant motion, the clarity of the observations is decreased. There are computer software packages that can overcome some of these problems, but they cannot remove the effect of the moving atmosphere completely. Another way to alleviate the problem is to build telescopes in areas where the atmosphere is naturally calm, or high up in the mountains, where the light arriving from cosmic objects has less atmosphere to pass through. That is why most of the premier observatory sites today are located in high-altitude locations such as Chile and Hawaii. Still, even the best ground-based observations suffer from some atmospheric effects.

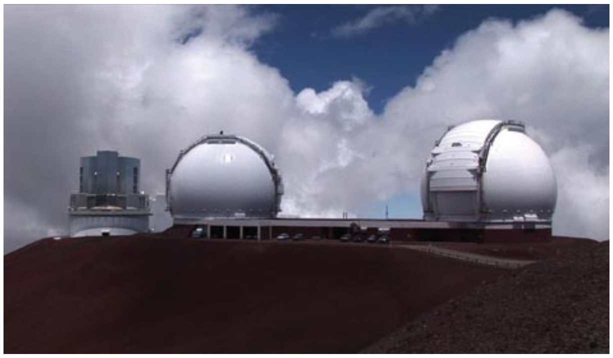


Figure 2. The Keck Observatory in Mauna Kea, Hawaii, includes two telescopes whose 10-meter mirrors are the largest in the world. The telescopes are located inside the domes seen in the figure; the domes protect the telescopes from the environment and are opened for observations. (Picture credit: NASA; http://www.nasa.gov/centers/jpl/images/content/135066main_Keck-9-29-05-browse.jpg)

Observations from Space Near the Earth

One way to solve the problem of the atmosphere is to place the telescopes in space. This is a popular approach not only because of the limited seeing from the ground, but also because there are many kinds of light that are blocked by the Earth's atmosphere but are observable by telescopes in space. Ground-based telescopes can observe in the visible, radio and some infrared and ultraviolet light, but only telescopes above the Earth's atmosphere can observe gamma rays, X-rays, and most of infrared and ultraviolet light. As a result, space telescopes have become very popular over the last few years.

Probably the best known space telescope is the Hubble Space Telescope (HST; see Fig. 3), which was placed into orbit around the Earth by the Space Shuttle in 1990. While the size of the HST's mirror is small (2.4 m; 94 inches) compared with the large ground-based telescopes, by not having to suffer from atmospheric distortions, HST's observations have revolutionized many aspects of astronomy. The telescope has taken hundreds of thousands of pictures, observing more than 25,000 astronomical targets. There probably are many new discoveries in store before the end of HST's operational lifetime sometime after 2014. The cost of HST at launch was $1.5 billion, which included the design, the building, the testing, and the launch of the telescope. Five additional Shuttle missions have repaired components of the HST and swapped instruments over the years, most recently in 2009. The cost estimates for the Shuttle missions have ranged from $600 million to $2 billion, increasing the cost of the Hubble Space Telescope significantly. There are many other important space-based observatories; for example, NASA's Great Observatories program includes not only the HST, which studies the Universe using visual, ultraviolet and near-infrared light, but also the Compton Gamma Ray Observatory, Chandra X-Ray Observatory, and the Spitzer Space Telescope, which study the Universe using gamma rays, X-rays and infrared light, respectively.

One drawback of space telescopes is that they are difficult (if not impossible) to repair and upgrade. For example, the Hubble Space Telescope has many redundant electronic circuits, but the needed repairs and maintenance tasks involved missions using astronauts on a Space Shuttle flight. Most space telescopes are on orbits that are not serviceable by the Shuttle, and so no repairs are possible for these telescopes. Furthermore, while both ground-based and space telescopes can quickly switch between different cameras and point to different parts of the sky, only ground-based telescopes allow an observer to use his or her own instrument packages or other observational devices that may be necessary to make the observations.

Figure 3. Hubble Space Telescope (HST) was placed into orbit around the Earth by the Space Shuttle in 1990. It has taken hundreds of thousands of pictures since then, observing more than 25,000 astronomical targets, and in so doing has become perhaps the most important telescope in the history of astronomy. (Picture credit: NASA; http://hubble.nasa.gov/hubble/full/img94.jpg)

Robotic Exploration of the Solar System

Almost everything that we know about the Universe beyond the Solar System was discovered through observations made on the Earth or in space near the Earth. However, much of what we know about the Solar System has been discovered by robotic spacecraft sent to make close-up observations of the objects in our planetary system. In fact, we have learned more about the Solar System in the last 50 years using robotic spacecraft than all the previous ground-based observations.

After the launch of Sputnik 1 satellite in 1957 ushered in the Space Age, robotic spacecraft (and in the case of the Moon, human space flight) have been used to study various worlds in the Solar System, with at least one spacecraft visiting each planet. In addition, robotic spacecraft have visited moons, asteroids, and comets. There are spacecraft currently on their way to examine the dwarf planets Ceres and Pluto, and the spacecraft flying by Pluto may also examine at least one of the Kuiper Belt Objects, which are icy worlds beyond the orbit of Neptune discovered in the last few years. Other spacecraft missions are carrying out more detailed observations of the many different worlds in the Solar System, and many more are being planned. While spacecraft are often unique in their detailed design, there are three basic types of missions: flyby, orbital or lander missions.

Flyby Mission

The simplest way to explore a world close-up is to have a spacecraft just fly by the body without going into orbit around it or landing on it. A flyby can get much more detailed information on the object than Earth-based observations. However, the spacecraft can only make useful observations of the world while it is nearby, and depending on the trajectory of the spacecraft, the time for observations may be limited and only a small portion of the object facing the spacecraft as it flies by may be viewable. This means that a flyby mission requires a lot of planning to optimize the way the data is gathered. Usually, the details of the planned observations—which instrument to use at each moment, where to point the instrument, what kind of data to take, etc.—are stored in a computer program on the spacecraft before the flyby, and the program begins executing automatically at some distance from the target. The gathered data is then sent back to the Earth for analysis after the flyby is concluded.

The costs of a robotic flyby mission vary depending on the world that is being explored. Typically the costs involve consideration for the following aspects:

- Designing and building the instruments needed to get the desired science data;
- The power needed to run the spacecraft and its instruments;
- Launching the spacecraft;
- The amount of fuel needed to fly to the world;
- Communications needed between the Earth and the spacecraft;
- Human labor for the scientists and engineers working on the mission;
- The length of the mission.

The basic design and structure of the spacecraft is usually done in concert with designing the instrument suite. After all, the spacecraft is really just a vehicle to take the instruments to the target world, create an environment where the instruments can operate properly, and make it possible for gathered data to be returned to the Earth for analysis. There is always a trade-off between the amount and type of science data that is desired and the cost of the instruments to gather this data. If a similar mission has been done before, there can be great cost savings by using similar instruments that were used in the earlier mission. There are also engineering costs associated with incorporating the instrument into the spacecraft, but they are significantly lower. A typical instrument on a spacecraft costs a few million dollars, while the design and construction of the whole spacecraft can vary from a few tens of millions of dollars to $1 billion dollars, depending on the kind of engineering needed to complete the project.

In addition to selecting the instruments, the power needed to operate them must be considered when designing the mission. If the spacecraft is exploring the inner Solar System (Mercury, Venus, or Mars, for example), solar arrays can be used to get power from sunlight. If the mission is to worlds farther out, there is not enough sunlight to produce sufficient power, and the spacecraft will need to rely on nuclear energy. In this case, the power is derived from the natural decay of a radioactive isotope, most often plutonium-238. For example, the Voyager 1 and 2, Galileo, Cassini-Huygens and New Horizons spacecraft use this power source. Future long-duration missions exploring worlds in the outer reaches of the Solar System may need new technology, such as a small nuclear reactor incorporated to the spacecraft.

The cost of launching a spacecraft from the Earth depends on a number of factors, especially on the size and weight of the spacecraft and the amount of propellant aboard. The cost of lifting a spacecraft from the ground to space is about $22,000 per kg ($10,000 per pound); additional costs come from sending the spacecraft toward the target world. The typical cost is around $40 million per launch for spacecraft heading to the inner Solar System and Mars, and roughly $100 million for spacecraft heading to the outer reaches of the Solar System.

The spacecraft carries propellant (mixture of fuel and oxidizer) for course correction maneuvers that may be necessary to adjust the trajectory toward the target world. The spacecraft is usually launched on a trajectory that requires as few course corrections using the spacecraft's engines as possible. The typical spacecraft carries a few hundred kilograms of propellant, at a cost of about $80/kg ($36/lb.) 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. However, this is only the direct cost and does not include the cost of lifting the propellant to space (which is included in the launch cost mentioned above.) For example, in the case of MESSENGER, the cost of lifting the propellant to space cost $13 million, much more than the cost of the propellant itself.

Communications with spacecraft studying other worlds are done using radio waves, which travel at the speed of light. As a result, the time between sending a signal to the spacecraft and receiving the response varies from a couple of seconds (for missions exploring the Moon) to several hours (for missions investigating the outer reaches of the Solar System.) This delay makes it necessary for the spacecraft to be able to execute many commands on their own, without direct input from ground control on the Earth. Therefore, the computer programs operating robotic spacecraft must be designed carefully. For example, before firing the spacecraft's engines to make a course correction maneuver, a signal is sent from the ground control to the spacecraft to have the computer execute a series of commands to complete the necessary operations, but providing additional commands is usually not possible before the maneuver is completed. Communication with spacecraft is done using large radio antennas on Earth, such as NASA's Deep Space Network, which includes three radio antenna facilities located around the world. The time to use the network must be planned in advance. The cost for using these communication facilities can be several million dollars, depending on the frequency of communications and the amount of data transmitted.

An important cost item is to reserve sufficient funds to pay for the scientists and engineers working on the mission. The mission team spends considerable time designing and testing the spacecraft and the instruments, making sure that the mission events from launch to the end of the mission occur smoothly, monitoring the spacecraft during its entire mission, and, of course, analyzing and interpreting the gathered data.

The length of the mission increases the total cost, since a longer duration results in not only continued communications with the spacecraft, but also additional human labor on the Earth to monitor and communicate with the spacecraft, as well as to analyze the larger amount of data returned by the spacecraft. Mission length depends on many factors, such as the distance to the target world, the way the spacecraft travels there, the power available to operate the spacecraft, and the scientific goals of the mission. The mission also becomes longer if the spacecraft is directed to fly by multiple targets. For example, after flying by Jupiter in 1979, the Voyager 2 spacecraft flew by Saturn in 1981, Uranus in 1986, and Neptune in 1989.

Designing a spacecraft mission often involves making compromises with the different aspects of the program to keep the total costs within budget. This may require changes in the spacecraft or instrument design, or in the amount of data that can be returned back to the Earth. On the other hand, a successful spacecraft may also earn an extended mission, which allows the spacecraft to continue its exploration with additional funds even after the original mission is completed.

Orbital Mission

While a flyby mission is the simplest, and therefore the most likely to be successful, spacecraft mission to explore another world, it usually only offers a snapshot of one part of the world. A more complicated mission, but also one that can offer a more comprehensive science investigation, is an orbital mission, in which the spacecraft goes into an orbit around the target world (e.g., Fig. 4.) The main complication in this kind of mission compared with the flyby is the orbit insertion maneuver: firing the spacecraft's engines to change the trajectory so that the gravity of the target world can "capture" the spacecraft into an orbit around the object. An orbital mission can obtain more detailed information than a flyby since it not only will be able to see much more of (if not the entire) world, but it also can spend a longer time making repeated observations of the same area.

Figure 4. An artist's impression of the MESSENGER spacecraft exploring Mercury. MESSENGER is the first spacecraft to explore the innermost planet in our Solar System since the 1970s, and the first ever to investigate the planet from orbit. (Picture credit: NASA/JHU-APL/CIW; http://messenger.jhuapl.edu/the_mission/artistimpression/atmercury_br.html)

In addition to the costs described in the context of a flyby mission, the following additional aspects must be considered for a robotic orbital mission:

- Propellant required for the orbit insertion maneuver and for possible orbit correction maneuvers needed later;
- Hardware and software engineering necessary to prepare the spacecraft for the orbit insertion maneuver and for orbital operations;
- Additional instruments that may be desired for a more comprehensive science investigation;
- More involved communications with ground control on the Earth.

Lander Mission

The landing of a spacecraft, or the landing of a probe launched from a flyby or orbiting spacecraft, to another world entails additional complexity over an orbital mission. In addition to flying to the world, the mission must plan for a safe landing of the probe. In some cases, the probe is designed to just crash on the world and provide as much information as possible before the crash, but in most cases careful planning is required to ensure a soft, safe landing on the target world's surface. Spacecraft can be slowed down during descent by firing the engines at precise moments for a pre-determined duration, or by using parachutes if the target world has a substantial atmosphere. The spacecraft may also include cushioning (such as air bags) to prevent a jarring landing on the surface. Often, these options are combined to ensure a safe landing. A lander mission is riskier than a flyby or an orbital mission, since there are more chances for something to go wrong. For example, about half of all lander missions sent to Mars have failed for one reason or another. On the other hand, a lander mission can provide much more detailed information on the world than the other kinds of missions, often making the higher risk acceptable. A lander can examine the world's surface features close-up and use tools to burrow underground, drill into rocks, or take samples for analysis within the spacecraft. While most landers are stationary, some have been designed to move around the surface, providing detailed information over a larger area (see Fig. 5.)

In addition to the costs of a flyby mission, as well as those of the orbital mission (if the mission includes an orbiting component), a lander mission involves the following additional cost considerations:

- Fuel to slow down the spacecraft for landing;
- Engineering and additional hardware for landing (e.g., parachute, cushioning);

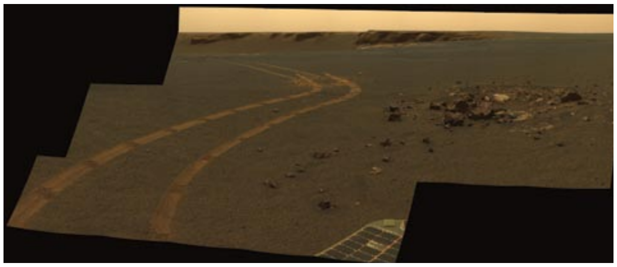


Figure 5. This image taken by the Martian Exploration Rover Opportunity shows not only natural features of the surface of Mars, but also the tracks the rover has left behind. On the lower part of the picture, a section of the rover itself is visible. (Picture credit: NASA/JPL-Caltech/Cornell University; http://photojournal.jpl.nasa.gov/catalog/PIA10213)

- Software engineering to prepare the spacecraft for landing;
- Engineering necessary to make communications from the surface back to the Earth reliable;
- Additional instruments that may be desired for a more comprehensive science investigation.

Spacecraft Instruments

The instruments used by spacecraft exploring other worlds depend on the kind of science the mission designers want to gather about the world. Typically, spacecraft include one or more of the following:

Camera: Cameras provide images not only to astonish us with views from another world, but also to give basic information on the target world for scientists to analyze. Cameras aboard spacecraft are in many ways similar to the digital cameras in wide use today in the way they capture images, though they usually have additional tools as part of the image capturing system, such as a (small) telescope to take more detailed images, a microscope to allow for detailed analysis of sampled material, or color filters to take images sensitive to different colors, which can then be combined to provide color pictures. Depending on how wide a view needs to be captured, the spacecraft may have a narrow angle (small field of view but more detailed images) or a wide angle (wider field of view but less detailed images) camera. A device with an exceptionally wide field of view is called a panoramic camera. A stereo camera has two lenses that make it possible to take three-dimensional images of a target, in this way mimicking human binocular vision. Cameras may also be sensitive to different kinds of light, producing images using infrared light, for example.

Spectrometer: An optical instrument that is used to measure properties of different colors, a spectrometer is often used to provide information on the composition of the object that is emitting or reflecting the light captured by the instrument. Spectrometers are sensitive to different kinds of light, and the exact kind of device placed aboard the spacecraft depends on what kind of information the scientists want to gather. Because spectrometers sensitive to different kinds of light can provide different information on the same targets, spacecraft often carry several spectrometers aboard, ranging from infrared and visible to ultraviolet, x-ray and gamma ray spectrometers. Spectrometers can also be designed to measure the properties of particle radiation, such as cosmic rays or neutrons, or the properties of geologic or atmospheric samples. Spectrometers are essential in providing information on the composition of the target world's atmosphere, rocks, and soil, as well as providing information on the space environment near the world.

Magnetometer: A magnetometer measures properties of the magnetic field near the spacecraft. The data gathered by a magnetometer can be used to provide information on the target world's magnetic field, the solar wind, and the behavior of the Sun's magnetic field in space near the world.

Laser altimeter: A laser altimeter uses a laser beam bounced off the surface of the world to determine the distance to various points on the body. It is used on orbital missions to map the heights or depths of the geologic features on the world.

Radar: A radar can be used like a camera to take images of the target world, but instead of capturing reflected or emitted light, it uses microwaves bounced off the surface of the world. Advanced radar systems can also be used to analyze the properties of the world's atmosphere, or features below the surface.

Seismometer: Just like similar devices on the Earth, seismometers can be used on a lander spacecraft to see if there are seismic quakes on the world (e.g., marsquakes or moonquakes.)

Meteorology instrument: To monitor weather on the target world, the spacecraft may be equipped with a suite of meteorology instruments to measure the temperature, air pressure, humidity and wind properties, for example.

Geologic exploration tool: For a more comprehensive analysis of the surface of the world, a lander may include an arm designed to take soil samples from the surface or dig underground. The lander may also be equipped with drills that can bore into rocks for a more detailed analysis of their properties. In this case, the lander becomes a robotic geologist.

Life experiment suite: If there is a chance of living beings existing on the target world, a package of laboratory experiments may be included. The experiments may look for life in different ways, such as searching for organic molecules or for chemical signs of microbial feeding or respiration.

The instruments described above are the most common types carried by spacecraft exploring other worlds in the Solar System, but there are many other tools that can be used, as well. More information on the instruments used by past and current spacecraft can be found on the mission Web pages.

The Total Cost of a Spacecraft Mission

While the design of the mission becomes more complicated as the type changes from a flyby to an orbital or a lander mission, there is sufficient variance in the costs discussed above for each type of mission that a lander mission is not always more expensive than a flyby mission, for example. Many factors can change the total cost of a mission, and it is often the overall budget that sets limits on how much science can be done with what kind of mission, and not vice versa. For a few examples of the total costs of various types of mission exploring different worlds in the Solar System, see Table 1.

Table 1: Examples of past and current spacecraft missions exploring other worlds in the Solar System.

World	Mission	Timeline	Type	Total Cost
Mercury	MESSENGER	2004 –	Orbiter	$446 million
Venus	Magellan	1989 – 1994	Orbiter	$680 million
Mars	Mars Express	2003 –	Orbiter	$150 million
	Mars Reconnaissance Orbiter	2005 –	Orbiter	$720 million
	Viking 1 and 2	1975 – 1982	Landers and orbiters	$3.5 billion ($935 million in 1974 dollars)

(continued on the next page)

Table 1 (continued): Examples of past and current spacecraft missions exploring other worlds in the Solar System..

World	Mission	Timeline	Type	Total Cost
Mars, *continued*	Mars Exploration Rovers (Spirit and Opportunity)	2003 –	Lander / rover	$820 million
	Phoenix Mars	2007 –	Lander	$417 million
Jupiter	Pioneer 10	Flyby in 1973	Flyby	$350 million
	Voyager 1	Flyby in 1979	Flyby	$905 million[1]
	Galileo	1989 – 2003	Orbiter, atmosphere probe	$1.5 billion
Saturn	Pioneer 11	Flyby in 1979	Flyby	$350 million
	Cassini-Huygens	1997 –	Orbiter, lander to Titan	$3.4 billion
Uranus	Voyager 2	Flyby in 1986	Flyby	$905 million[1]
Neptune	Voyager 2	Flyby in 1989	Flyby	$905 million[1]
Dwarf planet (Pluto)	New Horizons	2006 –	Flyby	$550 million
Kuiper Belt Object	New Horizons	2006 –	Flyby	$550 million
Dwarf planet (Ceres); asteroid (Vesta)	Dawn	2007 –	Flyby	$446 million
Asteroid (433 Eros)	NEAR Shoemaker	1996 – 2001	Flyby, orbiter, lander	$220.5 million
Comet (9P/Tempel 1)	Deep Impact[2]	2005 –	Flyby; probe crashed on comet	$240 million
Comet (67 P/ Churyumov-Gerasimenko)	Rosetta	2004 –	Orbiter, lander	$980 million

Notes on Table 1:

[1] Voyager 1 and 2 costs are the combined cost of the twin spacecraft.

[2] Deep Impact flyby spacecraft was granted an extended mission (under the name EPOXI) to study another comet and extrasolar planets.

Note that many of the missions listed in the table were designed to have the spacecraft fly by multiple targets, in some cases to perform gravity assist maneuvers to modify the spacecraft's trajectory toward other targets. For example, Voyager 2 flew by Jupiter, Saturn, Uranus and Neptune, and Cassini-Huygens flew by Venus and Jupiter before arriving at Saturn.

Data in Table 1 from NASA National Space Science Data Center Spacecraft Project Page (http://nssdc.gsfc.nasa.gov/planetary/projects.html) and references therein.

While the mission costs listed in Table 1 may look extravagant, especially considering that there are many problems right here on the Earth that could benefit from additional funding, it is good to remember that there are benefits from space exploration that go well beyond learning more about the target of the mission. For example, the bulk of the money given to a space mission goes into funding people and companies that design, construct, and conduct the mission. In this way, space exploration creates jobs which drive our economy and help create a financial environment in which additional funds can be assigned to other causes, as well. Furthermore, there are often technological solutions which are developed to make a spacecraft mission possible and which may be spun off for more Earth-bound applications. Therefore, while the primary goal of space exploration missions is to answer scientific questions about the target world, they often provide benefits that reach into our daily lives.

Journey to the Target World

How does a spacecraft travel from the Earth to another planet? Your first guess might be to launch a rocket from the Earth directly toward the planet in a straight line. However, because the planets move in their orbits around the Sun, that method does not work. If the spacecraft heads toward the location where the other planet is when the spacecraft is launched, the planet would have moved along on its orbit by the time the spacecraft reaches the location, and the spacecraft would miss its target. Consider the following analogy. You and a friend are playing catch with a football in a large open field. Your friend runs away from you, and you throw the football to your friend's current location. By the time the football gets there, your friend will be farther away and the football will just fall to the ground. Instead, you need to estimate where your friend will be in a few seconds and throw the ball to that point. If you have guessed correctly, your friend and the football will get to the same point at the same time, and the ball will be caught. You would also notice that the football does not travel in a straight line. This is because once the football leaves your hand, the motion of the ball is controlled mainly by the Earth's gravity, which is pulling the ball toward the ground as it flies through the air, causing the ball to fly in an arc.

Now consider sending a spacecraft from the Earth to Mars. When the spacecraft is launched, it does not fly in a straight line, but rather in a curve bending around the Sun. This is because the force of the Sun's gravity is pulling it toward the Sun, just like the same force is pulling the Earth toward the Sun. And just like this causes the Earth to orbit the Sun in an elliptical orbit, the spacecraft at the time it leaves the Earth is on a similar orbit around the Sun. The properties of the initial orbit are determined by the launch details, and they can be modified later with course correction or gravity assist maneuvers.

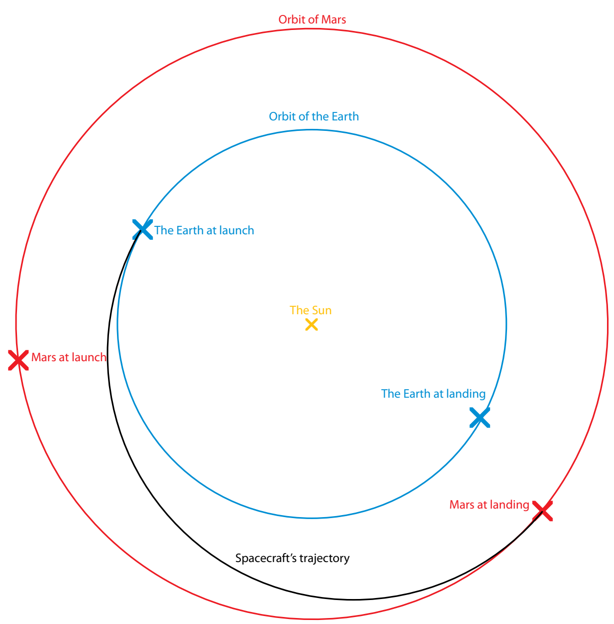


Figure 6. The trajectory of a spacecraft traveling from the Earth to Mars.

If the spacecraft had enough fuel, it could use its engines to overcome the gravitational pull of the Sun and fly in a more straightforward manner toward its target. However, to carry enough fuel, the spacecraft would need to be larger, it would be much heavier and, therefore, it would be much more expensive to launch. This is one of the basic problems to consider when launching a spacecraft. Mission designers want spacecraft to get from the Earth to Mars (or any other planet) using the least amount of fuel. It turns out that the best way to send a spacecraft to Mars using the least amount of fuel is to have the spacecraft travel in a trajectory that is an orbit around the Sun where the orbit's closest approach to the Sun is at the Earth's distance (at launch) and the farthest distance from the Sun the same as Mars's distance (at arrival; see Figure 6.) In this case, the spacecraft does not need to use any fuel while traveling from one planet to the other after being set on the so-called transfer orbit: the spacecraft can cruise through space toward its target.

Mission Length and Gravity Assists

How long does it take to go from the Earth to different places in the Solar System? There were six landings on the Moon during the Apollo era (Apollo 11, 12, 14, 15, 16, 17 in 1969-1972); it took just over three days for the spacecraft to get to the Moon. For a quick estimate for the travel times to other worlds in the Solar System, let's assume that a spacecraft is flying at 11.2 kilometers per second (25,000 miles/hour); this is the escape velocity from the Earth; that is, the speed which an object (such as a spacecraft) needs to have to overcome the gravitational pull of the Earth and travel into space. We can then make a quick estimate that it would take 95 days to travel to Mercury, 43 days to Venus, 81 days to Mars, 2 years to Jupiter, and 16 years to Pluto! Note that this quick "back-of-the-envelope" calculation is based on the differences in the target worlds' and the Earth's average distances from the Sun, and it does not include the more realistic curved trajectories discussed earlier; for example, the real travel time to Mars is typically about six months instead of the 81 days calculated above. However, the calculation does give a basic order-of-magnitude idea of how long it takes to travel to the different worlds in the Solar System.

One way to shorten the travel time is to use more fuel to boost the speed of the spacecraft. However, extra fuel raises the cost of the mission significantly and is rarely worth the cost. Another way to boost the speed without using more fuel is through a method known as gravity assist where a spacecraft can use a planet's gravity to change its speed and direction in a similar way as a tennis ball thrown at a moving train causes the ball to change direction and speed when bouncing off the train (though with the difference that the spacecraft does not actually strike the planet.) Using this method can aid the mission significantly. For example, the New Horizons spacecraft, launched in 2006, left the Earth at a speed of 16 km/s (36,000 mph.) After flying by Jupiter in 2006, the spacecraft sped up to the speed of 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. In some cases, a mission might not be even possible without gravity assist maneuvers. For example, without the complicated gravity assist trajectory, the MESSENGER spacecraft would not be able to go into orbit around Mercury. In this case, the complicated trajectory actually increases the travel time, but the requirement to perform an orbital mission makes the extra travel time worthwhile.

Human Exploration versus Robotic Missions

Space is a dangerous environment for humans to operate, with hazards ranging from the airless vacuum to temperatures that are either scorching hot or freezing cold, depending on whether one is in sunlight or in shade, or close to or far away from the Sun. As a result, humankind has never sent astronauts anywhere other than the orbit around the Earth and to our Moon, and no human has been on the Moon since the Apollo 17 crew returned from their three-day visit in 1972. There are plans to build a permanent settlement on the Moon and send humans to Mars in the next few decades, but these kinds of missions require extensive planning and are very expensive. This is due to many reasons. The mission must be self-sufficient all the way to the target world and back; the astronauts cannot depend on getting more supplies from the Earth. For example, establishing a settlement on the Moon or Mars would require that the astronauts grow their own food and have a system to recycle water. They would have to have equipment to generate oxygen and remove carbon dioxide from the air. They may also need to produce fuel at their landing location or settlement, making locating and securing resources on the target world necessary. Additional thought must be given to secure the health of the astronauts in other ways, from combating muscle weakness caused by lower gravity to making sure the dangerous forms of radiation coming from the Sun and elsewhere in the Universe does not cause severe harm to the astronauts. On the Earth, we are protected from this kind of hazardous radiation by the atmosphere, but the astronauts would not have this protection on a long journey through space, or while on a world without as substantial an atmosphere as the Earth. While designing robotic spacecraft missions require taking into account many of the same issues (cold and/or hot temperatures, radiation, vacuum), the concern is nowhere near on the same level as it would be for humans performing the same functions. As a result, robotic exploration of the Solar System remains more cost-effective than human spaceflight.

Proposing Exploration of Other Worlds

An exploration of another world typically begins with a proposal to a funding agency (such as NASA) providing details for the proposed mission. The science team must explain why their target is worth studying, identify science goals, and explain how the goals can be met with their particular mission design. A detailed budget for each aspect of the mission must be provided, and the total budget must be within specified limits. The proposal must also consider the risks associated with the mission and estimate how likely it is to succeed. Often, the proposing team has to modify their initial idea for the mission based on budgetary constraints. Sometimes science goals may have to be scoped down, or some investigations may have to be abandoned to keep the proposal within constrains. For example, NASA Discovery Program allows scientists to propose highly focused planetary science investigations. The program solicits proposals from the planetary science community every so often, and after careful review of all received proposals, the winning missions are announced. The selected missions are cost-capped; that is, the mission teams are given a maximum allowed budget within which they must plan the mission, construct the spacecraft, launch it, monitor its journey, and receive and analyze the data. A lot of work goes into making a winning proposal, but once selected, the mission design team can use the proposal as a blueprint to guide their mission to a successful completion.

Lesson Plan

Warm-Up & Pre-Assessment

1. Make an overhead transparency of each of the three *Earth and Mars Orbit Transparencies* found in the back of the lesson.

2. Have the students share experiences that require reacting to a moving target. Examples might be passing a football, catching a fly ball, driving vehicles to avoid being hit, or playing dodge ball. Lead the students to discuss the how and why of the necessary movements to complete the tasks.

3. Display the first transparency with the locations of the Earth and Mars. Ask the students to imagine that NASA wants to launch a spacecraft from the Earth to Mars, and it will take about six months to get there. What would happen if they aimed directly to where Mars is at that moment? *(Desired answer: Mars would have moved on its orbit and the spacecraft would miss it!)*

4. Remind the students how planets move in their orbits: planets closer to the Sun move in their orbits faster than those farther away from the Sun. Ask the students where the Earth would be when the spacecraft lands on Mars, if the journey takes six months. *(Desired answer: since the Earth takes one year to orbit the Sun, it will be exactly on the other side of the Sun in six months.)* Make a dot on the transparency where the Earth would be in six months. Ask the students where Mars would be in its orbit. *(Desired answer: since Mars is slower in its orbit, it will not be on the other side of its orbit, and would not have moved as far as the Earth had moved.)* Display the second *Mars and Earth Orbit Transparency*, which shows the locations of the planets six months later.

5. Ask the students to imagine the trajectory (path) of the spacecraft as it leaves Earth and meets up with Mars six months later. Have a discussion about what the path may look like.

Materials

Per class:

- *Earth and Mars Orbit Transparency 1, 2, 3*

Teaching Tip

You can make class copies of the second transparency and have the students draw on their copy their guess of the trajectory rather than leaving it an open discussion.

6. Place the third transparency on top of the second, and line up the transparencies so that students can see the trajectory of the spacecraft. Discuss why it would be difficult to have the spacecraft travel in a straight line from the Earth to Mars. *(Desired answer: to travel in a straight line, the spacecraft would have to fight the gravitational pull of the Sun, which tries to make the spacecraft move on a curved orbit around the Sun, all the way to Mars, while this trajectory allows the spacecraft to cruise most of its journey without using additional fuel. It is more energy-efficient and, therefore, more fuel- and cost-efficient, to use this kind of trajectory.)*

7. Discuss with the students issues that scientists and engineers have to consider when planning a robotic spacecraft exploration of another world, such as what they want to learn of the world, how to travel to the world, whether to land on the world, or just observe it from a distance, how to send data back to Earth, etc.

Activity 1: Strange New Planet

In this activity, students explore the advantages and disadvantages of different kinds of explorations of another world, such as Earth-based observations, or flyby, orbital, and lander missions to the world. Students use an object such as a plastic ball or round fruit to represent a planet, and decorate it with stickers to simulate landforms, create clouds using cotton and glue, carve channels, apply scents, place moons around it, etc. The students simulate four different types of missions and list the strengths and weaknesses of each. They also discuss the advantages and disadvantages of planning a human spaceflight versus a robotic spacecraft mission.

Materials

Per class:

- Roll of masking tape
- Yard or meter stick
- Stopwatch or clock

Per group of 3 or 4:

- Plastic ball, Styrofoam© ball, or round fruit (cantaloupe, pumpkin, orange, etc.)
- Modeling clay, e.g., Playdoh©
- Vinegar, perfume, or other scents
- Small stickers, sequins, candy, marbles; anything small and interesting
- A few cotton balls
- A few toothpicks
- Glue
- Towel or a large sheet of opaque paper (to drape over the model planet)
- Push-pin
- Pen, pencil, or marker
- Index card
- Sheet of colored cellophane; large enough to cover the model planet (optional)
- Knife (optional)

(continued on the next page)

Preparation

1. Make one copy of Student Worksheet 1 per student.
2. Gather group materials to pass out or lay out materials for groups to take as needed.
3. Divide students into groups of three or four.
4. Pair up each group with another. Each group will study the planet designed by their partner team.

Procedures

A. Class discussion

1. Ask the students to describe the planet Earth. What are some of its characteristic features? How does the Moon look different from the Earth? What do the students know about the Moon by just looking at it? How would their observations change if they got closer to the Moon? If they landed on it?
2. Ask the students to come up with different ways they can explore another planet in the Solar System. Make sure the students come up with all the mission possibilities discussed in this activity.
3. Pass out Student Worksheet 1. Explain that the groups will investigate the differences between the various ways to explore another planet.

B. Creating a model planet

1. Have each group choose an object such as a plastic ball or fruit (e.g., a cantaloupe) that allows for multi-sensory observations. Instruct the students to decorate the object with stickers, toothpicks, scents, etc., to make the object interesting to observe. Some of the materials should be placed discreetly so that they are not obvious upon distant or brief inspection. Some suggestions for features are:
    - ▼ Carve channels with a toothpick or a knife;
    - ▼ Attach small stickers or embed other objects onto the ball or fruit (to represent different kinds of landforms);
    - ▼ Apply scent sparingly to a small area;
    - ▼ Use a sheet of clear or colored cellophane to wrap up the model planet (to represent different kinds of atmosphere);
    - ▼ Create clouds by using cotton and glue;
    - ▼ Attach a toothpick with a piece of modeling clay at the end (to represent a moon).
2. Make sure the students record on Student Worksheet 1 what each feature is and what it represents in their model planet. Their partner team will explore the planet later, and there needs to be a record of what the features are versus what the other team sees.
3. When the teams are finished, place the model planets on a desk in one side of the room. Make sure the students place an index card next to each planet identifying the team whose model it is. Cover each model planet with a towel (or a large sheet of opaque paper.)
4. Hand out to the students their Viewers – paper towel rolls or rolled-up sheets of paper.

Materials

(continued from page 21)

Per student:

- ▼ Student Worksheet 1
- ▼ Paper towel roll or a sheet of letter-size paper rolled up and taped on the side to form a tube
- ▼ 5”x5” square of clear cellophane (optional)
- ▼ 6” piece of tape or a rubber band (optional)

C. Mission 1: Earth-based observations (simulating observations made from observatories on the Earth or with space telescopes near the Earth)

1. Have the students gather in teams in the opposite side of the room from where the model planets are located. This space will act as the Mission Control for each team.

2. If you want to include a representation of the Earth's atmosphere, you can have the students crumple up a piece of clear cellophane, then straighten it out and place it on the end of their Viewers, taped or held in place by a rubber band. This helps to simulate the variation that occurs when viewing objects through the Earth's atmosphere. You can also leave out the piece of cellophane, in which case the observations would be similar to those made by space telescopes near the Earth.

3. Uncover the model planets. Have the teams observe the model planet of their partner team using their Viewers for two minutes. Rotate each model planet so that the other side can be observed (to simulate the rotation of a real planet.) Allow another two minutes for new observations. Cover the model planets with towels.

4. Have the teams discuss and record their observations in Student Worksheet 1. At this point, most of the observations will be visual and will include color, shape, texture, and position. The teams should also discuss and write down questions to be explored in future missions to the planet before moving on to the next section.

D. Mission 2: Flyby

1. Use masking tape to mark a distance of about five feet from the desk holding the model planets.

2. Partially uncover the model planets so that one side of each planet is in sight, but the rest is still covered by the towel.

2. Have the teams quickly walk by their target planet and use their Viewers to make their observations. Make sure no-one approaches the planet closer than the distance marked on the floor.

3. Place the towels back over the model planets.

4. Have the teams reconvene at the Mission Control to record and discuss their observations. The teams should also discuss what they will be looking for in their orbiter mission.

E. Mission 3: Orbiter

1. Use masking tape to mark a distance of two feet from the desk holding the model planets all around the table. If the desk is large, you may want to move the planets to individual desks to make sure all sides of the target planets can be observed from roughly the same distance.

2. Uncover the model planets.

3. Give each team two minutes to orbit (circle) their target planet at the marked distance and to look at the features on the model planet through their Viewer. Remind the students that they have to move around their target planet the whole time; they cannot stop and look closer at any point. Have the students reconvene at their Mission Control to record and discuss their observations. The teams should also develop a plan for their landing expedition onto the planet's surface. Plans should include the landing spot and a list of features to be examined.

F. Mission 4: Lander

1. If pieces of cellophane were wrapped around the model planets to simulate atmospheres, remove them carefully and make sure no other features are disturbed. Removing the model atmosphere simulates the effect of making observations from the ground, without having to look through the atmosphere when making observations from a distance. Have the teams mark their landing sites on their target planets with a push-pin (or a piece of masking tape if the model planet will not accommodate a push-pin.) Have the team place their Viewer around the push-pin, draw a circle on the model planet's surface around the Viewer, and then remove the Viewer and the push-pin. The circle marks the maximum area around the landing site which can be explored with this mission. Remind the students that they are not to make any observations of features beyond the circle.

2. Have the team members observe the area around the landing site close-up for five minutes.

3. Have the students reconvene at their Mission Control to record and discuss their observations. The teams should also discuss additional features they might want to investigate with a follow-up mission.

Discussion & Reflection

1. Have the students compare their observations with the list of features placed on the model planet by their partner team. Did they see all features with all missions? Were there any they did not observe at all?

2. Discuss with the students, and make a class list, of the pros and cons of each type of exploration. Your table might look something like the following:

Mission 1: Earth-based observations		Mission 2: Flyby		Mission 3: Orbiter		Mission 4: Lander	
Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons

3. Discuss with the students other differences besides just the kind of observations one can make with the different missions, such as: Which mission is the easiest to do? Which ones are most likely to require complicated tools and machinery? Which one would be the most likely to succeed? What kinds of hazards could each mission face? Which ones would be most expensive? See the *Science Overview* for a more detailed discussion.

4. Ask the students what kind of mission they would design to explore an object in the Solar System that has never been visited by a spacecraft before. An example could be Pluto, a dwarf planet in the outer parts of the planetary realm of the Solar System (note that the New Horizons spacecraft will fly by Pluto in 2015, so after that Pluto will no longer be a good example.) What do the students know about Pluto already? What would they want to learn with the new mission? Would they want to do a flyby, orbiter, or a lander mission? The total cost of the flyby New Horizons mission is $550 million, and it will fly by Pluto nine years after launch. What if the cost of the orbiter mission is two times more, and it takes five years

longer to do it? What if the lander is five times more expensive and takes another five years longer? Would the additional cost and time influence the students' decision?

5. Discuss with the students how what scientists want to learn about a world determines how a mission is initially planned, but real-world constraints such as available funding can influence mission design significantly. In the next activity, students will plan a mission to explore another world, and they must take into account not only what they want to learn about the world to decide if it will be a flyby, an orbiter, or a lander mission, but also consider the costs involved with the different kinds of missions.

6. Ask the students what additional problems mission designers might face when planning a human spaceflight mission instead of using robotic spacecraft. *(Desired answers include: equipment and supplies necessary to sustain the life of the astronauts, such as food, water, air, and ways to recycle the resources; shielding from the dangers of the harsh space environment, such as vacuum, extreme temperatures, and damaging radiation. See the* Science Overview *for more details.)* Discuss with the students how these considerations have limited human spaceflight so far to the space near the Earth and to the Moon, and why only robotic spacecraft have journeyed further into space.

Activity 2: Mission Design

Students create a plan for a spacecraft exploration of another world. They will consider different aspects of mission planning, including science goals, engineering constraints, and financial considerations. They have to consider how their exploration would be affected in terms of whether the spacecraft would land, orbit, or just fly by the target. Students will come to understand that what one wants to learn about a world determines how one plans a mission, but real-world constraints such as cost and time determine what actually can be accomplished.

Materials

Per group of 3 or 4:

- Student Worksheet 2
- *Mission Log*
- Presentation materials, such as access to PowerPoint or poster board and markers, depending on how you decide to have the groups present their mission proposal

Preparation

1. Students will design a mission to explore another world in the Solar System. You can have the students plan their mission without budgetary limits, or you could make the activity a NASA Discovery Program mission design process, for example, with a cost cap of $450 million. Examples of past and current Discovery Program missions include Deep Impact, which studied the comet 9P/Tempel 1, and the MESSENGER mission to Mercury. The cost restriction makes the mission design more challenging, because the students have to meet their mission goals with limited funding. However, the restriction also makes the decision of which mission to fund more balanced, since all missions would cost roughly the same.

2. Reserve appropriate materials for the students to present their final mission proposals: access to PowerPoint or materials to create a poster.

3. Make copies of Student Worksheet 2 and *Mission Log* (found at the back of the lesson), one per group of three or four students.

Procedures

1. Divide students into groups of three or four.

2. Ask each group to choose a world in the Solar System (such as a planet or a moon) that they would like to explore. Tell the students that they will be designing a spacecraft mission to this world using one of the methods they investigated in Activity 1.

3. Pass out copies of the *Mission Log*, which is a description of some of the different worlds in the Solar System, including a list of missions that have explored these worlds to date. Have the groups take a few minutes to examine the whole *Log* to understand the history of investigating other worlds in the Solar System, and then focus on the description of the world of their choice. Science builds on previous studies, so the students need to design a mission to investigate unknown aspects of the world and not just repeat something that has been done before (unless something new could be learned from a repeat experiment.) Be sure to point out that even though each *Log* page mentions the likelihood of life existing on the different worlds, the search for life is by no means the only, or in many cases even a very important, reason to explore other worlds in the Solar System. There are open science questions about all worlds discussed in the *Log*, making them well worth exploring.

4. Pass out Student Worksheet 2. Have the students follow the instructions to plan a mission to the world of their choice.

Teaching Tips

- The dollar figures given for the costs of spacecraft missions can be put to a better perspective by relating them to more familiar matters, such as the population of the United States and common expenses. For example, funding a $450 million spacecraft mission would be equivalent to every person in the U.S. skipping buying a $1.50 soda bottle.

- You may want to have the students conduct more research into what is known about their target world, open questions about it, and the past missions that have explored their world. The Web sites listed in the *Internet Resources & References* section are good places to look for more information.

- In Student Worksheet 2, the students are asked to re-think their mission designs due to constraints introduced during the planning process. This is an important part of creating a mission. Encourage students to re-design their mission in order to come up with the most complete and comprehensive mission possible.

- If you have completed the first lesson in the *Mission Design* Education Module, “Exploring Exploring”, you can have students form the same groups that they had in that lesson and plan the mission to the world that they chose to investigate there.

Discussion & Reflection

1. Ask the students to identify any difficulties in completing this assignment. Ask the students to relate these difficulties to real-world constraints. How do they think this relates to what scientists and engineers go through when designing a real mission?

2. Discuss how financial considerations introduced constraints on the students' missions. How do they think space exploration would be different if these constraints did not exist?

3. Have the students present their mission proposal to the rest of the class, which can act as a NASA review panel. These kinds of panels are charged with reviewing mission proposals and selecting one or more for funding. In their proposal, the students must include an explanation for why they decided to go with a flyby, an orbiter, or a lander mission, and they must defend their exploration in terms of the science that can be accomplished, the risk, and the total cost of the mission. The class can vote for which missions they would fund and why. Perhaps you can offer extra credit to the winning proposal teams.

Curriculum Connections

- *Technology*: Have the students explore further the differences between the technology needed for human spaceflight versus robotic spacecraft missions.

- *Social Studies*: Remind the students how financial considerations introduced many constraints on the students' missions. You can take this opportunity to discuss how NASA is funded with federal tax dollars. Have the students research how NASA funding compares with other federal programs. Do the students think the allocation of funds to NASA is appropriate? If NASA were to receive more money to fund more missions to explore other worlds, funding for other programs would have to be reduced, or federal taxes would have to be raised. Discuss how the government must be able to allocate its resources in a reasonable manner, and that there is not an unlimited supply of funding available for any one agency.

Closing Discussion

1. Discuss with the students how the kinds of questions we want to answer about a specific world may dictate the kind of mission we want to perform. Stress that understanding the similarities between different worlds in the Solar System allows scientists to plan their missions better, for example by using similar instruments to study different worlds.

2. Discuss with the students how designing new missions to study other worlds builds on previous explorations, from defining science questions to providing instrument designs that are used to answer those questions.

3. Discuss with the students how available technology sets constraints on the kinds of missions that are possible at present time, while sometimes it is necessary to develop new technologies to answer particularly important science questions. Therefore, it is possible for science to drive technology, or for the available technology to define the kind of science that is possible, but the two always go hand-in-hand.

4. Hand out copies of the *Mission Information Sheet* located at the back of the lesson. Discuss with the students how the mission designers had to consider the same kinds of issues that the students faced in planning their missions.

Assessment

4 points

▼ Student listed pros and cons for each type of mission in Student Worksheet 1.

▼ Student completed Student Worksheet 1.

▼ Student used reasoning to support the mission design in Student Worksheet 2.

▼ Student presented his/her team's mission proposal to the class and used evidence and reasoning to support the mission design.

3 points

▼ Three of the four above criteria were met.

2 points

▼ Two of the four above criteria were met.

1 point

▼ One of the four above criteria was 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/publications/bsl/online/bolintro.htm

National Science Education Standards

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

Cassini-Huygens Mission to Saturn

http://saturn.jpl.nasa.gov/

Dawn Mission to Asteroids

http://dawn.jpl.nasa.gov/

Deep Impact Mission to a Comet

http://deepimpact.umd.edu/

Galileo Mission to Jupiter

http://solarsystem.nasa.gov/galileo/

Hubble Space Telescope

http://hubblesite.org/

Keck Observatory

http://www.keckobservatory.org/

Magellan Mission to Venus

http://www2.jpl.nasa.gov/magellan/

Mars Express Mission

http://www.esa.int/SPECIALS/Mars_Express/

Mars Exploration Rover Mission

http://marsrovers.jpl.nasa.gov/home/

NASA: Discovery Program

http://discovery.nasa.gov/

NASA: Gravity Assist Primer

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

NASA: Human Space Fight

http://spaceflight.nasa.gov/station/

NASA: Mars Exploration Program

http://mpfwww.jpl.nasa.gov/

NASA National Space Science Data Center Spacecraft Project Page

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

NASA: Planetary Photojournal

http://photojournal.jpl.nasa.gov/

NASA Solar System Exploration

http://solarsystem.nasa.gov/

NEAR-Shoemaker Mission to Asteroids

http://near.jhuapl.edu/

New Horizons Mission to Pluto and the Kuiper Belt

http://pluto.jhuapl.edu/

Phoenix Mars Mission

http://phoenix.lpl.arizona.edu/

Pioneer 10 and 11 Missions to Jupiter and Saturn

http://www.nasa.gov/centers/ames/missions/archive/pioneer10-11.html

The Nine Planets

http://nineplanets.org/

The Nine Planets – Planetary Science Spacecraft

http://nineplanets.org/spacecraft.html

Rosetta Mission to a Comet

http://sci.esa.int/rosetta/

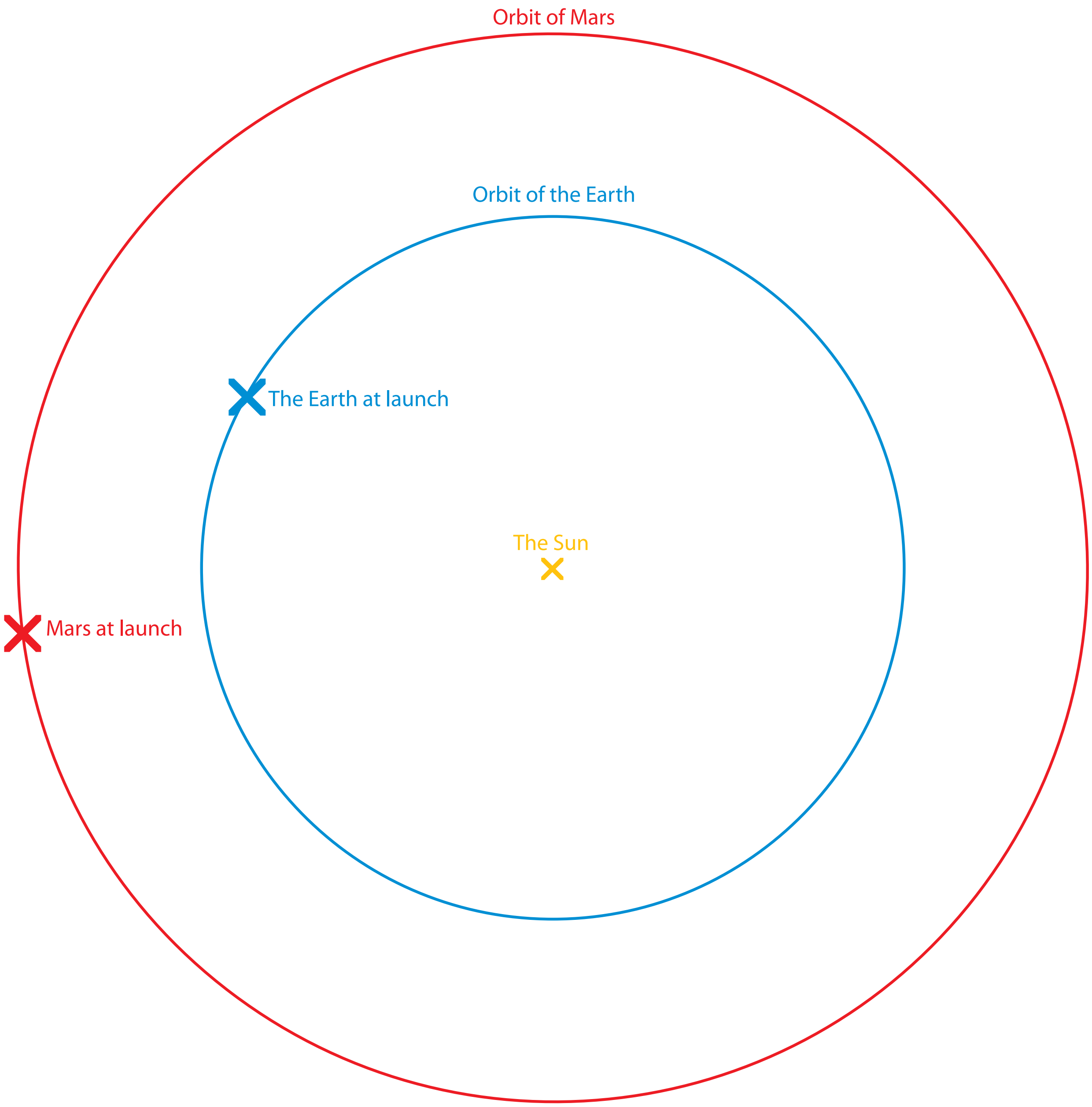
Voyager 1 and 2 Missions to Jupiter, Saturn, Uranus, and Neptune

http://voyager.jpl.nasa.gov/

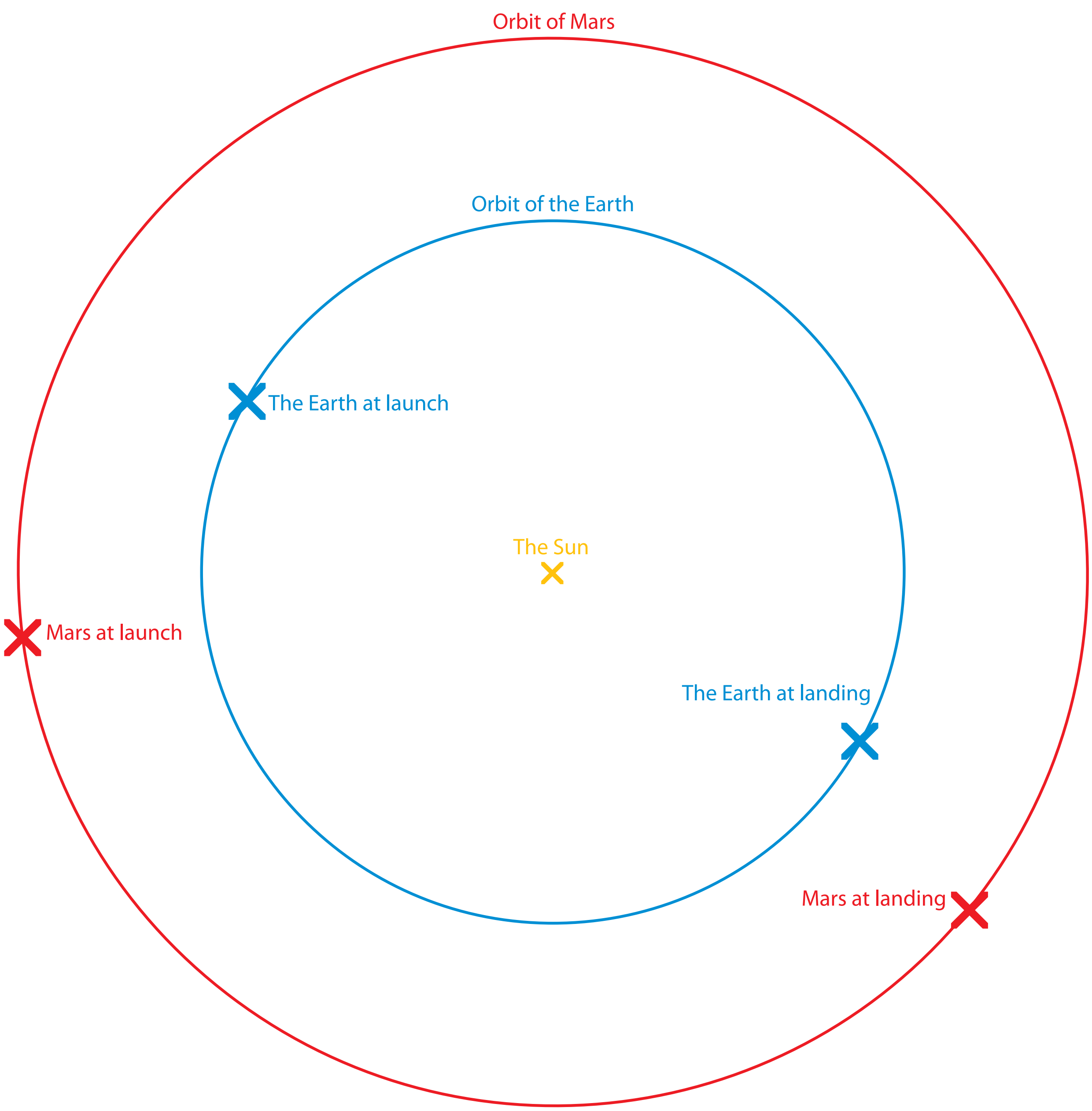
Acknowledgements

Activity 1 was adapted from "Strange New Planet" from the ASU Mars K-12 Education Program 6/99 (http://quilt.jpl.nasa.gov/docs/Strange_New_Planet.pdf), which in turn was adapted from NASA Education Brief "EB-112: How to Explore a Planet" 5/93..

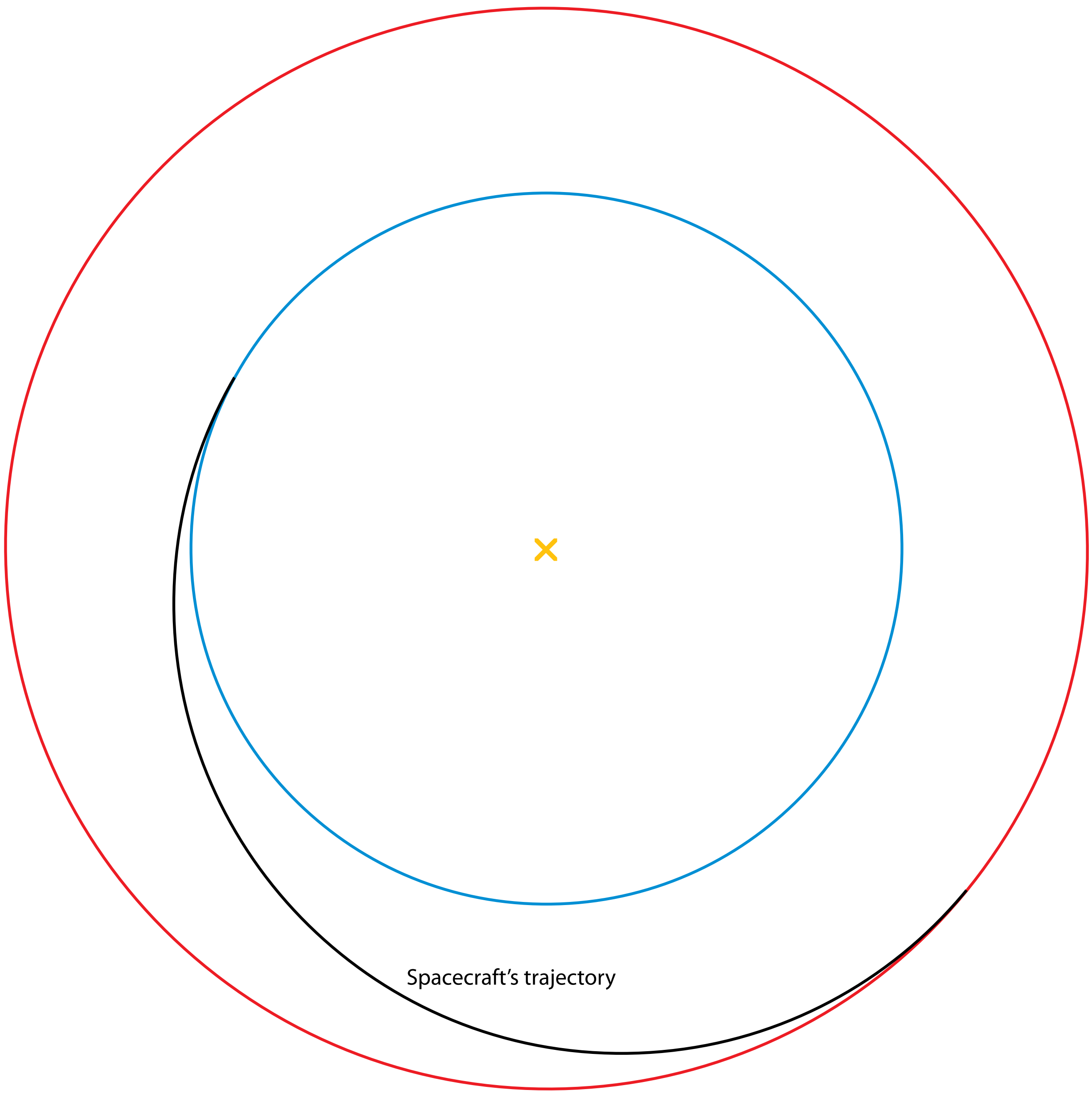
Earth and Mars Orbit Transparency #1



Earth and Mars Orbit Transparency #2

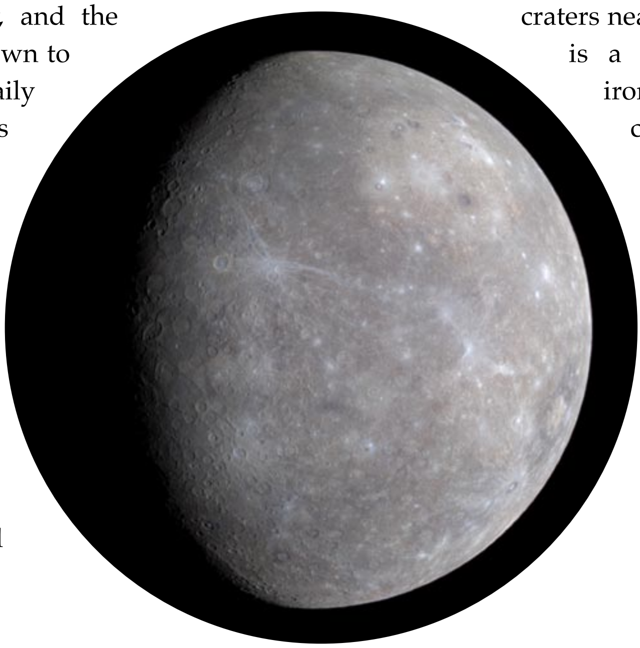


Earth and Mars Orbit Transparency #3



Mission Log: Mercury

Mercury is the closest planet to the Sun. Its diameter is only a little more than a third of the Earth. It has a very thin atmosphere, which is only a little more substantial than a vacuum. Sunlight heats up the surface of the planet to high temperatures during the day, up to 450ºC (840ºF). At night, the surface cools off rapidly, and the temperatures can drop down to –180ºC (–300ºF). This daily temperature variation is the largest of all planets. Mercury orbits the Sun once every 88 Earth days; that is, its year is 88 Earth days long. Mercury's day is much longer than the Earth's. It rotates once around its axis every 59 Earth days; the slow rotation rate, combined with the planet's fast orbital period around the Sun, makes the the length of one day on Mercury is equal to 176 Earth days; that is, the time from one sunrise to another is 176 Earth days. There is no liquid water on Mercury, although it is possible that water ice could exist in the permanently shadowed craters near Mercury's poles. Mercury is a planet with a very large iron core and a thin mantle compared with the Earth. Mercury is bombarded by intense solar radiation since its atmosphere is not sufficiently thick to provide much protection (unlike the atmosphere of the Earth), and it is so close to the Sun. It is unlikely that any life forms could live on Mercury.



Spacecraft Missions to Mercury:

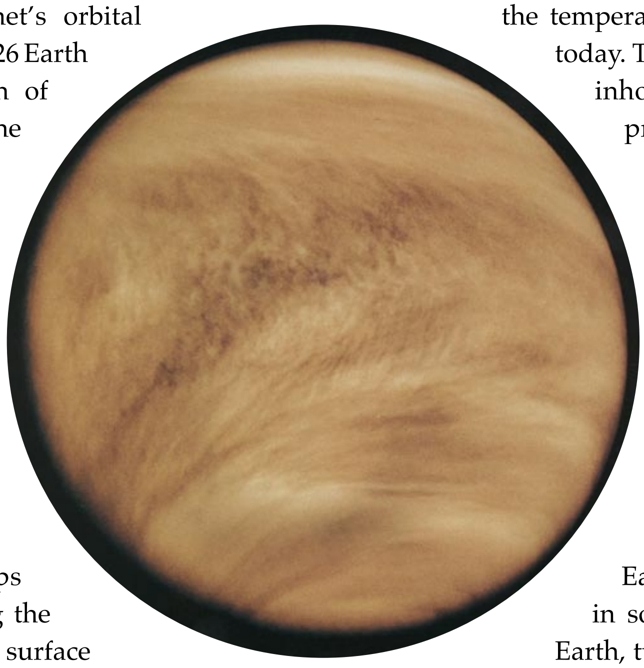
- Mariner 10 (1974-1975): The spacecraft flew by the planet three times, took images of 45% of the surface and revealed that Mercury had greater mass than previously thought.
- MESSENGER (launched in 2004): This orbiter mission flew by Mercury three times in 2008 and 2009 and will go into orbit around the planet in 2011. During its year-long orbital mission, the spacecraft will map the entire surface and conduct a comprehensive study of the planet and its space environment.

For a complete list of past, current, and future missions to Mercury, see http://nssdc.gsfc.nasa.gov/planetary/planets/mercurypage.html

(Picture credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington; http://solarsystem.nasa.gov/multimedia/gallery/messenger_new_big.jpg)

Mission Log: Venus

Venus is the second planet from the Sun. It is a near twin in size to the Earth but otherwise very different. Venus's rotates around its axis very slowly, once every 244 Earth days. The slow rotation rate, combined with the planet's orbital period around the Sun—226 Earth days—makes the length of one day on Venus (from one sunrise to another) equal to 117 Earth days. In addition, Venus rotates in a clockwise direction as viewed from above the north pole of the Sun; this is opposite to the rotation of the Earth and most other planets. Venus has a very thick carbon dioxide atmosphere that traps heat from the Sun during the day and does not let the surface cool at night. As a result, the temperatures on the surface of Venus are over 464ºC (867ºF). Similar greenhouse effect operates also on the Earth, but on Venus the process went to extremes and raised the temperature to the high value seen today. To make the planet even more inhospitable, the atmospheric pressure on the surface of Venus is about 90 times as high as the air pressure at sea level on Earth. Any water that might have existed on the surface of Venus in the past has long since evaporated, and finding life on the planet is not likely (though not entirely impossible.) We may learn a lot about the Earth by learning why Venus, in so many ways similar to the Earth, turned out so differently.



Some of the Most Successful Spacecraft Missions to Venus:

- Mariner 2 (1962): This flyby mission confirmed that Venus is a very hot planet with a cloud-covered atmosphere composed primarily of carbon dioxide.
- Venera 7 (1972): This lander was the first human-made probe to send back data from the surface of another planet.
- Venera 9 (1975): The mission featured an orbiter, as well as a lander, which sent back the first images of the surface of Venus.
- Pioneer Venus (1978-1992): Consisted of an orbiter, which used radar to make the first high-quality map of the surface of Venus, and atmosphere probes, which descended into the atmosphere to analyze it in greater detail.
- Magellan (1990-1994): This orbiting mission mapped 98% of the surface of Venus. Most of what we know of the surface features of Venus is due to the work of this spacecraft.
- Venus Express (Arrived in 2006): This orbiter mission is studying the atmosphere to understand its greenhouse effect better; also looking for volcanic and seismic activity.

For a complete list of past, current, and future missions to Venus, see http://nssdc.gsfc.nasa.gov/planetary/planets/venuspage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Venus_Clouds.jpg)

Mission Log: The Moon

The Moon is Earth's celestial neighbor. It is 384,000 km (239,000 miles) from the Earth, and its diameter is about one quarter of the Earth's. It takes the Moon 27 1/3 days to go once around the Earth. The Moon's composition is very similar to those of the Earth and the other rocky, Earth-like planets in the Solar System. In fact, its similar composition to the Earth's crust material was a crucial clue in developing an understanding of its origin. The Moon is thought to have formed when a Mars-sized object smashed into the forming Earth billions of years ago. Material was blasted into orbit around the Earth by this collision and later collected together to become the Moon. The surface of the Moon is heavily cratered as a result of meteoroid bombardment in the past. There are two main types of terrain on the Moon: the old, light-colored, heavily cratered highlands, and the younger, dark, smooth areas called maria. About 382 kg (842 lbs) of rock samples from the surface of the Moon have been returned for laboratory studies, which have revealed lots of information about the composition, the structure, and the history of the Moon. Recent spacecraft have revealed the presence of water ice in the permanently shadowed craters near the Moon's poles. There are currently plans to send humans back to the Moon and even establish a permanent colony.

Some of the Most Successful Spacecraft Missions to the Moon:

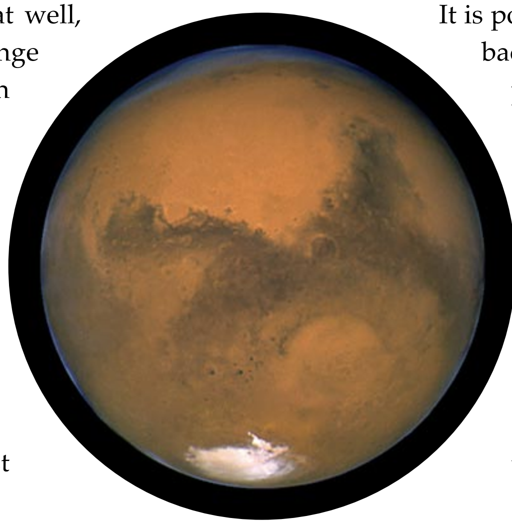
- Luna 1 (1959): This flyby mission was the first spacecraft to reach the Moon.
- Luna 2 (1959): This lander mission was the first spacecraft to reach the surface of another world: it crashed on the surface (as planned) and provided data on the conditions near the surface
- Luna 3 (1959): This flyby mission took the first pictures of the far side of the Moon.
- Luna 9 (1966): This lander mission was the first to make a soft landing on another world and return data from the surface.
- Lunar Orbiter 1-5 (1966-1967): These orbiter missions mapped the surface of the Moon and looked for landing sites for future missions.
- Apollo 11,12,14,15,16,17 (1969-1972): These orbiter/lander missions were the first to take humans to the surface of another world. The astronauts made close-up observations of the surface and brought back samples for analysis.
- Clementine (1994): This orbiter discovered that there might be water ice under the surface.
- Lunar Reconnaissance Orbiter (Launched in 2009): Maps the surface of the Moon in great detail and will help identify possible landing sites and resources for future missions.
- Lunar Crater Observation and Sensing Satellite (2009): Crashed on the surface (as planned) and confirmed the presence of water ice in the permanently shadowed craters.

For a complete list of past, current, and future missions to the Moon, see http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html

(Picture credit: NASA/JPL; http://solarsystem.nasa.gov/multimedia/gallery/PIA00405.jpg)

Mission Log: Mars

Mars is the fourth planet from the Sun. It is about half the size of the Earth in diameter. The Martian day is about 43 minutes longer than the Earth day, and its year is 686 Earth days. Mars has a carbon dioxide atmosphere, but it is extremely thin, only about 1/100 as thick as the Earth's atmosphere. The thin air does not retain heat well, and surface temperatures range from a frigid –130ºC (–200ºF) on a winter night to 27ºC (80ºF) at the equator on a summer day. Mars appears red because the iron contained in the rocks and the sand has combined with the oxygen in the atmosphere through the same process that produces rust on the Earth. Mars occasionally has dust storms that can cover almost the whole planet for months. Mars has polar ice caps made of carbon dioxide ice ("dry ice") and water ice. The size of the polar ice caps changes significantly during the planet's seasons. While Mars is very dry today, it used to have lots of liquid water in the form of rivers and seas on its surface in the past. It is possible that living beings (such as bacteria) could have existed on the planet then. Or, perhaps there are simple life forms still on Mars similar to bacteria on the Earth that can survive in frigid conditions by creating anti-freeze chemicals that keep the water in their cells from freezing. In any case, Mars looks like the likeliest place for life to exist outside of the Earth.



Some of the Most Successful Spacecraft Missions to Mars:

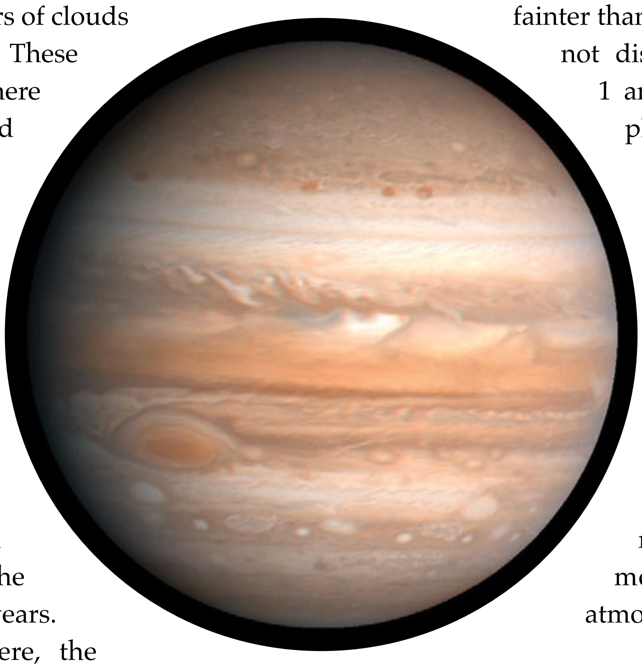
- Mariner 4 (1964-1965): This flyby mission took the first close-up images of the Martian surface.
- Mariner 9 (1971-1972): This orbiter mission provided detailed views of the huge volcanoes on the Martian surface, the giant canyon systems, the polar ice caps and Mars's two moons, Phobos and Deimos.
- Viking 1 and 2 (1976-1982): These combined orbiter/lander missions sent back the first images from the surface, made life-detection experiments (with inconclusive results), recorded a marsquake, and monitored weather.
- Mars Pathfinder (1997): Included a stationary lander and the first robotic surface rover that successfully operated on another planet.
- 2001 Mars Odyssey (2001-2006): This orbiter found evidence for large amounts of water ice under the surface near the south pole of Mars.
- Mars Exploration Rovers (Arrived in 2004): These roving landers confirmed that Mars had a lot of water on its surface in the past.
- Mars Express (Arrived in 2003): This orbiter mission has gathered detailed information on the surface features and minerals, as well as the atmosphere.
- Phoenix Mas (2008): The lander mission to the north polar regions confirmed the presence of ice just under the surface, looked for potential nutrients in the soil, and observed snow falling in the Martian atmosphere.

For a complete list of past, current, and future missions to Mars, see http://nssdc.gsfc.nasa.gov/planetary/planets/marspage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Hubble_Mars.jpg)

Mission Log: Jupiter

Jupiter is the fifth planet from the Sun and the largest planet in the Solar System. Its mass is 318 times the mass of the Earth, and over 1,300 Earths could fit inside it. Jupiter is a gas giant mostly made of hydrogen and helium. Jupiter has no solid surface that we can see, and the apparent visible surface is just the top layers of clouds in its massive atmosphere. These upper layers of the atmosphere show complicated wind patterns. The winds blow in opposite directions in the light-colored zones and dark belts. Perhaps the most recognizable feature on Jupiter's visible surface is the Great Red Spot, a huge storm, more than twice the diameter of the Earth, which has been seen by observers on the Earth for more than 300 years. Deeper in the atmosphere, the gases become thicker until they eventually turn into a liquid. At its center, Jupiter may have a solid, rocky core a few times the size of Earth, though based on current data, it is also possible that it does not have a solid core at all. Jupiter has at least 63 moons and a faint ring system. The ring system is much fainter than the rings of Saturn and was not discovered until the Voyager 1 and 2 spacecraft flew by the planet in 1979. Jupiter's day is about 10 hours long, and its year is about 12 Earth years. Jupiter radiates more energy into space than it receives from the Sun. This excess energy, produced by the massive planet being compressed under its own gravity, is thought to be ultimately responsible for the complex motions in the planet's atmosphere.



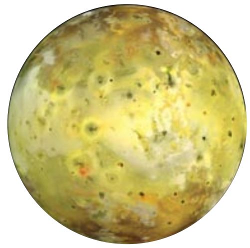
Some of the Most Successful Spacecraft Missions to Jupiter:

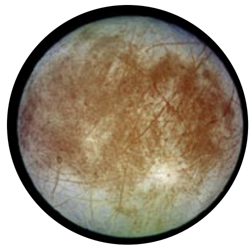
- Pioneer 10 (1973): This flyby mission provided the first close-up images of Jupiter.
- Pioneer 11 (1974): This flyby mission took dramatic images of the Great Red Spot and made the first observations of the planet's polar regions.
- Voyager 1 and 2 (1979): These flyby missions discovered that Jupiter features complicated atmospheric phenomena, as well as lightning and aurora. They also made observations of the planet's moons and discovered that Jupiter has rings.
- Galileo (1995-2003): There were two components to the mission: the orbiter was the first spacecraft to orbit Jupiter and provide information on the giant planet for a long period of time; the probe plunged into the planet's atmosphere and provided the first measurements of the properties of a giant planet underneath the surface clouds.

For a complete list of past, current, and future missions to Jupiter, see http://nssdc.gsfc.nasa.gov/planetary/planets/jupiterpage.html

(Picture credit: NASA; http://nssdc.gsfc.nasa.gov/imgcat/hires/vg2_usgs_1990.jpg)

Mission Log: Galilean Moons
Io, Europa, Ganymede, Callisto





The four largest moons of Jupiter are known as the Galilean moons, since they were discovered by Galileo Galilei in 1610. Jupiter's immense gravity exerts strong tidal forces on the moons. The tides bend and flex the rock of the crust and core of the moons, creating heat. The level of this heating depends on the moons' distances from Jupiter. The tidal forces on Io (pictured top left), the innermost of the Galilean moons, generate enough heat to produce volcanoes and evaporate any ice the moon may have once had. With at least 180—and possibly as many as 400—active volcanoes, Io is the most volcanically active object in the Solar System, with a surface covered by brightly colored sulfur. Europa (second from top), the smallest of the Galilean moons and slightly smaller than the Earth's Moon, has a very smooth surface with few craters. The moon is covered by water ice that is probably a few kilometers thick, and underneath the ice there probably is a liquid water ocean. Ganymede (third from top) is the largest moon in the Solar System, larger than the planet Mercury. It is the only moon known to have an internal magnetic field, created probably in a manner similar to the magnetic field of the Earth. Ganymede is thought to have an underground ocean, though the evidence is not quite clear as for Europa. Callisto (bottom) is the second largest of the Galilean moons, and the third largest moon in the Solar System (after Ganymede and Saturn's Titan). Its surface is heavily cratered and ancient, and it does not appear to experience as much tidal heating as the other moons. However, it still may have a liquid water ocean under the surface. Since liquid water is thought to be one of the requirements for living beings, could life exist in the underground oceans? This question remains currently unanswered, but the Galilean moons will undoubtedly see new missions exploring this possibility in the future.

Spacecraft Missions to the Galilean Moons:

- Voyager 1 & 2 (1979): These flyby missions mapped parts of the Galilean moons' surfaces as they passed through the Jupiter system.
- Galileo (1995-2003): This mission, while orbiting Jupiter, flew by the Galilean moons several times. Much of what we know of the moons, especially of their internal structure, comes from the observations made by this spacecraft.

For a complete list of past, current, and future missions to the Jupiter system, including Europa, see http://nssdc.gsfc.nasa.gov/planetary/planets/jupiterpage.html

(Picture credits: Io: NASA/JPL/University of Arizona, http://photojournal.jpl.nasa.gov/catalog/PIA02308; Europa: NASA, http://nssdc.gsfc.nasa.gov/imgcat/hires/gal_p48040.jpg; Ganymede: NASA/JPL, http://photojournal.jpl.nasa.gov/catalog/PIA00716; Callisto: NASA/JPL/DLR, http://photojournal.jpl.nasa.gov/catalog/PIA03456)

Mission Log: Saturn

Saturn is the sixth planet from the Sun and the second largest planet in the Solar System after Jupiter. Its diameter is about 85% of Jupiter's but it is a lot lighter: its mass is about a third of Jupiter's. This means that it has a very low density. In fact, its density is the lowest of all the planets and less than the density of water. Still, in composition and internal structure, the planet is thought to be fairly similar to its larger sibling. Like Jupiter, Saturn is a gas giant mostly made of hydrogen and helium gas. Saturn has no solid surface we can see, and the apparent visible surface is just the top layers of clouds in its atmosphere. These outer layers of the atmosphere have light-colored zones and dark belts, where the winds blow in opposite directions, but the bands are not as prominent as on Jupiter. Deeper in the atmosphere, the gases get thicker, until finally they turn into a liquid. At its center Saturn may have a solid, rocky core a few times the size of Earth, though based on current data, it is also possible that it does not have a solid core at all. Saturn's day is about 10.5 hours long, and its year is about 29.5 Earth years. Saturn has at least 61 moons, and perhaps many more that are yet to be discovered. Saturn's most striking property may be its exquisite ring system. The rings are surprisingly thin: they are 250,000 km (155,000 miles) in diameter, but their thickness is typically less than 10 meters (30 feet), though this varies somewhat within the ring system depending on the location and the size of the ring particles. Even though the rings look solid when viewed from the Earth, they are actually composed of millions of small icy particles varying in size from a centimeter (less than an inch) to a few meters (yards), and perhaps even to a size of a kilometer (half a mile). Scientists are still trying to determine the origin of the ring particles; the most commonly accepted suggestions are that they are particles blown off the planets' moons by asteroid or meteoroid impacts, or leftovers from the breakup of larger moons. Saturn radiates more energy into space than it receives from the Sun. Some of the excess energy comes from the planet being compressed under its own gravity, but some may come from other sources, such as helium gas condensing in Saturn's atmosphere into droplets and raining down deeper into the planet.

Spacecraft Missions to Saturn:

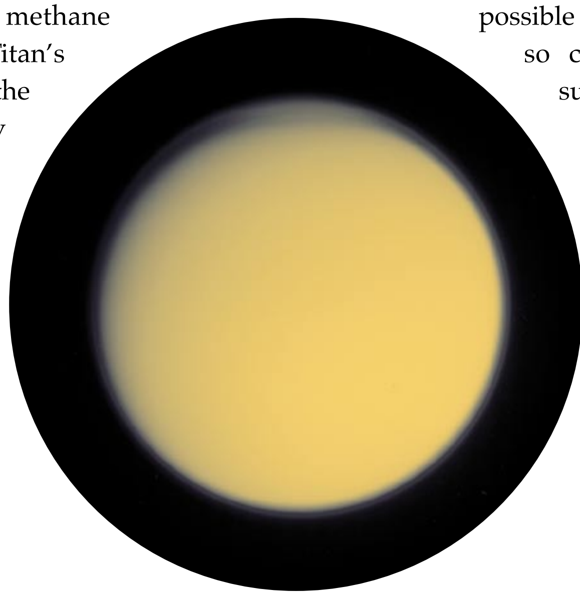
- Pioneer 11 (1979): This flyby mission provided the first close-up images of Saturn.
- Voyager 1 and 2 (1980-1981): These flyby missions provided detailed information on the planet, its atmosphere, moons and rings. For example, they discovered shepherd moons that keep the rings stable.
- Cassini-Huygens (Arrived in 2004): This orbiter mission was the first to explore the Saturn system from orbit. The mission has provided detailed information on the planet's clouds and magnetic field, as well as made close-up studies of the moons and the rings.

For a complete list of past, current, and future missions to Saturn, see http://nssdc.gsfc.nasa.gov/planetary/planets/saturnpage.html

(Picture credit: NASA/JPL/Space Science Institute; http://solarsystem.nasa.gov/multimedia/gallery/Saturn_Approach.jpg)

Mission Log: Titan

Titan is one of the 61 known moons of Saturn. Titan's most interesting feature is that it is the only moon in to Solar System to have a significant atmosphere. At Titan's surface, the atmospheric pressure is 1.5 times that of the Earth's at sea level. The atmosphere is composed primarily of molecular nitrogen with a little argon and methane mixed in. In many ways, Titan's atmosphere is similar to the conditions on the Earth early in its history when life first emerged on our planet. But it is this thick hazy atmosphere that makes it so hard to see Titan's surface. The images taken by spacecraft exploring the moon close-up have revealed an active surface with flowing liquids (composed of methane, rather than water) and many meteorological and geologic processes in action. Titan could have been a possible host for life, if it had not been so cold—the temperature on the surface of Titan is frigid –180ºC (–290ºF)—that no living beings that we know of could survive on its surface.



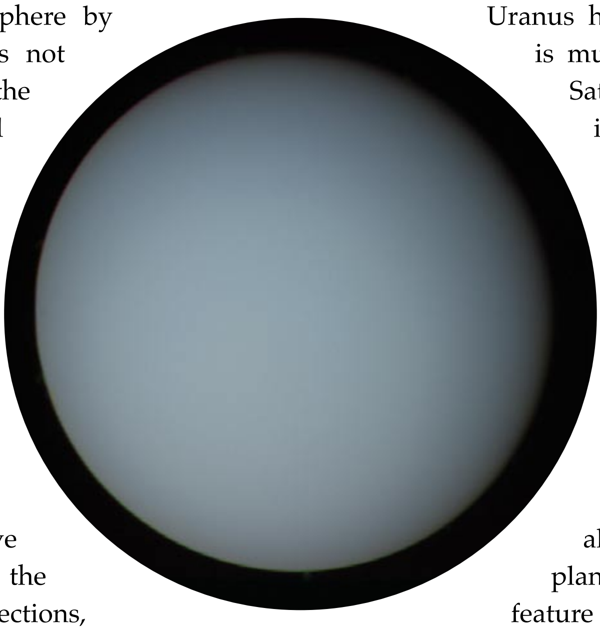
Spacecraft Missions to Titan:

- Pioneer 11 (1979): This flyby mission provided the first close-up images of Titan as it passed through the Saturn system.
- Voyager 1 and 2 (1980-1981): These flyby missions provided more information on Titan's hazy atmosphere but were not able to see the surface.
- Cassini-Huygens (Arrived in 2004): The main spacecraft, Cassini, orbits Saturn and has flown by Titan several times, providing detailed information on the moon's atmosphere and surface features. In 2005, the Huygens probe descended through Titan's thick atmosphere and landed on the moon. The probe sent back images from the surface and provided other detailed data for about 90 minutes.

For a complete list of past, current, and future missions to the Saturn system, including Titan, see http://nssdc.gsfc.nasa.gov/planetary/planets/saturnpage.html

(Picture credit: NASA/JPL/Space Science Institute; http://photojournal.jpl.nasa.gov/tiff/PIA06122.tif)

Mission Log: Uranus



Uranus is the seventh planet from the Sun. It is smaller than Jupiter and Saturn, but similar to Neptune in size. Uranus's composition is a little different from Jupiter and Saturn in the sense that it seems to be made of mostly of a mixture of icy and rocky materials, and even though it has an extensive atmosphere by the Earth's standards, it is not as large a component of the planet as it is on Jupiter and Saturn. As a result, Uranus (as well as Neptune) is sometimes called an "ice giant" instead of a gas giant. Uranus has no solid surface that we can see, and the apparent visible surface is just the top layers of clouds in its atmosphere. These outer layers of the atmosphere have light and dark bands where the winds blow in opposite directions, but they are very faint and not visible in images taken of the planet without extensive image enhancements. However, it may be that the visibility of the bands changes according to the planet's seasons. Underneath Uranus's atmosphere, the mixture of icy and rocky materials is probably distributed uniformly, and the planet may not have a solid core at all. Uranus's day is about 17 hours long, and its year is about 84 Earth years. Uranus has at least 27 moons (and perhaps many more yet to be discovered.) Like the other giant planets, Uranus has a ring system, though it is much fainter than the rings of Saturn. Uranus's unique feature is that it appears to have been knocked over sometime in the past. Most planets orbit around the Sun spinning upright; that is, their rotational axes are almost perpendicular with respect to their orbit (with small deviations, like the Earth's 23.5° tilt). Uranus's rotation axis, however, is almost lying within its orbital plane. The cause of this unique feature is not certain, but it may have been caused by an impact of a large object, such as an asteroid or a moon. Unlike the other giant planets in the Solar System, Uranus does not appear to have an internal heat source. Why this is the case is not certain.

Spacecraft Missions to Uranus:

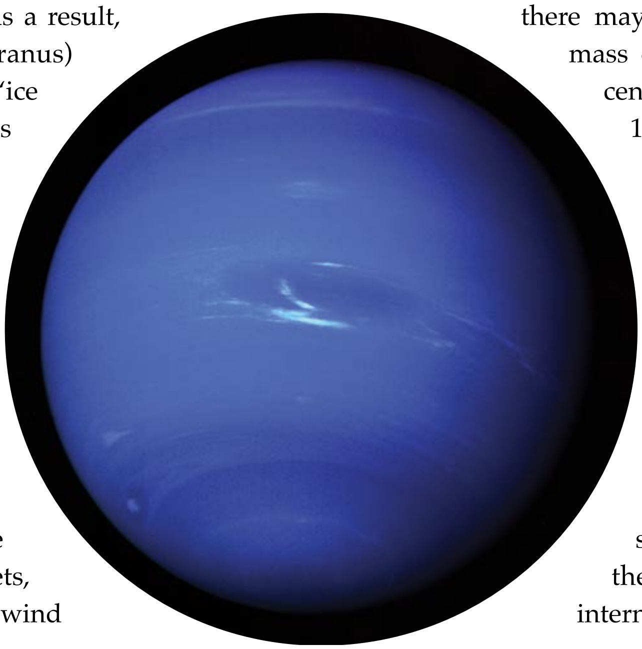
- Voyager 2 (1986): This flyby mission provided the first close-up images of Uranus. Its observations have provided much of our current knowledge of the planet, its rings and moons. It also discovered that the magnetic field is peculiar in its properties (origin, orientation, etc.)

For a complete list of past, current, and future missions to Uranus, see http://nssdc.gsfc.nasa.gov/planetary/planets/uranuspage.html

(Picture credit: NASA/JPL; http://photojournal.jpl.nasa.gov/tiff/PIA00032.tif)

Mission Log: Neptune

Neptune is the eighth planet from the Sun. It is smaller than Jupiter and Saturn, but similar to Uranus in size. Neptune's composition is a little different from Jupiter and Saturn in the sense that it seems to be made of mostly of a mixture of icy and rocky materials, and even though it has an extensive atmosphere by Earth's standards, it is not as large a component of the planet as it is on Jupiter and Saturn. As a result, Neptune (as well as Uranus) is sometimes called an "ice giant" as opposed to a gas giant. We cannot see Neptune's solid surface, and the apparent visible surface is just the top layers of clouds in its atmosphere. Giant storm centers can be seen on its visible surface, similar to those on the other giant planets. Also, like on the other giant planets, the atmosphere has great wind patterns creating bands on the atmosphere where winds blow in different directions. In fact, the winds on Neptune are the fastest in the Solar System, reaching speeds of 2,000 km/hour (or 1,200 miles/hour) relative to the planet's interior rotation rate. Underneath the atmosphere, the mixture of icy and rocky materials making up the bulk of the planet is probably uniformly mixed, though there may be a solid core about the mass of the Earth at the planet's center. Neptune's day is about 17 hours long, and its year is about 165 Earth years. It has at least 13 moons; probably many more are yet to be discovered. Like the other giant planets, Neptune has a ring system, though it is much fainter than the rings of Saturn. Neptune radiates more energy into space than it receives from the Sun; the source of this internal energy is uncertain.



Spacecraft Missions to Neptune:

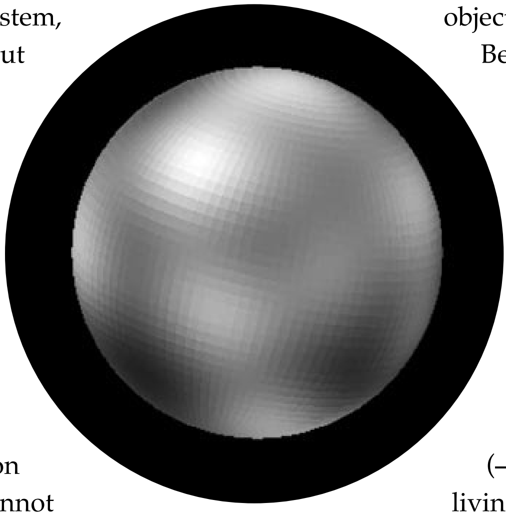
- Voyager 2 (1986): This flyby mission provided the first close-up images of Neptune. Its observations have provided much of our current knowledge of the planet, its rings and moons. It detected auroras on Neptune, and showed the atmosphere to be very active with high winds and large storms.

For a complete list of past, current, and future missions to Neptune, see http://nssdc.gsfc.nasa.gov/planetary/planets/neptunepage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Neptune_Full.jpg)

Mission Log: Pluto

Pluto used to be known as the ninth planet, but it always seemed a bit odd when compared with the other eight planets. Like the terrestrial planets (Mercury, Venus, the Earth, and Mars), it is small, but, because it is a mixture of rock and ice, its density is low, and it is not located in the same part of the Solar System as the terrestrial planets. Instead, it is located in the outer part of the planetary realm of the Solar System, where the giant planets reside, but it certainly is not a gas or an ice giant, either. Instead, Pluto appears to be more closely related to the hundreds of objects astronomers have discovered beyond Neptune's orbit in recent years. When one of these so-called Kuiper Belt Objects was discovered to be larger than Pluto, the International Astronomical Union decided in 2006 that Pluto cannot be considered a major planet any more, and belongs to a new class of objects called dwarf planets, instead. As a result, there are now only eight major planets in the Solar System, and Pluto is just an example of the new group of objects called dwarf planets. There are probably many more dwarf planets in the outer regions of the Solar System yet to be discovered. Pluto has three moons, but this is not unusual for small Solar System objects: many dwarf planets, Kuiper Belt Objects, and even asteroids have moons. Not much is known about the properties of the dwarf planet or of its thin atmosphere. Pluto's day is about 6.4 Earth days long, and its year is about 248 Earth years. The frigidly cold temperatures—the temperature on the surface of Pluto is thought to reach –230ºC (–450ºF)—make it unlikely for any living beings to live on the dwarf planet.



Spacecraft Missions to Pluto:

- New Horizons (will arrive in 2015): This flyby mission will be the first to make close-up observations of Pluto and its moons.

For a complete list of past, current, and future missions to Pluto, see http://nssdc.gsfc.nasa.gov/planetary/planets/plutopage.html

(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/nssdc_hst_pr96_09a.jpg)

Mission Log: Asteroids

Asteroids are small rocky objects that can be found in different regions of the Solar System. They orbit the Sun like planets, but they are a lot smaller. Ceres used to be known as the largest asteroid; it is about 950 km (590 miles) in diameter. However, Ceres is now classified as a "dwarf planet", a new category of objects in the Solar System defined by the International Astronomical Union in 2006 to include objects like Ceres and Pluto, which are too small to be considered major planets, but resemble them in many other ways. Ceres is still associated with asteroids, since it is located in the same part of the Solar System as the vast majority of asteroids—the Asteroid Belt, a region between the orbits of Mars and Jupiter. The largest asteroids are Pallas, Vesta and Hygiea, which are between 400 km (249 miles) and 525 km (326 miles) in diameter. There are hundreds of thousands of known asteroids. Astronomers probably have seen almost all of the asteroids larger than 100 km, and about half of those with diameters in the 10-100 km range. But there are probably millions of asteroids with sizes in the 1 km range that have never been seen. Some of the moons of planets, such as the two moons of Mars and the outer moons of Jupiter and Saturn, are similar to asteroids, and they may be captured asteroids rather than having formed in the same way around the planet as other moons. Asteroids are thought to be remnants of the formation of the Solar System that did not accrete onto planets. Because asteroids are small, they are unlikely to host living beings.

Some of the Most Successful Spacecraft Missions to asteroids:

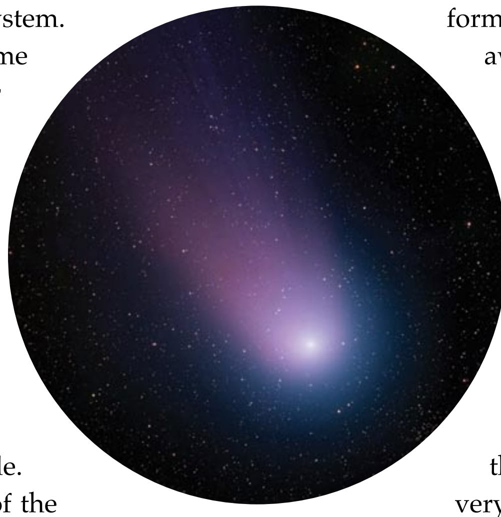
- Galileo (1991, 1993): On its way to Jupiter, the spacecraft flew by Gaspra and Ida, providing the first close-up images of asteroids, and also discovering the first moon (Dactyl) of an asteroid (Ida).
- NEAR Shoemaker (2000-2001): After flying by Mathilde, the spacecraft orbited Eros before landing on it. This marked the first time a spacecraft made a soft landing on a small Solar System object.
- Dawn (Launched in 2007): The spacecraft will fly by Ceres and Vesta in 2011-2015.

For a complete list of past, current, and future missions to asteroids, see http://nssdc.gsfc.nasa.gov/planetary/planets/asteroidpage.html

(Pictured above: Asteroid Gaspra; picture credit: NASA/JPL; http://photojournal.jpl.nasa.gov/tiff/PIA00118.tif)

Mission Log: Comets

Comets reside in the outer regions of the Solar System. They are basically dirty ice balls composed of ices (water ice, as well as other kinds, such as carbon dioxide, ammonia, and methane ices), rock, and dust. They are thought to be remnants of or the actual building blocks of (at least the outer) planets, and, therefore, are a subject of great interest for researchers interested in understanding the early history of the Solar System. Comets spend most of their time in the outer reaches of the Solar System and are not visible to observers on the Earth. There, the comet consists of only its solid body, the nucleus, which is only a few kilometers across and darker than charcoal. It is only when a comet's orbit takes it to the inner parts of the Solar System that a comet becomes observable. The Sun heats the frozen body of the comet, and causes ices on the comet's surface to sublimate—change directly from solid to gas. The gases blown off the nucleus, as well as specks of dust caught in the outflow, form a large cloud of gas and dust particles around the nucleus, called the coma, which can be over 1.6 million km (1 million miles) in size. Sunlight pushes against the dust particles in the coma, while the solar wind—fast outflow of electrically charged particles from the Sun—interacts with the gas. As a result, material in the coma is pushed away from the nucleus, forming a very long tail stretching away from the comet pointed away from Sun. It is not unusual for the tails of comets to extend tens of millions of kilometers. If comets venture close to the Earth, they can be some of the most striking objects in the sky. Because comets are small, because they are located in the far reaches of the Solar System during much of their orbit, and because they have very unstable surfaces when they get close to the Sun, they are unlikely to host living beings.



Some of the Most Successful Spacecraft Missions to comets:

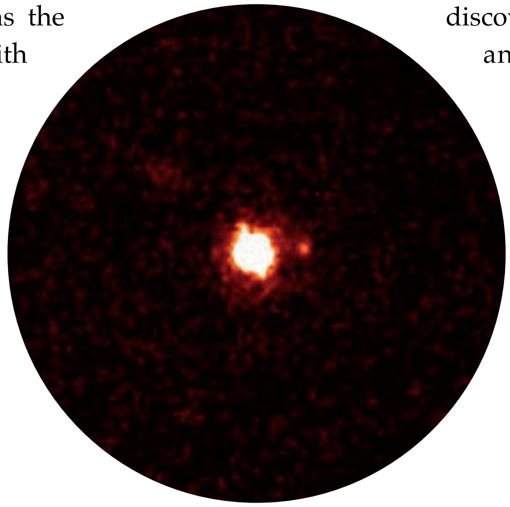
- International Cometary Explorer (1985): This flyby mission was the first to observe a comet close-up.
- Stardust (2004): This flyby mission collected samples from the coma of comet Wild 2 and returned them to the Earth for analysis.
- Deep Impact (2005): The flyby spacecraft included a lander/impactor that smashed into comet Tempel 1.
- Rosetta (Launched in 2004): Arriving at the comet 67P/Churyumov-Gerasimenko in 2014, the main spacecraft will orbit the comet while a probe will land on the nucleus.

For a complete list of past, current, and future missions to comets, see http://nssdc.gsfc.nasa.gov/planetary/planets/cometpage.html

(Pictured above: Comet C/2001 Q4 – NEAT; picture credit: T. Rector (University of Alaska Anchorage), Z. Levay and L. Frattare (Space Telescope Science Institute) and National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation; http://solarsystem.nasa.gov/multimedia/gallery/Comet_NEAT.jpg)

Mission Log: Kuiper Belt Objects

Since 1992, astronomers have found hundreds of objects similar to Pluto beyond Neptune's orbit. These objects are all small icy worlds most commonly called Kuiper Belt Objects (KBO), after the astronomer Gerard Kuiper, though they are sometimes also called trans-Neptunian objects, because they reside in space beyond the orbit of Neptune. The Kuiper Belt region, located at a distance of 30 to 50 times as far from the Sun as the Earth, may have 35,000 objects with diameters larger than 100 km (60 miles). These objects are similar to Pluto: they are small bodies made of a mixture of rock and ice. Most of the Kuiper Belt Objects discovered to date are smaller than Pluto, but detailed observations of an object named Eris, first discovered in 2003, revealed that it is larger than Pluto. This led the International Astronomical Union to decide in 2006 that Pluto (as well as Eris) belongs to a new class of objects called dwarf planets. There probably are more dwarf planets, in addition to smaller KBOs, yet to be discovered in the Kuiper Belt. Because the objects there are so far away from the Sun and are so small, they are hard to discover without powerful telescopes and advanced observation techniques. The frigidly cold temperatures in the Kuiper Belt—the temperatures on the surfaces of KBOs are not thought to reach much above –230ºC (–450ºF)—make them unlikely hosts for any living beings.



Spacecraft Missions to Kuiper Belt Objects:

- New Horizons: After flying by Pluto in 2015, the spacecraft probably will be directed to fly by one or more Kuiper Belt Objects, providing the first close-up observations of these objects.

(Pictured above: Dwarf planet Eris; picture credit: Courtesy W. M. Keck Observatory; http://www.keckobservatory.org/images/gallery/solar_system/4_73.jpg)

Strange New Planet

Materials

- Plastic ball, Styrofoam© ball, or round fruit
- Modeling clay, Playdoh©
- Vinegar, perfume, or other scents
- Small stickers, sequins, candy, marbles, etc.
- A few cotton balls
- A few toothpicks
- Glue
- Towel or a large sheet of opaque paper
- Push-pin
- Pen, pencil, or marker
- Index card
- Sheet of clear or colored cellophane
- Knife (optional)
- Paper towel rolls or a few sheets of letter-size paper rolled up
- 5″x5″ square of clear cellophane (optional)
- 6″ piece of tape or a rubber band (optional)

Your name: ______________________________

Other members of your team: ______________________________

____

____

The name of your team: ______________________________

Date: ______________________________

Introduction

In this activity, your team will make a model planet for your partner team to explore. You will then explore the model planet created by your partner team through different methods of exploration.

A. Create a Model Planet

Use a plastic ball, a Styrofoam© ball, or round fruit as your model planet. Use the materials available to your class to decorate the planet with features modeling landforms, moons, atmosphere, etc. For example, you can:

- Carve channels with a toothpick or a knife;
- Attach small stickers or embed other objects onto the ball or fruit (to represent different kinds of landforms);
- Apply scents (vinegar, perfume, etc.) sparingly to a small area;
- Use a sheet of clear or colored cellophane to wrap up the model planet (to represent an atmosphere);
- Create clouds by using cotton and glue;
- Attach a toothpick with a piece of modeling clay at the end (to represent a moon).

Record each feature in the table below (example: 1 – toothpick with clay – moon.) Use your imagination to create a unique planet! Make sure to place some features so that they are not obvious when seen from a distance. Write down on an index card the name of your team and the name of your planet to identify it when all planets are gathered together.

The name of your planet: ______________________________

Feature Number	Item Used	Feature Modeled

B. Mission 1: Earth-Based Observations

1) Estimate your distance from your target world (meters or feet):

2) A paper towel tube or a rolled-up sheet of paper will act as the Viewer with which you will make your observations. If your teacher wants you to simulate the effect of the Earth's atmosphere, crumple up and then straighten out a piece of clear cellophane. Attach the piece to the end of your Viewer. If you don't use the cellophane, your observations would be similar to using a space telescope located near the Earth. What types of things do you observe? Use your Viewer to observe the world. Remove the cellophane from your viewer (if you used it) and record your observations (color, size, features seen, etc.):

3) Discuss your observations with the rest of your team. Record any team observations that are different from yours:

4) As a team, write questions to be explored in future missions to the world. What else do you wish to know and how could you find out that information?

a.

b.

c.

d.

C. Mission 2: Flyby

Each person on your team will have a turn walking quickly past the model planet and observing it using the Viewers. Make sure you keep farther from the planet than the distance marked on the floor. Answer the questions below when you have returned from your flyby.

1) Record your observations of the planet. What did you see that was the same as your Earth-based observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

2) Discuss your observations with the rest of your team. Record any team observations that are different from yours:

4) As a team, write observations you would like to make on an orbiter mission:

a.

b.

c.

d.

D. Mission 3: Orbiter

Each team member gets two minutes to orbit (circle) the planet and observe it using the Viewers. Make sure you keep farther from the planet than the distance marked on the floor. You must circle the planet the whole time; do not stop to look more carefully at any part of the planet. After your observations, return to the Mission Control and answer the questions below.

1) Record your observations of the planet. What did you see that was the same as your Earth-based or flyby observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

2) Discuss your observations with the rest of your team. Record any team observations that are different from yours:

3) As a team, develop a plan for a lander expedition onto the planet's surface.

a. Where will you go and why? How did your team decide where to land?

b. What are the risks and benefits of landing there?

c. What specifically do you want to explore at this site?

d. What type of special equipment or instruments would you need to accomplish your exploration goals? (Remember, anything you bring has to be small and light enough to fit aboard a spacecraft.)

E. Mission 4: Lander

If your partner team used colored cellophane on their model planet to represent an atmosphere, have your teacher remove it carefully. Removing the model atmosphere simulates the effect of making observations on the ground, and not having to look through the atmosphere. Mark your landing site on your target planet with a push-pin or a small piece of masking tape. Place the Viewer around the push-pin, and draw a circle on the model planet's surface around the Viewer. Set the Viewer aside and remove the push-pin. The circle marks the maximum area around the landing site that you can explore. Do not make any observations of features beyond the circle! You have a total of five minutes to explore the landing site. After your observation, return to the Mission Control and answer the questions below.

1) Record your observations of the planet. What did you see that was the same as your Earth-based, flyby, or orbital observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

2) Discuss your observations with the rest of your team. Record any team observations that are different from yours:

3) Was your mission successful? Why or why not?

4) Now that you have landed once on the planet, are there any additional questions you would like to answer during follow-up missions?

5) What were the greatest challenges of this mission (personally and as a team)? What would you change for the next mission?

F. Compare Different Mission Types

Write down the pros and cons of the different mission types. For example, what kind of science can you do with each? What may be the difficulties or the hazards? Think of both your own experiences in this activity and those of professional scientists designing different types of missions.

1) Earth-Based Observations:

Pros:

____

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Cons:

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2) Flyby Mission:

Pros:

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Cons:

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____

____

3) Orbiter Mission

Pros:

Cons:

4) Lander Mission

Pros:

Cons:

Mission Design

Members of your team: ______________________________

____

____

____

____

Date: ______________________________

Introduction

Your team will design a spacecraft mission to explore another world in the Solar System. You must decide which world you want to explore, what you want to learn about your target world, and how you want to accomplish your mission. It can be tricky because space exploration is expensive and hazardous. Along the way, you may need to re-examine your mission goals based on available funding and other constraints. At the end, you must prepare a comprehensive proposal that you could submit to NASA. In your proposal, you must make a convincing argument why your mission should be selected for funding. Good luck!

1. Choose a World to Explore

As a team, choose a world you would like to explore. You can use the *Mission Log* given by your teacher to find an interesting world to investigate. If you are operating with a limited budget, you may also want to look at Table S1 in the Mission Cost List (at the end of this Worksheet) to help decide which world to investigate, since some worlds are more expensive to explore than others.

Your target world: ______________________________

A) The basic cost to explore this world (table S1, Mission Cost List): ______________________________

This includes the approximate costs associated with building the spacecraft, sending it on the journey to explore your target world, communicating with the spacecraft, as well as the labor costs of the scientists and engineers designing and testing the spacecraft and the instruments, monitoring the spacecraft during its entire mission, and analyzing and interpreting the gathered data.

2. Mission Goals

Examine the *Mission Log* to see what is known about your target world. Come up with three questions that the previous missions have not answered. These are your mission goals:

Mission Goal 1:

____

____

Mission Goal 2:

____

____

Mission Goal 3:

____

____

3. Type of Mission

Now that you understand what your mission needs to accomplish, you can decide what type of mission (flyby, orbiter or lander) will best help you meet your goals. Remember the pros and cons of each type of mission, and what you can learn through the different methods. You may also want to check the costs in Table S2 in the Mission Cost List, since some types of missions cost more than others. Also, the more complicated the mission you want to perform, the more chances there are for something to go wrong. The possibility of failure can be estimated by using a risk factor: the higher the factor, the riskier the mission.

Your mission will be (circle one): Flyby Orbiter Lander

Why?

____

____

B) Additional cost for this mission (Table S2, Mission Cost List): ____________________

B1) Risk Factor (Table S2, Mission Cost List): ________________________________

4. Length of Mission

Once you have selected the type of mission, you need to consider the length of the mission. The longer the mission, the greater the cost due to:

- Communications with ground control on the Earth to operate the spacecraft and transmit data for analysis;
- Spacecraft operations to make course corrections that may be necessary, to maintain the well-being of the spacecraft, and to respond to any emergencies that may arise;
- Data analysis by scientists on the Earth; the more data that is gathered, the more time (and/or more scientists) are needed for analysis; even after the spacecraft has ceased functioning, there usually is additional time scheduled for data analysis;
- Extra propellant that may be necessary to make course corrections, etc.

The length of the mission depends on the time it takes to travel to the target world, as well as the time spent observing the world. The cost of traveling to the world was considered in cost item A. You must now decide how long your spacecraft will operate once it arrives to your target world. See Table S3 in the Mission Cost List to determine how much the length of your mission affects your plan. While a longer mission means that you have more time to meet your science goals, the additional length also means that there are more chances for something to go wrong before the end of the mission. Mark the appropriate risk factor below, as well.

Time spent to explore the world: ____ years

C) Additional cost for the length of the mission (Table S3, Mission Cost List): ________________

C1) Risk Factor (Table S3, Mission Cost List): ____

5. Payload

Now you have to decide which instruments to include in your spacecraft to help you accomplish your mission goals. These instruments together are called the spacecraft's payload or instrument suite. See Table S4 in the Mission Cost List for the different kinds of instruments available for your spacecraft. You can pick up to five instruments. Explain why each instrument is necessary to meet your mission goals.

Instrument 1: ____

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

Instrument 2: ____

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

Instrument 3: ____

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

Instrument 4: ____

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

Instrument 5: ____

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

____

____

D) The total cost of your instrument suite (add up the cost of individual instruments):

____

6. Spacecraft Construction

The cost of building the spacecraft depends on how complicated the spacecraft is due to the kind of exploration it will conduct and the environment in which it will operate. Spacecraft and its instruments are often developed together so that each component can fit in their allotted space aboard the spacecraft. As a result, the size of the spacecraft and the size and types instruments must be considered in building a spacecraft. There are also additional costs involved in testing the instruments and the spacecraft. The base price for building your spacecraft has been included in cost item A. However, it is possible to find savings if you can use some components that are similar to those used by earlier spacecraft. In this case, you don't have to engineer new spacecraft components from scratch; you can use the same design used before. Review the Mission Log to see if a similar mission has been performed in the past to your target or another but similar world. If it has, you can deduct some construction costs.

Is there a similar previous mission (circle one): Yes No

If you answered "Yes", then:

Provide the name of the similar previous mission: ____

E) You receive a price reduction for using similar components from previous spacecraft: <u>– $10 million</u>

E1) Using similar components and design from a previous mission reduces the risk, so the risk factor is: <u>0.5</u>

7. Spacecraft Launch

Launching the spacecraft is a significant cost item, since you have to lift a massive spacecraft from the surface of the Earth to space, and then give the spacecraft a boost toward its target. As a result, the cost of the launch depends on both the target world and the mass of the spacecraft, which in turn can depend on many factors, such as the number of instruments, the environment in which the spacecraft has to operate, as well as the type and length of the mission. You can reduce the mass of the spacecraft by building your components smaller; for example, by creating miniature versions of your instruments. The basic cost of launching spacecraft to different worlds on missions of different lengths and types are included in the previous cost items, but in this step you must determine whether your spacecraft has so many instruments that the launch costs have to be increased. You can also decide if you want to spend additional engineering time to reduce the size of the spacecraft; however, engineering new, miniaturized components may also increase the risks.

Does your spacecraft have more than three instruments (circle one)? Yes No

If you answered "Yes":

F) Add __$50 million__ for extra launch costs.

Do you want to spend additional engineering funds to create a smaller version of your spacecraft (circle one)? Yes No

If you answered "Yes":

G) Cross out cost item E and risk factor E1). Instead, you gain __– $50 million__ for launch cost savings. Miniaturized instruments may require additional engineering, which increases your risk factor:

G1) Risk factor for miniaturized components: __2__

8. Total Cost and Risk

Write down the cost items for your mission:

A) ______________________________

B) ______________________________

C) ______________________________

D) ______________________________

E) ______________________________ (if not crossed out)

F) ______________________________ (if it applies to your mission)

G) ______________________________ (if it applies to your mission)

Add A) through G) together to calculate the total cost of your mission:

____

Write down the risk factors for your mission:

B1) ______________________________

C1) ______________________________

E1) ______________________________ (if not crossed out)

G1) ______________________________ (if it applies to your mission)

Multiply B1) through G1) with each other to calculate the total risk factor for your mission:

____

9. Human Spaceflight versus Robotic Spacecraft Mission

The costs discussed in the previous pages apply to both humans and robotic spacecraft exploring your target world. However, there are additional costs associated with keeping the astronauts alive and healthy, such as making sure there are enough supplies (food, water, and air) for the entire expedition. The astronauts must be protected from the harsh space environment, especially from the vacuum, damaging radiation, and freezing cold or scorching hot temperatures (depending on how far from the Sun the expedition goes.) The mission will also take longer to complete, because you not only need to take the astronauts to your target world and give them time to perform their exploration, but you also must return the crew safely back to the Earth. Estimating the additional costs involved with a human spaceflight mission instead of a robotic spacecraft is difficult. For the present purposes, just multiply both the total cost and the risk factor from Step 8 by 1,000.

Total cost of a human spaceflight mission: ______________________________

Risk factor for a human spaceflight mission: ______________________________

10. Final Cost

Make the final choice between a human spaceflight or a robotic spacecraft mission, and write your decision here:

Your mission will be done with (mark one):

☐ Robotic spacecraft; use numbers from Step 8

☐ Human spaceflight; use numbers from Step 9

Final cost of your mission: ______________________________

Final risk factor for your mission: ______________________________

11. Reconsider Mission Details

Look back at your mission goals and other details and decide if you want to change them. For example, if you think your mission costs too much, you might want to change your mission goals so that you can meet them with a smaller payload, and so reduce the cost of the mission.

Do you want to change the details of your mission? (Circle one)

Yes No

If "Yes," explain how your mission will change. If "No," explain why you want to keep the mission the way it is.

12. NASA Proposal

Prepare a proposal of your mission to NASA using the tools provided by your teacher. Be sure your proposal includes:

- Where your spacecraft is going and why;
- The goals of your mission; why are these goals important?
- What type of mission (flyby, orbiter, lander) will you use and why?
- Payload selection and why you chose these instruments;
- Total cost and justification for the costs.

Remember, you are competing with other mission proposals, and not all can be selected for funding. You must be convincing in your argument that your mission offers the best bang for the buck. Good luck!

MISSION COST LIST

Table S1. The basic cost to explore different worlds.

Destination	Cost
The Moon	$50 million
Mercury	$200 million
Venus	$100 million
Mars and/or its moons	$100 million
Asteroids and comets in the inner Solar System	$100 million
Jupiter and/or its moons	$300 million
Saturn and/or its moons	$350 million
Uranus and/or its moons	$400 million
Neptune and/or its moons	$450 million
Pluto and/or other dwarf planets	$500 million
Kuiper Belt Objects	$500 million
Comets far from the Sun	$500 million

Table S2. Considerations associated with different types of missions.

Type of Mission	Additional Cost	Risk Factor
Flyby	(none)	1
Orbiter	$100 million	2
Lander	$200 million	5

Table S3: Considerations associated with missions of different length.

Time Spent Exploring the World (in addition to the travel time to get to the world)	Additional Cost	Risk Factor
1 year	(none)	1
2 years	$1 million	1
5 years	$5 million	2
10 years	$10 million	3

Note: for a flyby mission, the longer time includes several flybys of the target world.

Table S4: Payload cost: the cost and purpose of instruments for various types of missions.

Instrument	Explanation and Purpose	Suitable Missions	Cost
Long-distance camera	Digital camera with a telescope; takes images of the target from a distance	Flyby Orbiter Lander	$3 million
Stereo Camera	Digital camera that can take 3D images of the target	Flyby Orbiter Lander	$3 million
Panoramic Camera	Digital camera with a wide field of view; provides panoramic images of the target	Lander	$3 million
Microscopic camera	Combination of a microscope and a digital camera; provides detailed images of the target's rocks and soils	Lander	$3 million
Spectrometer 1 (using visible or infrared light)	Measures the properties of different colors and types of light; determines the composition of the target (rocks, atmosphere)	Flyby Orbiter Lander	$1 million
Spectrometer 2 (using either visible and infrared *or* visible and ultraviolet light)	Combination spectrometer that measures the properties of different colors and types of light; determines the composition of the target (rocks, atmosphere)	Flyby Orbiter Lander	$3 million

(continued on the next page)

Table S4 (continued): Payload cost: the cost and purpose of instruments for various types of missions.

Instrument	Explanation and Purpose	Suitable Missions	Cost
Spectrometer 3 (high-energy and particle radiation)	Measures the properties of magnetic fields, the space environment, and the solar wind in detail	Flyby Orbiter Lander	$2 million
Magnetometer	Measures basic properties of magnetic fields, the space environment, and the solar wind	Flyby Orbiter Lander	$0.5 million
Basic Radar	Takes radar images of the target using microwaves bounced off the surface	Flyby Orbiter	$1 million
Advanced Radar	Measures the properties of the target's atmosphere and features below the surface	Flyby Orbiter	$2.5 million
Laser Altimeter	Determines the heights of planetary features using a laser beam bounced off the surface of the target	Orbiter	$1.5 million
Seismometer	Monitors quakes on the target world (e.g., marsquakes)	Lander	$0.5 million
Meteorology Instrument Suite	Monitors weather by measuring temperature, pressure, winds, etc.	Lander	$1 million
Geologic Exploration Tool: Rock Abrasion Tool	Powerful grinder that can drill into rocks on the target's surface to provide close-up observations and analysis	Lander	$2 million
Geologic Exploration Tool: Digger Arm	Can dig below the surface to take samples for detailed analysis	Lander	$2 million
Life Experiment Suite	Laboratory experiments designed to look for signs of life (e.g., organic molecules, chemical markers of feeding or respiration)	Lander	$2 million

Answer Key

Student Worksheet 1

B) – E) Answers will vary. The main goal of the activity is to have the students understand the differences in what kind of information can be gathered with the different mission types, and appreciate the amount of planning that is required for the different missions.

F) Answers will vary. Some possibilities are included below:

Mission 1: Earth-based observations

Pros:

- The lowest cost (unless the telescope is large or space-based, but even then the cost per observation is probably lower than for a spacecraft mission traveling to the target.)
- Can easily change instruments that are mounted on the telescope.
- Can easily point the telescope to observe many interesting targets.
- Can collect large amounts of data over long periods of time.
- Can be operated easier than the other mission types.

Cons:

- Observations limited: cannot provide detailed information on small-scale features.
- Observational problems due to the Earth's atmosphere (not for space telescopes.)
- Observational problems due to light pollution from cities (not for space telescopes.)
- If only one side of the target can be seen from the Earth, only that side can be observed (for example, the Moon.)
- Can only observe the target at night (unless observing the Sun or using radio waves.)
- Cannot observe in bad weather.

Mission 2: Flyby

Pros:

- Can observe more details of the world than Earth-based observations.
- Can observe the target all the time during approach and departure.

- Can observe the target with several instruments simultaneously.
- Can observe several targets (for example, a planet and its moons; or fly by several planets), if mission is so designed.

Cons:

- Costs more than most Earth-based observations.
- Cannot repair or replace instruments.
- Observation time and area observed is limited by the amount of time that the spacecraft spends near the target.
- Spacecraft and its instruments must be controlled at least part of the time through computer programs stored onboard the spacecraft.
- Since data must be stored onboard the spacecraft, and sent to the Earth at a specified time, there are limitations to the amount of data that can be returned.
- Communications become more difficult the farther the spacecraft is from the Earth.

Mission 3: Orbiter

Pros:

- Can observe more details of a target for a longer period of time than a flyby mission.
- Can observe more of the (if not the entire) target
- Can observe global and regional changes on the target's surface and atmosphere over time.
- Can observe the target with several instruments simultaneously.

Cons:

- Costs more than a flyby mission or observations from the Earth.
- Cannot repair or replace instruments.
- Needs more propellant than a flyby mission.
- More hazardous than a flyby mission.
- Communications with the Earth may be more difficult if the spacecraft is behind the target during part of its orbit.

- May need to perform orbit correction maneuvers to remain in orbit around the target.
- Spacecraft and its instruments must be controlled at least part of the time through computer programs stored onboard the spacecraft.
- Needs more complicated computer programs than a flyby mission.

Mission 4: Lander

Pros:

- Can observe more details of a portion of the target than the other mission types.
- Can observe changes on the surface of the world or its atmosphere in more detail (but only around the landing area.)
- Can observe the area around the landing site with several instruments simultaneously.
- If the lander is movable (e.g., it includes a rover), it can provide detailed observations on several interesting surface features that are within driving distance.
- Can investigate the rocks, and the soil in detail, for example through sample analysis.
- Can perform experiments to see if there are living beings present.
- Can record seismic events (e.g., moonquakes or marsquakes.)

Cons:

- Costs more than the other mission types.
- Cannot repair or replace instruments.
- Needs more propellant than a flyby mission (but maybe not more than an orbiter mission.)
- More hazardous than the other mission types.
- Communications are more difficult because data must be sent from the lander to the Earth (often via an orbiting spacecraft.)
- Communications with the Earth may be more difficult when the lander or the orbiter that acts as a communications relay is behind the target.
- Since data must be stored onboard the spacecraft, and sent to the Earth at specific times, there are limitations to the amount of data that can be returned.

- Spacecraft and its instruments must be controlled through computer programs stored onboard the spacecraft for at least part of the time.
- Needs more complicated computer programs than the other mission types.

Student Worksheet 2

2. Mission Goals

Answers will vary. Listed below are a few examples of currently open questions about the worlds described in the *Mission Log*. The students are encouraged to come up with their own questions, and the resulting mission goals may be quite different from the questions below.

Mercury

- Is there water ice in the permanently shadowed craters near Mercury's poles?
- Need to study surface features in detail to understand the history of Mercury's surface.
- Why is Mercury's core so large?
- Need to perform a geologic analysis of rocks and soil.
- What are the properties of Mercury's magnetic field?

Venus

- Need to study the atmosphere and its changes in greater detail.
- Need to study surface features, rocks and soil in greater detail.
- Why did Venus become so different from the Earth?
- Could there be life on Venus?
- Monitor weather on the planet.

The Moon

- How does the amount of undeground water vary on different parts of the Moon?
- Need to study rocks in greater detail.
- Are there any resources on the Moon that could be used by human colonists in the future?

Mars

- Why did the water on Mars disappear from the surface? Where did it go?
- Is there any life on Mars today (such as bacteria in ice), or is there any proof of past life?
- Need to study soil and rocks in greater detail.
- Monitor the weather on the planet.

Jupiter

- How can the Great Red Spot have lasted 300 years? What drives the storm?
- Why does Jupiter have an internal energy source?
- Does Jupiter have a solid core?
- Need to understand Jupiter's internal structure better.
- Why are Jupiter's rings so much smaller and fainter than Saturn's?
- Are there more moons yet to be discovered?

Galilean Moons

- Need to understand the interaction between Io and Jupiter better.
- Do Ganymede and Callisto have undersurface oceans?
- Could there be life in the ocean under Europa's icy surface?
- Need to map the surfaces of the moons in greater detail.

Saturn

- Need to understand the phenomena in Saturn's atmosphere better.
- Why does Saturn have such magnificent rings? What is their origin?
- Need to understand the behavior of Saturn's rings better.
- Why does Saturn have an internal energy source?

- Need to understand Saturn's internal structure better.
- Are there more moons yet to be discovered?

Titan

- Why is Titan the only moon in the Solar System with a substantial atmosphere?
- The Huygens probe returned photos of only a small part of Titan's surface. What does the rest of the surface look like close-up?
- If Titan's atmosphere is so similar to Earth's early atmosphere, what can we learn about the early Earth by studying Titan?
- Could there be life on Titan even though it is so cold there?

Uranus

- Why does Uranus appear to have fewer features on its atmosphere than the other giant planets? Do more features appear as the seasons change?
- Why are Uranus's rings so much smaller and fainter than Saturn's?
- Need to understand Uranus's internal structure better.
- Why does Uranus not have an internal energy source like the other giant planets?
- What happened when the planet was "knocked over"? Exactly what caused it?
- Are there more moons yet to be discovered?

Neptune

- What drives the strong storms and fast winds on Neptune?
- Why are Neptune's rings so much smaller and fainter than Saturn's?
- Need to understand Neptune's internal structure better.
- Why does Neptune have an internal energy source?
- Are there more moons yet to be discovered?

Pluto

- What does the surface of Pluto look like?
- What is Pluto’s composition?
- How does it compare with other dwarf planets?
- What is the composition of Pluto’s atmosphere?

Asteroids

- Need to explore more asteroids to see how they compare with each other.
- Need to study the composition of different asteroids in greater detail.
- Do asteroids have resources that could be used by humans in the future?

Comets

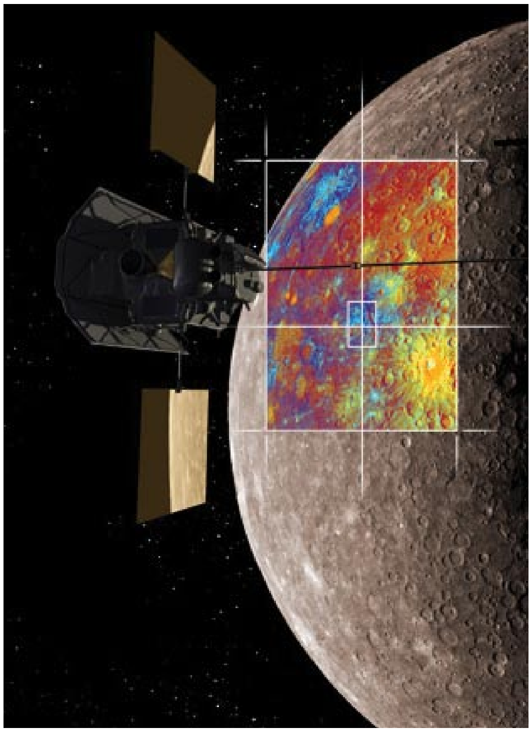
- Need to understand the structure of the comets better, especially the nucleus.
- Need to explore more comets to see how they compare with each other and what they can tell us about the formation of the Solar System.
- Do comets have resources that could be used by humans in the future?

Kuiper Belt Objects

- What do these objects look like close-up?
- Are there many Kuiper Belt Objects that could be classified as dwarf planets?
- How do these objects compare with Pluto?
- Are there many different kinds of Kuiper Belt Objects; how are they similar to or different from each other?

The answers to the rest of the Worksheet will vary. The main goal of this activity is to have the students understand that detailed planning is needed to send a spacecraft to explore another world and that there are significant costs and risks associated with these missions.

MESSENGER Mission Information Sheet



MESSENGER is an unmanned NASA spacecraft that was launched in 2004 to study the planet Mercury. After three flybys of its target planet in 2008 and 2009, the spacecraft will go into orbit around Mercury in 2011. It will not land but will make detailed observations from orbit. MESSENGER will never return to the 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, who, it was said, wore winged sandals and was somewhat of a trickster.

MESSENGER will be 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 about one Earth year, during which time it will make close-up and long-term observations, allowing us to see the whole planet in detail for the first time.

During its mission, MESSENGER will attempt to answer several questions about Mercury. 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? What is the nature and origin of Mercury's very tenuous atmosphere? Does ice really exist in the permanently shadowed craters near the planet's poles? Mercury is an important subject of study because it is the extreme of the terrestrial planets (Mercury, Venus, Earth, Mars): it is the smallest, one of the densest, it has one of the oldest surfaces and the largest daily variations in surface temperature—but is the least explored. Understanding this "end member" of the terrestrial planets holds unique clues to the questions of the formation of the Solar System, evolution of the planets, magnetic field generation, and magnetospheric physics. Exploring Mercury will help us understand how our own Earth was formed, how it has evolved, and how it interacts with the Sun.

Look But Don't Touch

Exploration with Remote Sensing

Lesson Overview

Grade Level
5–8

Duration
Three 45-minute class periods

Essential Question

What kind of tools can we use to explore unknown environments?

Lesson 3 of the Grades 5-8 Component of the *Mission Design* Education Module

Lesson Summary

Students will learn about one of the most valuable methods of investigating other worlds in the Solar System: remote sensing. In Activity 1, students study aerial photographs to identify geologic features, determine how they differ from one another, and examine the processes involved in their formation. In Activity 2, students investigate how remote observations of a planetary surface can be used to create geologic maps. By the end of the lesson, students will understand how data gathered by spacecraft can not only be used to investigate the properties of an object, but also how it was formed, how it has evolved over time, and how it is connected to other objects nearby.

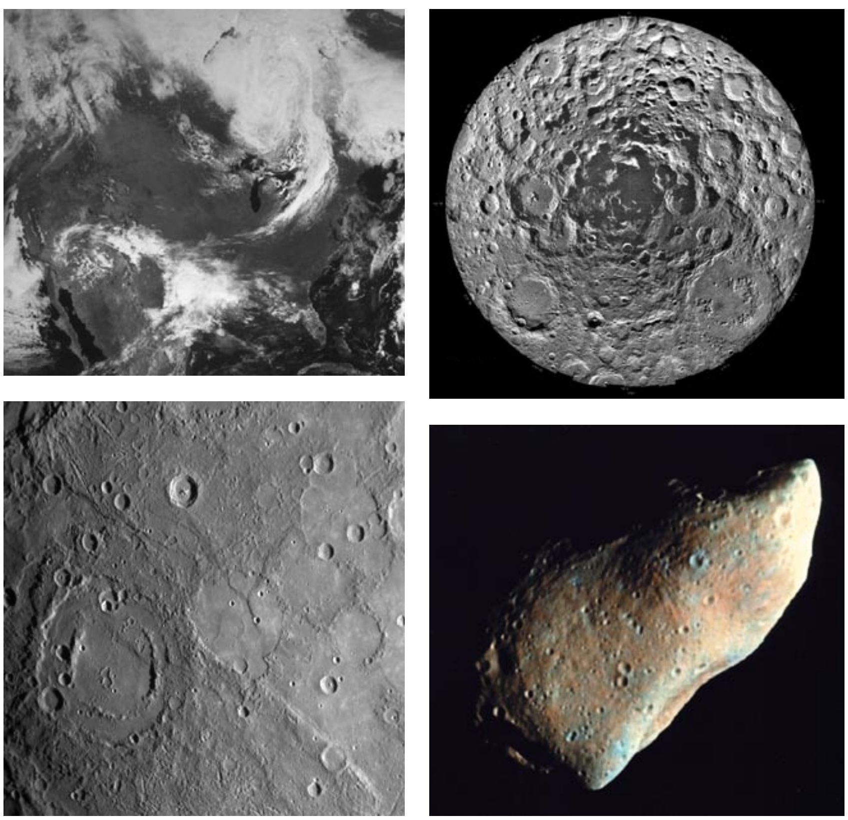


Figure 1. Remote sensing is an important tool for not only understanding the behavior of the Earth (top left: picture of North America taken by the GOES-8 satellite), but also for exploring other worlds in the Solar System such as the Moon (top right: picture of the lunar south pole area taken by the Clementine spacecraft), other planets (bottom left: an image of the surface of Mercury taken by the MESSENGER spacecraft) and small Solar System objects (bottom right: picture of the asteroid Gaspra taken by the Galileo spacecraft.)

(Picture credits: NOAA; http://www.colorado.edu/geography/gcraft/notes/remote/remote_f.html; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/clm_usgs_17.html; NASA/JHUAPL/CIW: http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/EN0108828359M.png; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/gal_p40450c.html)

This lesson was developed by the National Center for Earth and Space Science Education (http://ncesse.org).

Objectives

Students will be able to do the following:

- Describe different ways to explore objects remotely.
- Identify four major geologic processes operating on the Earth as shown in aerial photographs.
- Explain how data gathered remotely can be used to identify landforms on planetary surfaces, in this manner helping determine the geologic history of the explored area.

Concepts

- The large variety of geologic landforms on the Earth are formed by four basic geologic processes: volcanism, tectonism, erosion, and impact cratering.
- The same geologic processes can be found operating on other worlds in the Solar System, though not every world features all processes.

MESSENGER Mission Connection

The MESSENGER spacecraft is not going to land on the surface of Mercury, but will go into orbit around the planet, instead. Like many other probes exploring other worlds in the Solar System, MESSENGER will conduct its observations of its target plant via remote sensing, using the methods discussed in this lesson. The scientists will examine the data gathered by the spacecraft to form a better understanding of Mercury's properties, and how the planet has changed over time.

Standards & Benchmarks

National Science Education Standards

Standard D1: Structure of the earth system

- Land forms are the result of a combination of constructive and destructive forces. Constructive forces include crustal deformation, volcanic eruption, and deposition of sediment, while destructive forces include weathering and erosion.

Standard A2: Understandings about scientific inquiry

- Science and technology are reciprocal. Science helps drive technology, as it addresses questions that demand more sophisticated instruments and provides principles for better instrumentation and technique. Technology is essential to science, because it provides instruments and techniques that enable observations of objects and phenomena that are otherwise unobservable due to factors such as quantity, distance, location, size, and speed. Technology also provides tools for investigations, inquiry, and analysis.

AAAS Benchmarks for Science Literacy

Benchmark 4C/M2:

- Some changes in the earth's surface are abrupt (such as earthquakes and volcanic eruptions) while other changes happen very slowly (such as uplift and wearing down of mountains). The earth's surface is shaped in part by the motion of water (including ice) and wind over very long times, which acts to level mountain ranges. Rivers and glacial ice carry off soil and break down rock, eventually depositing the material as sediments or carrying it in solution to the sea.

Benchmark 4C/M8:

- There are a variety of different land forms on the earth's surface (such as coastlines, rivers, mountains, deltas, and canyons.)

Benchmark 3A/M2:

- Technology is essential to science for such purposes as access to outer space and other remote locations, sample collection and treatment, measurement, data collection and storage, computation, and communication of information.

Science Overview

During most of human history, exploration has consisted of people traveling to unknown environments and returning with tales, records, and samples of the explored area. With advancements in technology, new ways to explore have become available. New methods are especially important for space exploration, because human space travel is dangerous and expensive at present time. If our understanding of the Universe were limited to where human beings have traveled, we wouldn't know of anything beyond the Moon. But with telescopes peering into the farthest reaches of space, and with robotic spacecraft traveling to the many worlds of the Solar System, we have been able to form a good understanding of the Universe around us.

Remote Sensing

Of special importance in modern space exploration is the method of remote sensing: exploring an environment from a distance, without the need of humans or even robotic spacecraft actually going to the area that is explored. Remote sensing is the process of gathering information about an object or a phenomenon without direct physical contact by the instruments used in the investigation. Instead, devices such as cameras and telescopes are used to make observations remotely, even from space. By carefully studying the gathered data, scientists can form an understanding of the properties of the area, and even how it may have come to be the way that it is. Technically, all telescope observations of even the farthest reaches of the Universe are examples of remote sensing, but the term is most often used in the context of the exploration of the Earth as a planet and of other worlds in the Solar System, and the rest of the discussion here will concentrate on this aspect.

While remote sensing means that the investigators cannot touch or sample the explored environment directly, using this method allows them to see a larger area at one time. This makes it possible to make connections between the explored area and other nearby features, and so we can gain a better understanding of the "big picture" aspect of the environment. It is this property that makes remote sensing useful for studying the Earth as a planet. By studying aerial photographs—pictures taken from airplanes and balloons—and satellite images, it is possible to recognize surface features that might be difficult to see otherwise. By making observations of other nearby features, scientists can even form a narrative of how the different geologic features may have formed, and how their relationship may have changed over time.

Recognizing Geologic Processes Remotely

Geologic processes often result in distinctive surface features. For example, landforms such as steep, conical hills with a small summit crater indicate that they are volcanic in origin. Deep canyons, like the Grand Canyon, are the result of a river carving through rock over millions of years.

The challenge of remote sensing is recognizing the processes that created the observed features purely on the basis of the gathered data, without any actual sampling of the objects. The geologic processes shaping the surface of the Earth can be divided into four categories: volcanism, tectonism, erosion, and impact cratering. Many of them operate also on other worlds in the Solar System, though not all of them operate on every world. Please note that the discussion that follows is not intended to be a comprehensive description of each geologic process; rather, it is a brief listing of the various processes deemed important for the present purposes.

Volcanism

Volcanism is a process where a rupture on the planet's surface allows molten rock (lava), ash, and gases to escape from below the surface. The landform most commonly associated with volcanism is a conical hill or a mountain (called a volcanic cone or a volcano), which was built by accumulations of lava flows and which spews lava, ash, and gases from a crater at its summit. However, volcanism can be associated with many different kinds of surface features, such as lava domes, where viscous lava has accumulated, or lava plains, where lava has spread over a large area and formed a plateau. See Figure 2 for examples on volcanism in the Solar System.

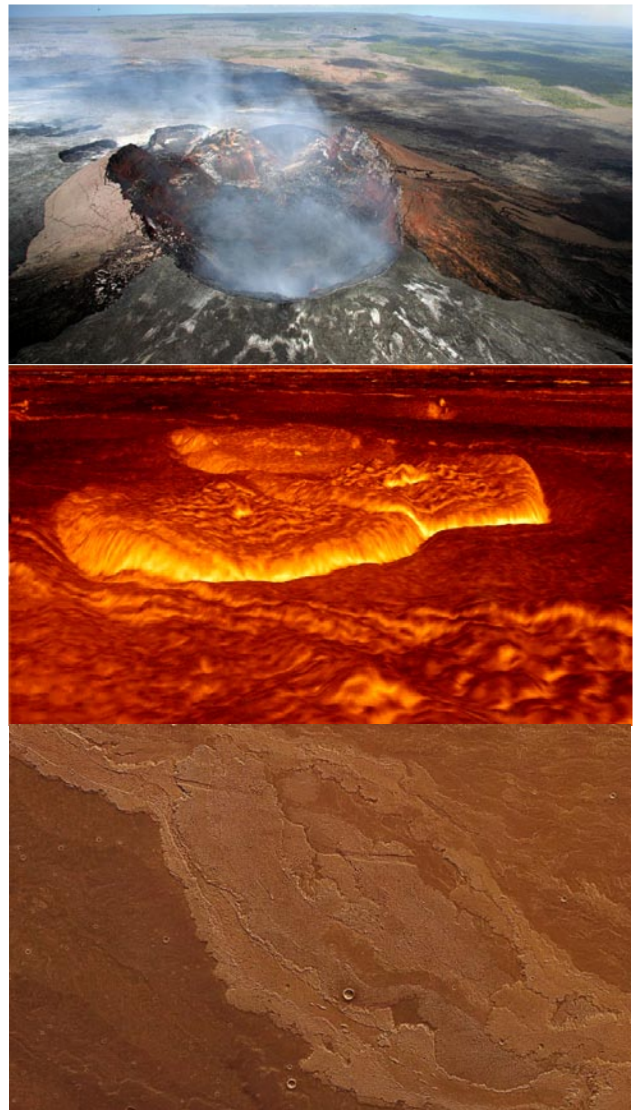


Figure 2. Examples of volcanism in the Solar System: the Pu'u 'Ō'ō crater in the Kilauea volcano in Hawaii (top); computer-generated image based on radar data of volcanic pancake domes in Alpha Regio, Venus (middle; the features in the image have been exaggerated in the vertical direction by 23x); lava flows have that have formed smooth plains in the Daedalia Planum region on Mars (bottom). (Picture credits: USGS/ Hawaiian Volcano Observatory: http://hvo.wr.usgs.gov/kilauea/update/archive/2007/Jul/IMG_5625c-CCH_L.jpg; NASA/JPL: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/mgn_p38870.html; ESA/DLR/FU Berlin, G. Neukum: http://esamultimedia.esa.int/images/marsexpress/444-20090909-6396-6-co-01-DaedaliaPlanum_H1.jpg)

There are other features called volcanoes that do not involve hot lava. For example, cryovolcanoes (ice volcanoes) involve the eruption of volatile materials such as water, ammonia, and methane from beneath the icy surfaces of the worlds in which they are located. They have been observed on Neptune's moon Triton and on Saturn's moon Enceladus. Indirect evidence of cryovolcanoes has been seen on other icy moons (such as Europa, Titan, Ganymede, and Miranda), and it is possible that they could operate on many different icy worlds in the Solar System.

Surface features associated with some kind of volcanism are common on solid Solar System bodies. While most worlds do not have signs of active volcanism at present, they have been volcanic at least at some point in their past. For example, the tallest known volcano in the Solar System is the 27-km (17-mile) high Olympus Mons on Mars, and Io, a moon of Jupiter, is currently the most volcanically active body in the Solar System.

Tectonism

Tectonism involves motions in the rocks under the surface of a planet, causing faulting, folding, or other deformation of the planet's crust. Many kinds of surface features can be created as a result of these motions. For example, mountains and valleys can be created on different sides of a fault, when one side of the fracture moves in the opposite direction (up in this example) from the other (down.) On the Earth, tectonic features are

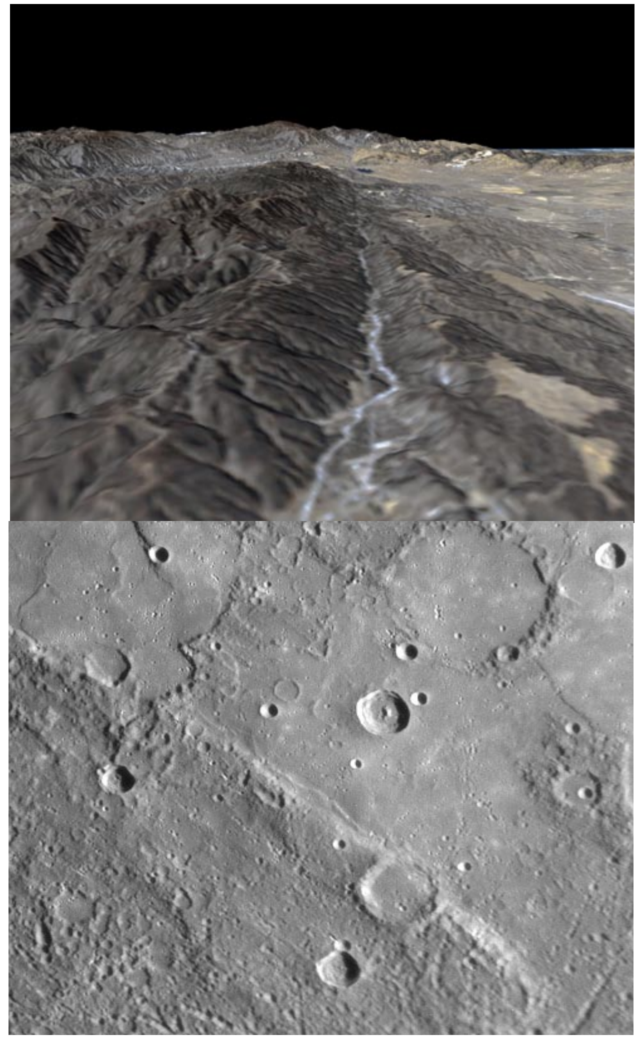


Figure 3. Examples of tectonism in the Solar System: the San Andreas Fault in California (top), depicted in a computer-generated perspective view based on spacecraft data, is the tectonic boundary between the North American plate on the right, and the Pacific plate on the left; a prominent scarp (cliff) that cuts through the side of an impact crater on Mercury is the surface expression of a major crustal fault system on the planet (bottom). (Picture credits: NASA/JPL/NIMA: http://photojournal.jpl.nasa.gov/catalog/PIA02745; NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington: http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/EN0108828359M.png)

caused mainly by the motion of tectonic plates. Our planet's lithosphere (the crust and the rigid, uppermost part of the mantle), is broken into eight major and several minor plates. When these plates move on the surface of the Earth (at a typical speed of 5-10 cm, or 2-4 inches, per year), tectonic features are created especially at the plate boundaries. As a result, the plate boundaries are the places on our planet where features such as tall mountain ranges or deep ocean trenches are located, or frequent earthquakes occur. Tectonic features also appear on other worlds in the Solar System, but there is no clear evidence for plate tectonics having occurred at any time on any other planet besides the Earth. Instead, the tectonic features on the other Earth-like worlds in the Solar System were probably created by other motions in the rocks under the surface, such as deformation associated with large impact craters or the shrinking of the world. See Figure 3 for examples of tectonism in the Solar System.

Erosion

Erosion is the degradation of a planet's surface caused by the action of water, ice, wind, gravity (or a combination of these agents.) The eroded materials are often transported to another location where they are then deposited. These processes can erode existing landforms (e.g., a cliff crumbling down due the action of wind, rain and gravity) or create new ones (e.g., a river carving a channel through rock.) The amount of erosion suffered by a surface feature can give information about its age. While not all agents of erosion exist on

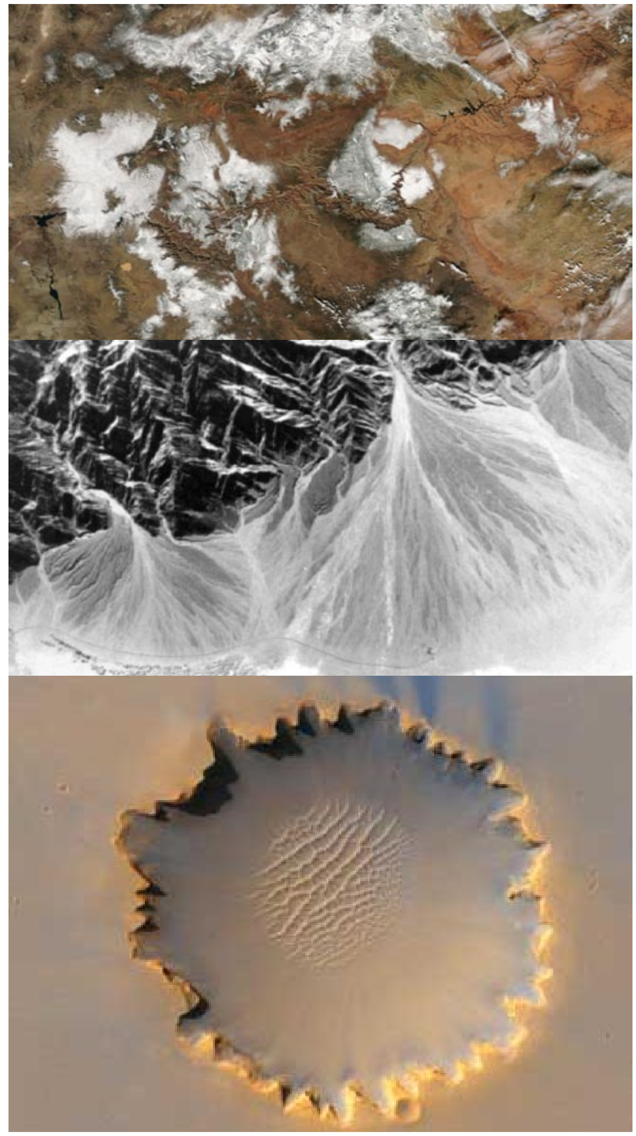


Figure 4. Examples of erosion in the Solar System: snow highlights the Grand Canyon, which has been carved onto the Colorado Plateau by the Colorado River over millennia (top); alluvial fans coming down from the Panamint mountains near Stovepipe Wells, California (center); the rims of the Victoria crater on Mars have been eroded by wind and gravity, and the crater has been partially filled by sand. (Picture credits: NASA Earth Observatory: http://earthobservatory.nasa.gov/IOTD/view.php?id=5033; UIllinois Catalog of Stereogram Aerial Photographs, #125; http://media.nasaexplores.com/lessons/01-056/images/fig25.gif; NASA/JPL/UA: http://photojournal.jpl.nasa.gov/catalog/PIA08813).

all worlds in the Solar System, all solid surfaces appear to have experienced at least some kind of erosion. For example, a world that does not have water flowing on its surface, such as the Moon, will experience different kind (and amount) of erosion than a planet with a complex water cycle such as the Earth. See Figure 4 for examples of erosion in the Solar System.

Impact Cratering

Impact craters (see Fig. 5) are geologic structures formed when a meteoroid, an asteroid, or a comet smashes into a world with a solid surface. Asteroids are large chunks of rock and metal, ranging in size from a few hundreds of meters to a few hundred kilometers. Comets are mixtures of ices (water ice, as well as carbon dioxide and ammonia ices), rock, and dust. A meteoroid is a piece of stone, metal, or ice debris from a comet or an asteroid that travels in space; they come in all sizes, even down to micrometeoroids. If one of these objects crosses the Earth's orbit, it may fall onto our planet. When the object flies through the atmosphere, it can be seen as a meteor in the sky as it burns up because of the heating by the atmosphere. If the falling object is sufficiently large, part of it may survive the flight through the atmosphere and strike the ground.

The impact causes surface material (rocks, dust, ice, and whatever else is located nearby) to be thrown away from the impact site. As a result, a (usually) circular depression on the ground—a crater—is

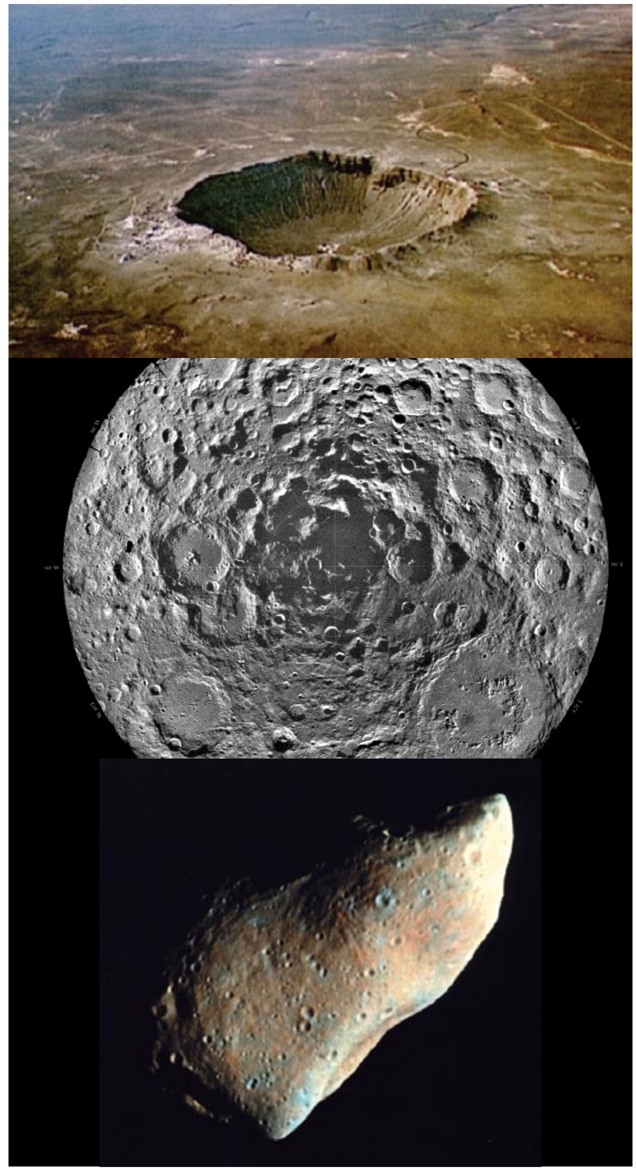


Figure 5. Examples of impact craters in the Solar System: The 1.2-km (0.7-mile) wide Meteor Crater (also called the Barringer Crater) in Arizona was created by the impact of a large meteor about 50,000 years ago (top); the lunar south pole area has numerous impact craters of all sizes (middle); even small Solar System objects such as the asteroid Gaspra have many impact craters (bottom.) (Picture credits: D.Roddy. LPI/USRA: http://www.lpi.usra.edu/publications/slidesets/craters/slide_10.html; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/clm_usgs_17.html; NASA/JPL/Brown University: http://photojournal.jpl.nasa.gov/catalog/PIA01609)

formed. Small impactors excavate a crater only slightly larger than the impactor, while a large impactor can create much more havoc on the surface. The material thrown out of the crater is called collectively the ejecta, and it can often be seen as a distinct feature around the crater.

All planets in the Solar System have been bombarded by meteoroids, asteroids, and comets during their history. The large atmospheres of the giant planets (Jupiter, Saturn, Uranus, Neptune) hide the evidence of impacts these massive worlds have experienced in the past, but there is plenty of evidence of impacts on the surfaces of the inner planets (Mercury, Venus, Earth, and Mars.) Craters can also be found on the surfaces of moons, dwarf planets, and even on asteroids and comets themselves. Large impacts were common during the early history of the Solar System, and most solid surfaces show evidence for a heavy bombardment period early in their history. On the Earth, evidence of this bombardment has been erased by the activity of the other geologic processes, but on other objects lower levels of geologic activity has left the evidence more visible. Another difference in the properties of impact craters on different worlds in the Solar System is that if a world has a substantial atmosphere, many small impactors burn up when they fly through the atmosphere, and no small craters are visible on the surface, while on objects that do not have this protective blanket, even micrometeoroids can impact the ground and create tiny craters.

Photogeologic Mapping

Recognizing the geologic processes which formed the surface features visible in aerial or satellite photographs is the first step in preparing geologic maps. A geologic map is similar to a regular map in that it shows what the features on the surface look like, but it includes additional information by portraying graphically the different types of rocks and structural features (such as folds and faults.) The map also features an interpretation of the basic geologic data, such as information on the processes thought to have created the features, and how the landforms are related to each other,. In this manner, a geologic map allows scientists to record their interpretations of the observations in a form that can be easily understood by others. This also makes it possible to compare observations from different locations to help us better understand the geologic history of the world.

The basic component of a geologic map is the rock unit, which is defined as a three-dimensional body of rock that has uniform composition and was formed during some specific interval of time. For example, a unit could be a lava plain or an impact crater on top of the lava plain. The map also identifies structural features, such as faults or riverbeds visible on the surface. In essence, photogeologic mapping starts with examining a surface depicted in a photograph, and dividing the surface features into different units and structural features according to their type, composition, origin, and estimated age. Different units can be identified based on their:

- ▼ ***morphology***: the size, shape, texture, and other distinctive properties of the landforms;
- ▼ ***albedo characteristics***: the range of brightness from light (high albedo) to dark (low albedo);
- ▼ ***color***: not only visible color differences, but also different types of light not visible to the human eye, such as infrared, ultraviolet, etc.;
- ▼ ***the degree of erosion:*** how much the surface has eroded or how well it has been preserved;

and other properties visible in the photograph. Once the rock units and the structural features have been identified, it must be determined how they were formed; that is, which geologic processes were responsible for creating them.

The next step is to determine how the units and structural features are related; most importantly, determine the order in which the units and features were formed. This process is called determining the stratigraphic relation of the features, since it is an example of stratigraphy, the branch of geology that studies the origin, composition, and distribution of rock layers. The principles used for this purpose include:

- ▼ ***the principle of superposition***: for units and structural features that are laid (even partially) on top of each other, the oldest (the one that formed first) is on the bottom, and the youngest (the one that formed most recently) on top.
- ▼ ***the law of cross-cutting relations***: for a unit or a structural feature to be modified (via volcanism, impacts, tectonic faulting, erosion, etc.) it must first exist. For example, if there is a fault going through a rock unit, the underlying unit is older than the tectonic event that created the fault.
- ▼ ***embayment***: if a bay-like feature is formed when one unit "floods into" (embays) another, the flooding unit must be younger than the one being flooded.
- ▼ ***impact crater distribution***: in general, older units have more craters, more large craters, and more degraded (eroded) craters than younger units.

Once the stratigraphic relation has been determined, the units are listed on the side of the map in order from the oldest (at the bottom of the list) to the youngest (at the top) as the stratigraphic column. Finally, using the information gathered during the previous steps, it is possible to write a geologic history of the area. The geologic history describes the events that created the observed surface in a chronological order from the oldest to the youngest. The history includes an interpretation of the observed units: the geologic processes that formed them and events that have modified them after their formation.

Figure 6 shows an example geologic map. The relative ages of the units marked on the map were determined in the following manner: The

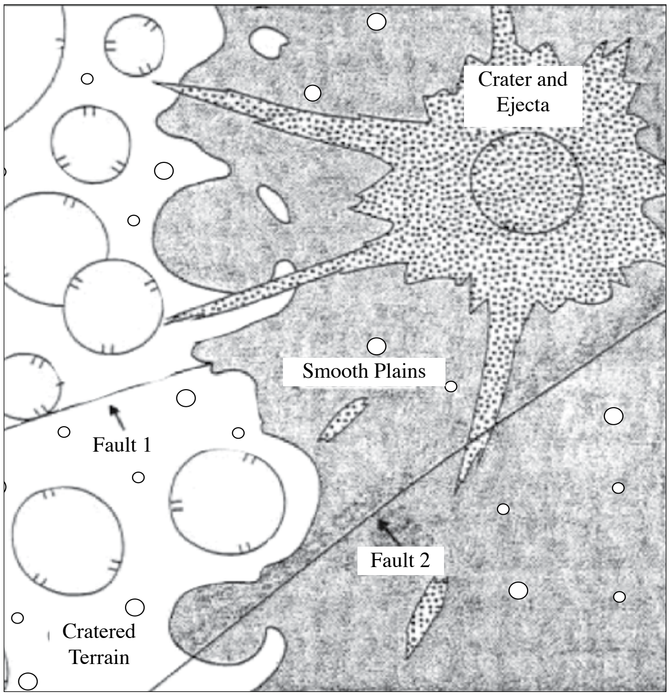


Figure 6. An example of a geologic map of a planetary surface. In addition to the graphical portrayal of the different rock units and structural features (top left), the complete map includes a description of the units, including observations of their characteristics and interpretation of their origin (top right), and a stratigraphic column describing the age relations between the units and structural events identified in the map (right.) (Picture credit: NASA: http://solarsystem.nasa.gov/educ/docs/Intro_Photogeologic_Map.pdf)

Unit Descriptions

Unit Name	Observation	Interpretation
Crater and Ejecta	Rough, blocky surface, high albedo, crater in the middle	Crater and ejecta formed by impact
Smooth Plains	Smooth plains, few craters, low albedo, rounded edges	Volcanic flow
Cratered Terrain	Rugged, heavily cratered plains, high albedo	Old unit, possibly of volcanic origin, has had extensive cratering

Stratigraphic Column

	Geologic Unit	Structural Event
Youngest		Fault 2
	Crater and Ejecta	
	Smooth Plains	
		Fault 1
Oldest	Cratered Terrain	

cratered terrain has more (and larger) craters than the smooth plains unit, indicating that the cratered terrain unit is older. Fault 1 cuts across the cratered terrain, but does not continue across the smooth plains. This suggests that the faulting occurred after the formation of the cratered terrain and prior to the formation of the smooth plains; the smooth plains unit is younger than the cratered terrain and fault 1. The large impact crater mapped as its own unit, as well as the crater's ejecta unit (material ejected from the crater into the surrounding area), occurs on top of the smooth plains unit, and thus is younger. Finally, fault 2 cuts across all the units, including the crater's ejecta; it is therefore the youngest feature in the region. The geologic history that could be derived from this map would be the following:

The cratered terrain is the oldest surface in the picture. It was cratered by impact activity over time, and then faulted by tectonic activity. After the tectonic activity, a smooth plains unit was created by volcanic activity. Cratering continued after the formation of the smooth plains, as seen by the craters visible on top of the smooth plains and the large, young crater (and its ejecta), which is mapped as its own unit. Finally, there has been additional tectonic activity after the impact that created the young crater, as indicated by the fault which goes through the crater's ejecta.

Anyone who reviews the map show in Figure 6 can now construct the same geologic history of the region without having to go through all the steps of constructing the map themselves.

Remote Sensing as One Tool in a Planetary Explorer's Toolbox

There are many other methods to explore worlds in the Solar System besides remote sensing that are important, from robotic spacecraft landing on planets and performing chemical analyses of soil samples to humans traveling to explore other worlds (such as the Moon) themselves. These other methods are used to answer questions that remote sensing cannot answer conclusively, for example to determine the absolute ages of lunar rocks or to look for water ice under the surface of Mars. However, because remote sensing can be done from a spacecraft flying by or orbiting a world, without the need to actually land on the explored world, it can be used in many different missions, and so it is the most commonly used tool in a planetary explorer's toolbox today.

Lesson Plan

Warm-Up & Pre-Assessment

1. Lead a discussion of what maps are and how they are useful. You can begin by asking, "If you wanted to explore a region of the country with which you are unfamiliar, what would you need?" As the students begin to offer suggestions, lead them to the concept of a map. Show the students a map of your home state and ask them to define what a map is and why it is useful. Use leading questions and statements: "What kinds of information are contained in a map?" and "How does the size of the map compare to the real size of the state?" Ask the students if a six-story-high map would be useful. Discuss how most maps are a size that makes it comfortable for the user to hold them. With the help of a map, we can explore things that may be much larger, further away, or more treacherous than we would normally be able to explore. A map can be a powerful tool of exploration.

2. Lead a discussion about the different kinds of information that can be shown on a map. Show the students the state map again and ask what types of information it tells them (examples include roads, city names, etc.) Ask the students what types of things this map does *not* tell them (examples include elevation, many natural features, climate, etc). Show the students other types of maps such as a topographic map and ask the same questions.

3. Discuss how the different types of maps are made. How was the information in the maps gathered? How difficult would it be for each of the different types of maps to be made? How did people make maps in ancient times? When was the first map of the whole Earth made? Explain that we had a good understanding of the layout of the continents on the surface of the Earth even before the space age, just by people exploring the surface of our planet by foot, land vehicles and airplanes. Point out that satellite technology has helped us make different kinds of maps of the Earth very accurately. If you have access to old maps, you can show the students how our understanding of the surface of the Earth changed from ancient times to medieval times to the present day. How do the students think we could make maps of other planets?

Materials

Per Class:

- Map of your home state
- A variety of other types of maps: topographic, weather, etc.

Activity 1: Geologic Landforms Seen in Aerial Photographs

The students will study a series of aerial photographs of different terrains on Earth. In answering questions about the areas depicted in the pictures, they will become acquainted with landforms created by four major geologic processes: erosion, impact cratering, tectonism, and volcanism.

Materials

Per Class:

- Overhead projector
- *Geologic Landforms on Other Worlds Transparency*

Per Group of 2 or 3:

- Metric ruler
- Student Worksheet 1

Preparation

1. Make an overhead transparency of the *Geologic Landforms on Other Worlds Transparency* located in the back of the lesson, and make copies of Student Worksheet 1 for the class.
2. You may want to review the four major geologic processes featured in this activity with the students before starting the activity. While there is a brief description of these processes in Student Worksheet 1, the activity assumes that the students are somewhat familiar with these concepts. Additional information can be found on the Web sites listed in the *Internet Resources & References* section.
3. Divide students into groups of two or three.

Procedures

1. Lead a brief discussion about how geologic processes often result in distinctive landforms or surface features. For example, steep, conic hills with small summit craters are distinctive as volcanic in origin. Ask the students how they think these features are studied best: from the ground or from the air? *(Desired answer: Both. Observations from the ground provide information on small-scale details, while observations from the air provide a large-scale overview that may be difficult to develop from the ground.)*
2. Ask the students to explain the following terms: erosion, impact cratering, tectonism, and volcanism. Ask what kind of landforms each of these processes would create and whether the features would look the same from the ground and from the air. If the students were flying in an airplane and saw one of these landforms, how could they tell what process created it? *(Desired answer: Each process creates landforms with distinctive features. By*

comparing the features of the observed landform with what is known from other sources, one can deduce the probable origin of the landform.)

3. Hand out copies of Student Worksheet 1, and make sure the students understand the vocabulary used in the activity. Have the students work in their groups and follow the procedures in Student Worksheet 1. The Worksheet is not intended to test the students' understanding of the different geologic processes, but to promote thinking about what the different landforms look like from the air, and how the processes responsible for creating the surface features can be identified from aerial or satellite photographs. The section "Synthesis" of Student Worksheet 1 brings the students' knowledge together to help them understand how scientists can identify surface features seen from the air or from space, as well as determine the order in which surface features located near each other were formed.

Teaching Tips

- Student Worksheet 1 can be given as a homework assignment if you do not have enough class time. However, it is important to have the *Discussion & Reflection* as a class because the conversation will lead into Activity 2.
- Remind the students that they will be graded on their ability to use evidence to support their answers in all cases.

Discussion & Reflection

1. Go through the photographs shown in Student Worksheet 1 with the class and ask each group what they learned from the pictures. What is the advantage of studying a photograph taken from the air rather than studying it from the ground at the actual location of the feature? *(Desired answer: you can see a larger area from the air, and so you can get the "big picture" of the feature. This can make it easier to determine how the features were formed and how they relate to other features nearby.)* Can the students think of any disadvantages from studying the landforms just from the air? *(Desired answer: you are limited by the resolution of the photograph and are not able to see small details, which may be important for deciphering the whole story of the landform.)* Which method do the students think is more useful in determining how a particular landform was formed? *(Desired answer: it depends on the situation, but an aerial photograph is a great starting point, since it allows us to understand the "big picture" of the area in*

general, including determining the probable origin of the feature. Additional studies on the ground concentrating on the small-scale features can be performed later to refine our understanding.)

2. Ask the students what they learned about the features other than just how to identify them (*Desired answers include: how landforms often relate to other features nearby; how similar features can look slightly different depending on their age or interaction with other nearby features.*)

3. Place the *Geologic Landforms on Other Worlds Transparency* on the overhead projector so the entire class can see it. Have the students identify the same four geologic processes that they were investigating on the Earth operating on other worlds in the Solar System. Would the students be able to determine what created these features based on what they have learned of landforms on the Earth? Explain to the students that this is how scientists studying other planets can determine what they see in similar pictures: they use the information that generations of explorers have gathered about the many planet-shaping processes on the Earth to understand the same processes occurring on other worlds in the Solar System. The students will do the same in Activity 2.

Activity 2: Photogeologic Mapping

The students will explore photographs of another world in the Solar System to see how they can recognize the same geologic processes that operate on the Earth. They create a geologic map of a planetary surface by identifying mapping units and structural features in a photograph and placing the units in a time sequence.

Materials

Per Class:

- Overhead projector

Per Group of 2 or 3:

- Blank overhead transparency
- Set of transparency markers
- Roll of tape
- Student Worksheet 2

Preparation

1. Gather together the materials needed for this activity.
2. Divide students into groups of two or three.

Procedures

1. Ask the students how they might identify surface features on other planets just by looking at them from above, as they did in Activity 1 for features on the Earth. (*Desired answers include: the size, shape and texture of the feature (morphology), the color, the brightness of the feature and how it changes from light to dark (albedo characteristics), and the amount of erosion the surface has suffered.*) This is a good time to introduce the vocabulary which is used in the activity but with which the students might not be familiar.
2. Lead a discussion about geologic mapping of other worlds in the Solar System. For example, remind the students of the maps discussed during the Warm-Up, and ask students why making a map of another planet might be useful. (*Desired answers may include: if we ever wanted to send spacecraft to land on these worlds, having a map would be a good idea so that we know where the spacecraft should land; mapping another world could help us learn more about its structure and history; comparing maps of different planets could help us understand how the planets are similar and how they are different.*)
3. Ask the students what might be a good first step in making a map. (*Desired answer: identify features that can be seen in a photograph of the area to be mapped.*) Discuss how identifying the basic features (rock units and structural features) in a photograph is the first step in making a geologic map. Explain that a

unit is a surface feature (three-dimensional body of rock) that has a uniform composition and was formed during some specified interval of time. For example, a unit could be a lava plain or an impact crater on top of the lava plain, while structural features could include faults or riverbeds.

4. Ask the students: after identifying the mapping units, what would a scientist want to know about them (based on what the students learned in activity 1)? (*Desired answer: which geologic process formed them.*)

5. Ask the students what might be the next task in preparing a geologic map? Take a few suggestions before discussing that scientists want to understand how the mapping units relate to each other. Explain that the relationships between the ages of the units and the structural features in a geologic map is called the *stratigraphic relation*. Ask the students what kind of information could be used to determine how the ages of the different units correspond with each other. Take a few suggestions before introducing the four stratigraphic relationships discussed in the activity: a) the principle of superposition, b) the law of cross-cutting relations, c) embayment, and d) impact craters. You can use the following examples to illustrate the four different principles:

   a) Ask the students to imagine their bedroom with dirty clothes on the floor. Imagine that every day, the students pile their dirty clothes on top of the ones from the day before. If their parents came in to do the laundry, how would they know which clothes have been in the pile the longest? (*Desired answer: the clothes at the bottom of the pile would have been there the longest.*) Similarly, the principle of superposition states that when mapping units are placed on top of each other, the oldest (those that were formed first) are at the bottom and the youngest (those that were formed most recently) on the top.

   b) Ask the students to imagine a crack in the sidewalk. Ask students: which happened first, the construction of the sidewalk, or the creation of the crack? (*Desired answer: the sidewalk had to exist before it got cracked.*) Similarly, the law of cross-cutting relations states that for a mapping unit to be modified (by impacts, tectonic faults, erosion, etc.), it must first exist as a unit. That is, if there is a fault going through a unit, the underlying unit is older than the tectonic event that created the fault.

   c) Ask the students if they have ever looked at downspouts after a spring rain when tree pollen, seeds and other debris have washed down from the roof. Does the water and the debris carried with it coming out of the spout tend to form a specific shape? (*Desired answer: it usually forms a fan-like shape.*) What would happen if the water and the debris flowed into a layer of sand on the ground? (*Desired answer: the water and debris would push sand away, creating the fan-shaped feature in the sand layer.*) This is an example of embayment. In a bay-like feature, the unit "flooding into" (embaying) must be younger than the unit being flooded; in our example, this means that the event of water and debris flowing onto the sand is younger (more recent) than whatever event caused the sand to be in front of the waterspout.

d) Ask the students to imagine two sidewalks: one that is old and another that has just been paved. How could they tell the difference? (*Desired answer: the older sidewalk would be more weathered than the newer one.*) Ask the students to imagine that the sidewalks are near a mining site, and, as rocks are hauled away for processing, a lot of them fall down on the sidewalks and create holes on the surface. How could the holes help tell which sidewalk is older? (*Desired answer: the older sidewalk would have more holes; maybe there could be holes on top of each other; maybe some of the older holes would have been smoothed out over the years from the rain, people walking on them, etc.*) Similarly, on planetary surfaces, impact crater frequency can be used to determine the relative ages of different surfaces. In general, older units show more craters, larger craters, and more eroded (degraded) craters than younger units.

6. Discuss different ways that one could graphically represent situations where one item is older than another. What if there is more than one item involved? For example: if there are five children in a family, how could you graphically portray the order of the children from the oldest to the youngest? Discuss how, in a geologic map, once the age relations of the surface features have been determined, the units and structural features are listed in order from the oldest (at the bottom) to the youngest (at the top) in what is called the stratigraphic column.

7. Hand out Student Worksheet 2. Make sure the students read the introduction before starting to work on the rest of the Worksheet to reinforce the basic concepts discussed as a class.

Teaching Tip

- Remind the students that they will be graded on the ability to use evidence to support their answers in all cases.

Teaching Tip

- After the teams have completed Student Worksheet 2, their maps can be overlaid for comparison with one another. There will be some variation in the maps based on the characteristics different teams chose to delineate each unit. Have the students discuss the reasoning behind their unit selections.

Discussion & Reflection

1. Discuss with the students how the basic process they went through in the activity is how much of science is done: exploring unknown environments such as planetary surfaces with the help of what is known from previous explorations in other contexts, such as exploring geologic processes operating on the Earth.

2. Ask the students why it is important to figure out what happened first, second, or third in the explored area. Discuss how the primary objective in preparing a photogeologic map is to derive a geologic history of the region. The geologic history synthesizes the events that formed the surface seen in the photograph—including interpretation of the processes in the formation of rock units and events that have modified the units—and is presented in chronological order from the oldest to the youngest. Combining maps and geologic histories from different regions helps us form an understanding of the global geologic history of the world, which in turn may help reveal the history of the part of the Solar System where the world is located.

Extension

- Have the students investigate the process of cratering and the way crater comparison can be used to establish relative ages of surfaces on different planetary bodies by completing the lesson *Impact Craters: A Look at the Past* (http://journeythroughtheuniverse.org/downloads/Content/Voyage_G58_L10.pdf) from the *Voyage: A Journey through Our Solar System* Education Module.

Curriculum Connections

- *Geography*: In this lesson, the students identify features on other worlds by recognizing what we know about the Earth. Have the students investigate how geographers use the techniques discussed in this lesson to prepare different kinds of maps.
- *Math*: In this lesson, the students use trigonometry to calculate the slopes of volcanoes, although it is done without going into details. If you want the students to have more practice connecting math and science, you can give them elevations of various mountains and have them calculate their slopes. You can then discuss what scientists can learn by looking at the slopes of volcanoes and mountains; for example, they can characterize different types of volcanoes.

Closing Discussion

1. Ask the students to identify other ways in which a spacecraft can study a planet, and what the benefits are for each of those ways. For example, a spacecraft could land on a planet and sample the soil, it could measure the magnetic field around the planet, etc. Discuss the benefits and drawbacks of remote sensing techniques versus more direct exploration methods. You can point put, for example, that by taking aerial photographs, scientists can get a big picture of an entire area, but they cannot sample the soil and determine its composition in detail, while exploring other worlds in the Solar System by landing on them and exploring just the areas around the landing site would not give us a global view of the world. By combining the different approaches one gains a deeper understanding than by exploring via one method alone.
2. Discuss with the students how the same geologic processes have created many of the features on Earth-like worlds. By examining similar features on different worlds, we can understand their relative ages, compositions, amount of activity at present time, etc. Having several different worlds with which to compare data gives us a better understanding of how the different processes act under slightly different circumstances.
3. Discuss with the students how all current explorations of unknown worlds build on the body of knowledge of not only the world being explored, but also of other similar worlds. For example, knowing what geologic processes are likely to operate on a given world

makes it easier to recognize and classify other features (e.g., one does not expect to find features created by rivers on worlds that do not have flowing liquids on their surface.) No investigation is made in isolation, and it is necessary to understand the previous work on similar topics to draw solid conclusions of the properties of the world under study.

4. Discuss with the students the limits that the current technology places on our desire to explore other worlds in the Solar System. For example, while we might want to send hundreds of human explorers to roam the surface of Mars to create a detailed map of the planet, it is not possible at present time. Instead, we can develop technological tools and methods to learn as much as we can from whatever vantage point is available. Remote sensing is a great solution to this problem, since it allows for a global view of other worlds without any human being having to physically travel to each explored location.

Assessment

4 points

- ▼ Student used evidence to support his or her answers in the "Synthesis" section of Student Worksheet 1.
- ▼ Student used evidence to support all other answers in Student Worksheet 1.
- ▼ Student used evidence to support his or her answers in the "Geologic of Planet Mercury" section in Student Worksheet 2.
- ▼ Student used evidence to support all other answers in Student Worksheet 2.

3 points

- ▼ Student met three of the four above criteria.

2 points

- ▼ Student met two of the four above criteria.

1 point

- ▼ Student met one of the four above criteria.

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/publications/bsl/online/bolintro.htm

National Science Education Standards

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

Google Earth

http://earth.google.com/

Lunar and Planetary Institute's "About Shaping the Planets" Web site (more information on volcanism, tectonism, erosion, and impact cratering)

http://www.lpi.usra.edu/education/explore/shaping_the_planets/background

NASA's Planetary Photojournal

http://photojournal.jpl.nasa.gov/

USDA's Aerial Photography Field Office

http://www.apfo.usda.gov/

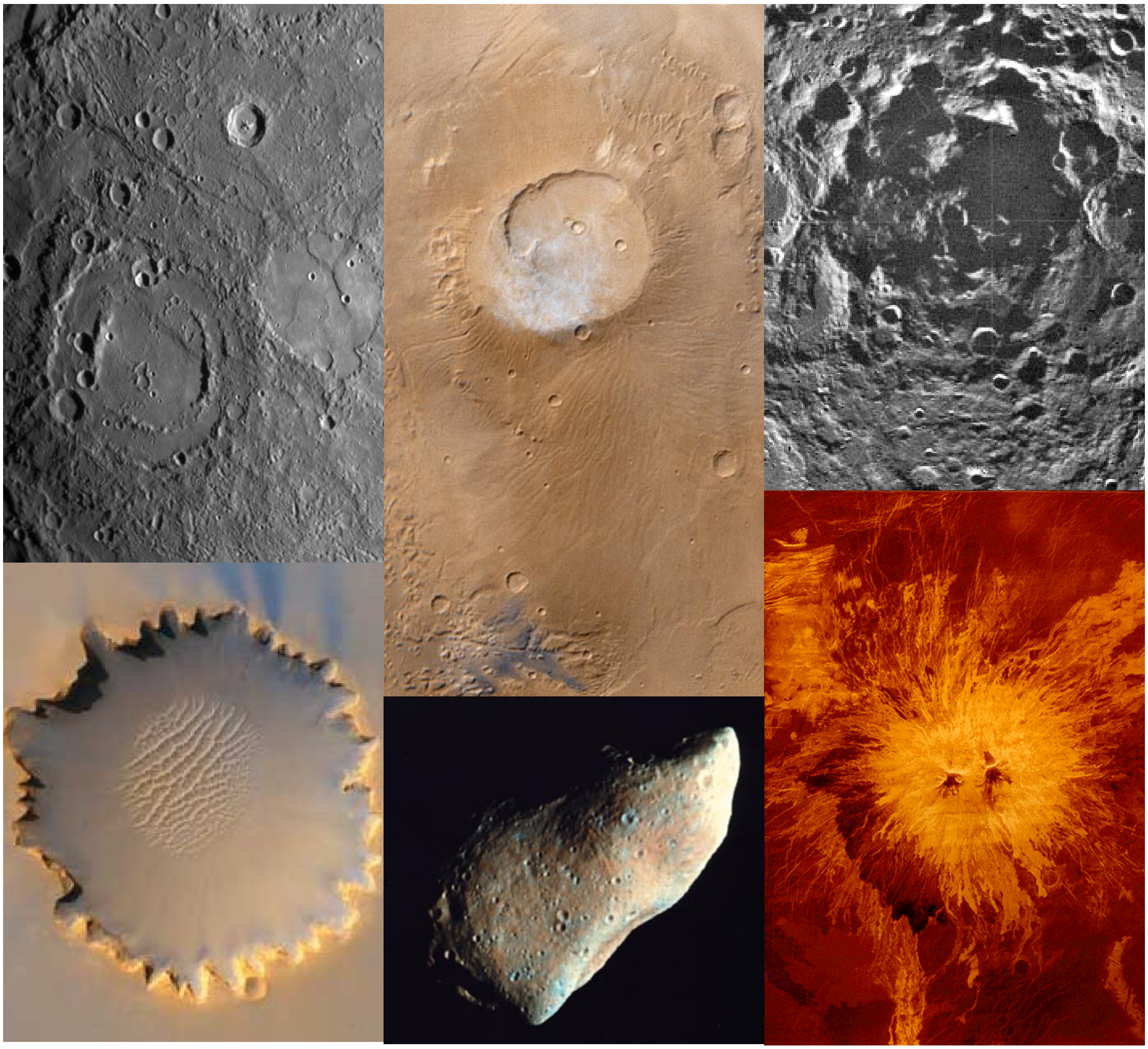
U.S. Geological Survey Aerial Photographs and Satellite Images

http://erg.usgs.gov/isb/pubs/booklets/aerial/aerial.html

Acknowledgements

Activity 1 has been adapted from "Geologic Landforms Seen on Aerial Photos" (http://solarsystem.nasa.gov/educ/docs/Geologic_Landforms_Aerial.pdf), and Activity 2 from "Introduction to Photogeologic Mapping (http://solarsystem.nasa.gov/educ/docs/Intro_Photogeologic_Map.pdf) from *NASA's Activities in Planetary Geology for the Physical and Earth Sciences*.

Geologic Landforms on Other Worlds Transparency



Shown above: top left: the surface of Mercury with impact craters and tectonic features; top middle: Apollinaris Patera volcano on Mars; top right: heavily cratered south polar region of the Moon; bottom left: eroded Victoria impact crater on Mars; bottom middle: the cratered surface of the asteroid Gaspra; bottom right: the Sapas Mons volcano on Venus.

(Picture credits: NASA/JHUAPL/CIW: http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/EN0108828359M.png; NASA: http://antwrp.gsfc.nasa.gov/apod/ap990513.html; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/clm_usgs_17.html; NASA/JPL/UA: http://photojournal.jpl.nasa.gov/catalog/PIA08813; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/gal_p40450c.html; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/mgn_p38360.html)

Geologic Landforms in Aerial Photographs

Materials
▼ Metric ruler
▼ Piece of paper (letter-size or smaller)

Your team: ______________________________

____

____

Date: ______________________________

Introduction

The geologic processes shaping the surface of the Earth can be divided into four categories:

- ***Volcanism*** is a process where a rupture on the Earth's surface allows molten rock (lava), ash, and gases to escape from the hot interior. The landform most commonly associated with volcanism is a conical hill or a mountain (called a volcanic cone or volcano), which is built by the accumulation of lava flows and which spews lava, ash, and gases from a circular crater at its summit. Old lava flows hardened to solid rock can often be seen coming down the sides of a volcano.

- ***Tectonism*** involves motions in the rocks under the Earth's surface, causing fractures, faulting, folding, or other deformation of the crust. Many kinds of surface features can be created as a result of these motions, for example mountains and valleys can form on the different sides of a fault, when one side of the fracture moves in the opposite direction from the other. On the Earth, tectonic features are caused mainly by the motion of the tectonic plates.

- ***Erosion*** is the degradation of the Earth's surface caused by the action of water, ice, wind, and gravity, with the eroded materials often transported to another location where they are deposited. These processes can either erode existing landforms (e.g., a cliff crumbling down due the action of wind, rain and gravity) or create new ones (e.g., a river carving a channel through rock.) The amount of erosion suffered by a surface feature can give information about its age.

- ***Impact craters*** are formed when pieces of rock and/or ice arriving from space (in the form of a meteoroid, an asteroid, or a comet) strike the Earth. The impact causes surface material (rocks, dust, ice, and whatever else is located nearby) to be thrown away from the impact site. As a result, a (usually) circular depression on the ground—a crater—is formed. Material thrown away from the impact site is sometimes visible around the crater and is called the crater's ejecta.

The geologic processes result in distinctive landforms, which can be recognized by their size, shape, texture, and other distinctive features. By studying aerial photographs you will learn to identify different geologic landforms and the processes involved in their formation.

Volcanism

1. Examine the aerial photograph of the Mount Capulin volcano in New Mexico (Figure S1.) The volcano is the dark area in the upper left of the picture. The small circular feature at its center is the volcanic crater, a depression in the ground from which molten rock (lava), ash, and gases escaped from under the surface. A white spiraling line leads from the crater to the base of the volcano. A lava flow (labeled A) is visible in the lower part of the picture.

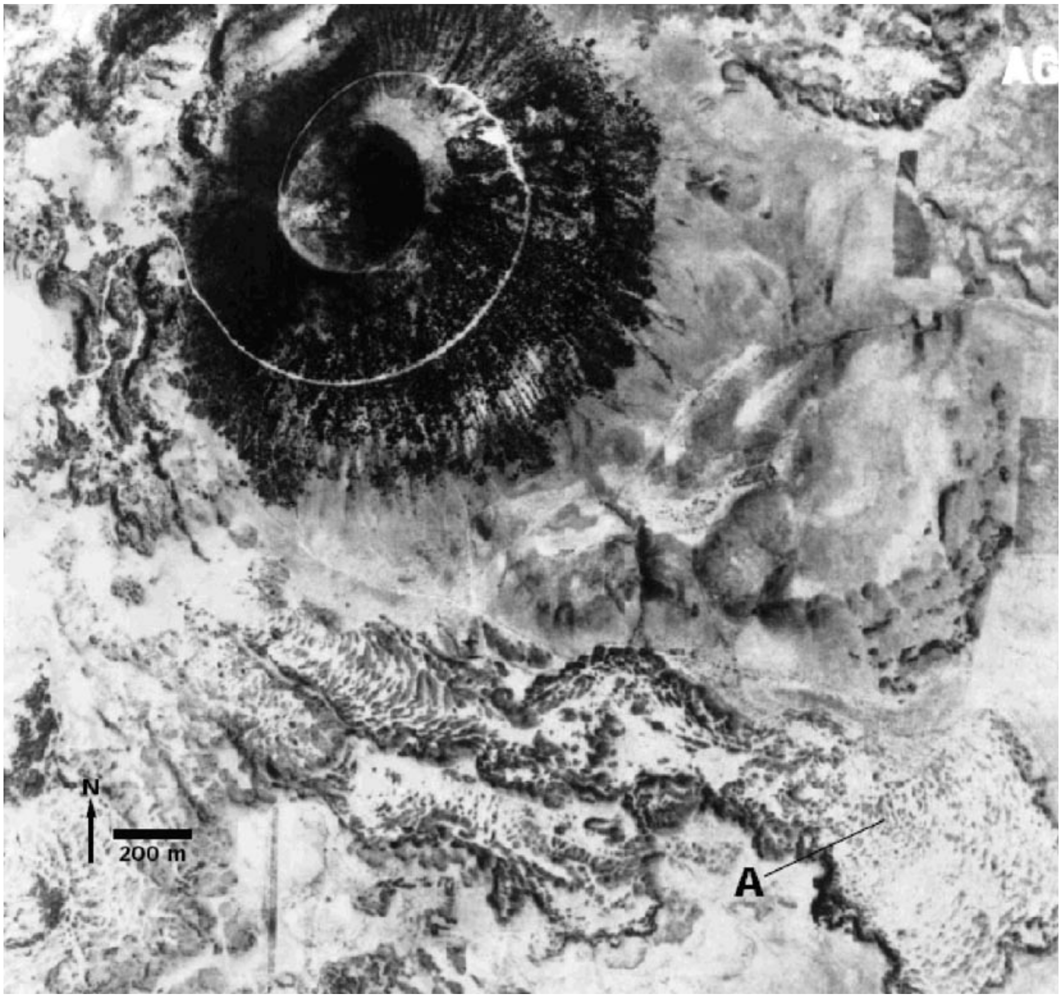


Figure S1. Aerial photograph of the Mount Capulin volcano in New Mexico. North is to the top of the picture. The small figure to the left shows a view of the volcano seen closer to the ground. (Picture credits: University of Illinois Catalog of Stereogram Aerial Photographs #105; U.S. Geological Survey: http://libraryphoto.cr.usgs.gov/htmllib/btch126/btch126j/btch126z/btch126/tde00005.jpg.)

a. Describe the general shape of the volcano and the crater at the top.

____

____

____

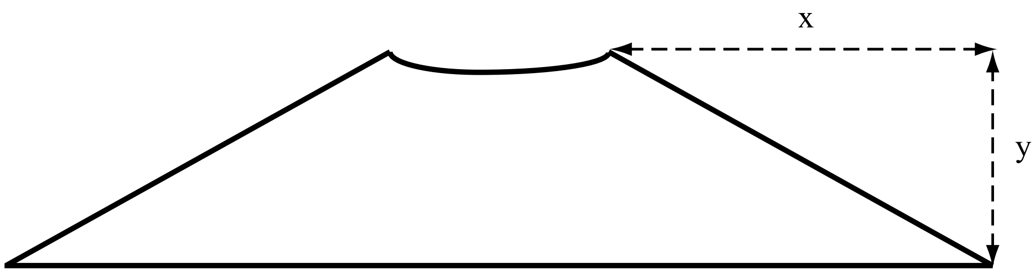
b. What is the winding, spiraling white line that goes from the base of the volcano to the crater rim?

____

____

____

2. Based on the known elevation of Mt. Capulin (334 m) and the information provided by the aerial photograph, it is possible to calculate the slope of the volcano's sides. This simple sketch of Mt. Capulin will help:



a. Using your ruler and the scale bar in Figure S1, determine the distance x, measured from the base of the volcano (which is at the edge of the dark area, the bottom of the hill) to the edge of the crater at the top. Place your ruler so that the "0" mark is at the easternmost edge of the crater and the ruler points due east, and then measure the distance to the base of the volcano.

Scale: 200 m in reality = ____________________ cm in the photograph

x = ____________________ cm in the photograph

= ____________________ m in reality

b. The height of the volcano, y, is 334 m. If the slope of a line is determined by dividing the height, y, by the distance, x, calculate the slope of the volcano's sides:

Slope $= \frac{y}{x} =$ ____________________

3. Examine the lava flow labeled A in Figure S1.

a. Describe the surface of the lava flow. (For example, does it appear rugged or smooth?)

____

____

b. Trace the flow back to its point of origin. Where is the probable source of the flow?

____

____

4. Study the aerial photograph of the Mt. Tavurvur volcano in Papua New Guinea (Figure S2.)

a. How is the volcano similar to Mt. Capulin?

____

____

Figure S2. Aerial photograph of the Mt. Tavurvur volcano on the eastern Pacific island of New Britain, Papua New Guinea. North is to the upper left corner. The small picture to the left shows a view of the volcano as seen from the ground. (Picture credits: Univ. Of Illinois Catalog of Stereogram Aerial Photographs, #102; U.S. Geological Survey: http://volcanoes.usgs.gov/Imgs/Jpg/Rabaul/30410142-032_large.jpg)

b. How is it different (for example, are there any differences in their shapes or sizes)?

____

____

5. Mt. Tavurvur has erupted many times during its existence. How does the shape of the crater at its summit support this statement?

____

____

____

6. Estimate the slope of Mt. Tavurvur's sides the same way as you did for Mt. Capulin.

a. First, draw and label a sketch similar to the one in Step 2:

b. The height of Mt. Tavurvur is 225 m. Measure the distance x from the edge of the volcano at the ocean to the rim of the summit crater and calculate the slope of the volcano.

Scale: 200 m in reality = ______________________ cm in the photograph

x = ______________________ cm in the photograph

= ______________________ m in reality

Slope = $\frac{y}{x}$ = ____________________

MESSENGER

c. Compare the two slopes. Which slope is higher; that is, which mountain is steeper? What does this mean? For example, which would be harder to climb and why?

7. List at least three factors that might affect the slope of a volcano.

Tectonism

Tectonic faults can be identified on aerial photographs as straight or gently curving features, often creating clear divisions between different landforms. Examine Figure S3 (next page), which shows in image of the San Andreas fault in California. A fairly straight valley extends from the bottom toward the top of the photograph. Over time, the ground on the left side of the fault is moving away from the viewer (toward the top of the picture), with respect to the ground on the right.

8. In what way has the fault affected the mountains visible in the photograph?

9. Tear a piece of paper in half. Place the two halves on a desk side by side. Draw a line from one piece across the tear to the other side. Making sure that the edges of the pieces remain in contact, slide the paper on the left away from you and the paper on the right toward you. This motion illustrates what

occurs along the San Andreas fault and how it affects the features along it. This type of fault is called a *strike-slip fault*.

a. What would have happened if the line on the paper was actually a road crossing the fault?

____

____

____

b. Are there any features like this visible in Figure S3?

____

____

____

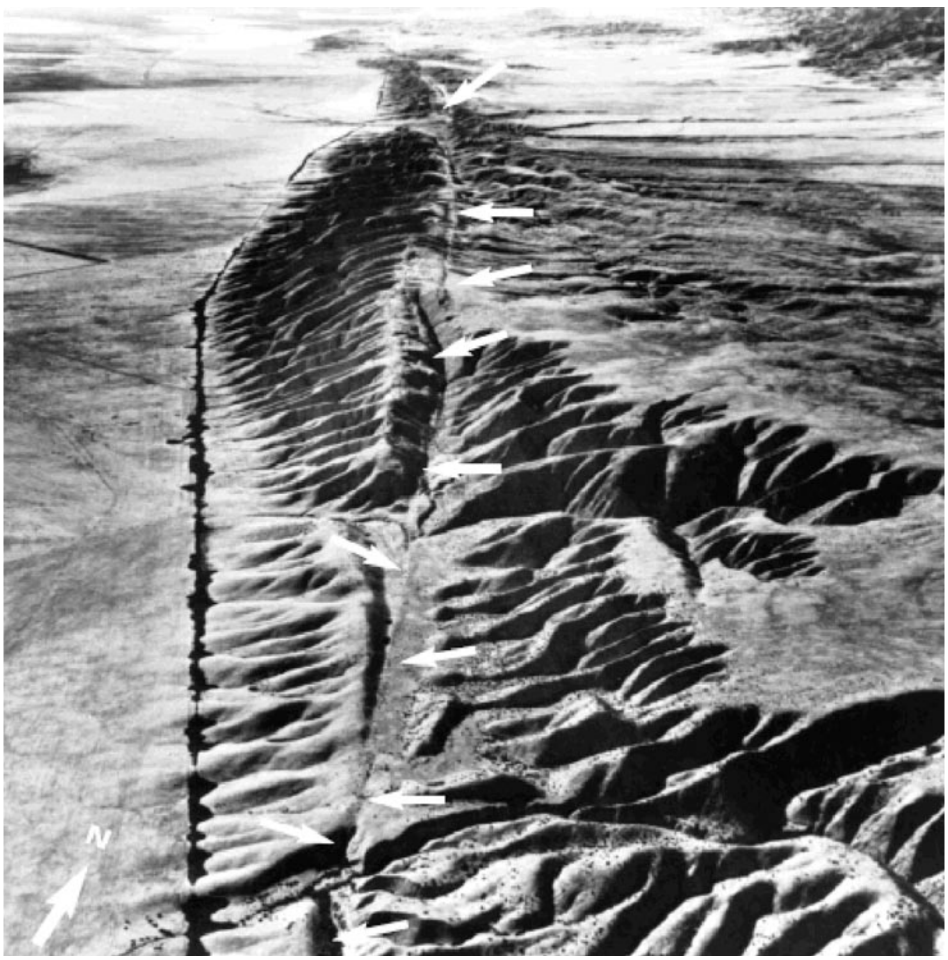


Figure S3. Aerial photograph of a part of the San Andreas fault north of Los Angeles. The white arrows in the picture point to the fault; the straight dark line to the left of the fault is vegetation. The foreground area is about 3.5 km (2.2 miles) across. (Picture credit: photograph by Robert E. Wallace, U.S. Geological Survey).

10. One landform distinctive to tectonism is called a *graben* (for an example, see Figure S4). A graben is a valley bounded on both sides by *normal faults*, which occur in a region that is being stretched. In this case, the central block is moving downward with respect to the sides. Note the difference with the strike-slip fault, where the movement took place horizontally along the fault. Investigate the diagram of a graben below Figure S4. Blocks A, B, and C are separated by normal faults. The direction in which the blocks want to move along the faults are marked by the arrows. For block B to have enough space to move down, what has to occur to blocks A and C?

____

____

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Figure S4. Aerial photograph of "The Grabens," Canyonlands National Park, Utah. These graben fault blocks are caused by the movement of underlying salt layers. (Picture credit: National Park Service, Canyonlands National Park)

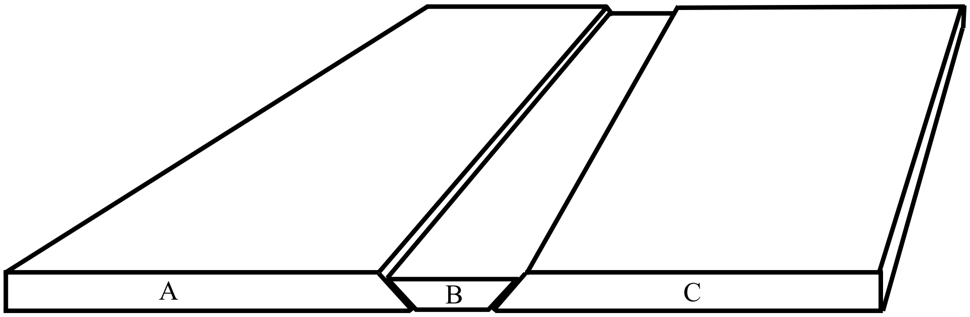

Diagram of a graben

Erosion

11. Figure S5 is an aerial photograph of alluvial fans at Stovepipe Wells, Death Valley, California. These features result from the build-up of alluvium (gravel, sand, and clay) that accumulates at the base of mountains. The term "fan" is used to describe the general shape of the feature.

a. By looking at the picture, what is the source of the alluvium that makes up the fans?

____

____

b. Which agents of erosion (wind, water, gravity) might have generated the alluvium? Support your answer with evidence from the picture.

____

____

Figure S5. Aerial photograph of alluvial fans near Stovepipe Wells, Death Valley, California. Panamint mountains lie to the top of the picture. North is to the bottom left. The small picture on the left shows a view of the mountains from the ground. (Picture credits: University Of Illinois Catalog of Stereogram Aerial Photographs, #125; U.S. Geological Survey: http://mojave.usgs.gov/rvde/images/DantesView-1328Small.jpg)

c. Which agents might have deposited it? Support your answer with evidence from the picture.

____

____

d. Once deposited, how might the alluvium be further eroded?

____

____

12. Figure S6 is an aerial photograph of the Delta River in central Alaska. The river carries melt water and silt from glaciers to the Pacific Ocean. Because rivers of this type are usually shallow and carry lots of sediments, they often deposit the sediments along the stream to form sandbars. The sandbars can redirect the river flow, giving the river the branching, braided appearance visible in Figure S6.

a. How is the Delta River an agent of erosion that works to change the surface?

____

____

Figure S6. The Delta River, a braided stream in central Alaska. North is to the top. The small picture below shows a view of the river from the ground. (Picture credits: U.S. Navy photograph courtesy of T. L. Péwé, Arizona State University; Bureau of Land Management: http://www.blm.gov/pgdata/etc/medialib/blm/ak/gdo/delta_river_plan.Par.73704.Image.360.480.1.gif)

b. Do the individual river channels appear to be permanent, or do they change position with time? Explain your answer.

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Impact Craters

13. Examine the photographs of the Meteor Crater in Arizona (Figure S7.)

a. Describe the crater's general shape.

____

____

____

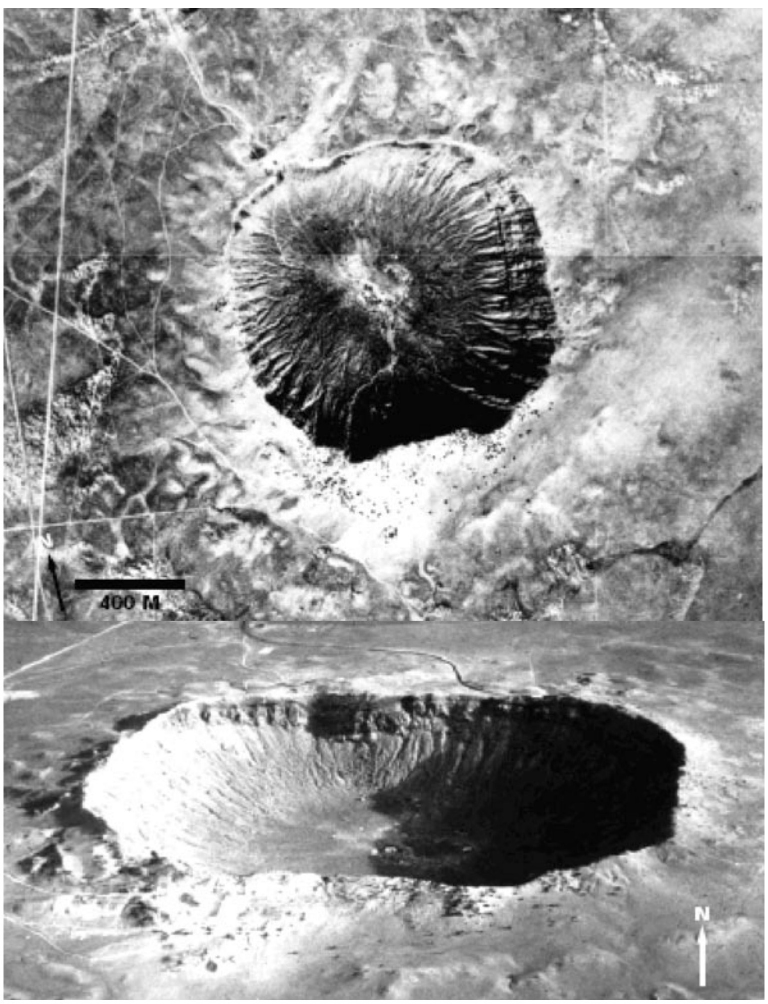


Figure S7. Aerial photographs of the Meteor Crater in Arizona taken from straight up (top left) and from an angle (bottom left.) One of the best preserved impact craters in the world, the Meteor Crater was formed about 50,000 years ago. The small figure below shows a view of the crater from the surface. (Picture credits: University of Illinois Catalog of Stereogram Aerial Photographs, #5; b, Photograph courtesy U.S. Geological Survey; Photograph courtesy of Tony Rowell via NASA Astronomy Picture of the Day: http://apod.nasa.gov/apod/ap090811.html)

b. Even though the Meteor Crater is one of the best preserved craters in the world, it has suffered some erosion. List some evidence for erosion visible in the photographs.

____

____

____

14. The asteroid that created the crater is estimated to have been about 50 m across. Measure the diameter of the Meteor Crater using your ruler and the scale marked in the picture. How do the sizes of the crater and the asteroid compare?

Scale: 400 m in reality = ____________________ cm in the photograph

Diameter of the Meteor Crater = ____________________ cm in the photograph

= ____________________ m in reality

Crater size versus meteor size: = $\frac{\text{crater size}}{\text{asteroid size}}$ = ____________________

15a. How is the shape of the Meteor Crater different from the volcanic landforms in Figures S1 and S2?

____

____

____

____

b. How is it similar to the volcanic landforms?

____

____

____

____

16. Examine the aerial photograph of the Roter Kamm impact crater in Namibia (Figure S8.)

a. Describe the shape of the crater.

b. Does the Roter Kamm crater look fresh or eroded compared to the Meteor Crater? Explain.

17a. How is the Roter Kamm crater different from the volcanic landforms in Figures S1 and S2?

b. How is it similar to the volcanic landforms?

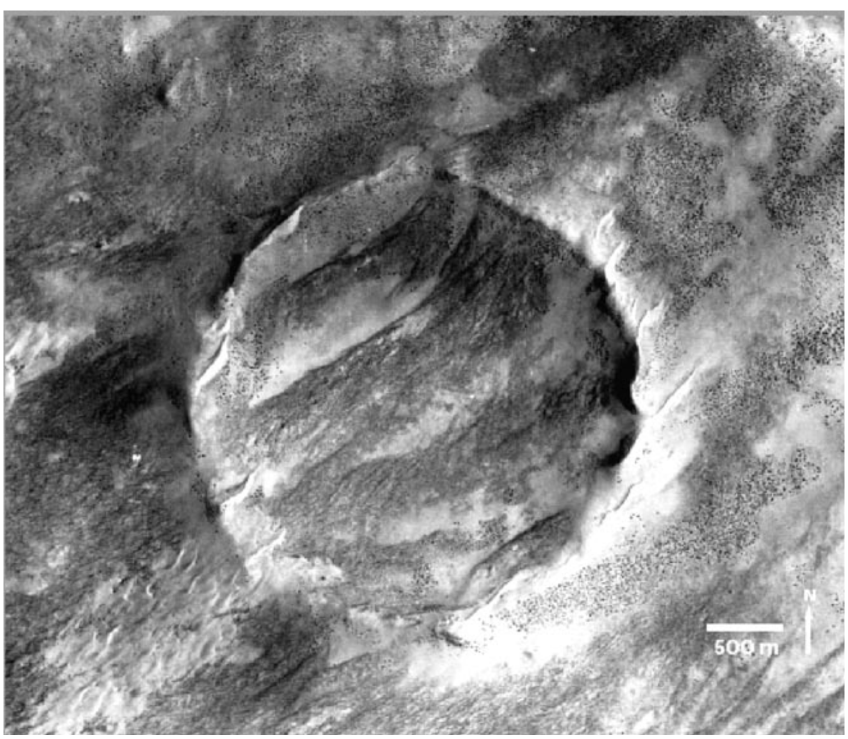


Figure S8. The Roter Kamm crater in Namibia. This impact crater is 2.5 km (1.6 miles) across and formed about 3.7 million years ago. (Picture credit: photograph courtesy Robert Deitz; from Meteoritics, vol. 2, pp. 311-314, 1965.)

Synthesis

18. Geologic processes produce landforms that have different morphology. Straight-line (or slightly curving) features tend to be formed by tectonics. More curving features (such as river valleys) are typically formed by erosion. Volcanism forms lava flows in irregular shapes and patches and often builds cone-shaped volcanoes with a small crater at the summit. Impact craters are roughly circular depressions in the ground caused by meteoroid, asteroid, and comet impacts.

Figure S9 shows a view of northern Arizona. There are landforms in the picture that were shaped by three of the four principal geologic processes discussed in this lesson. For each labeled landform (A-G), identify its type and the process that formed it. Write down evidence to support your claims.

A: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

B: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

C: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

D: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

E: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

F: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

G: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

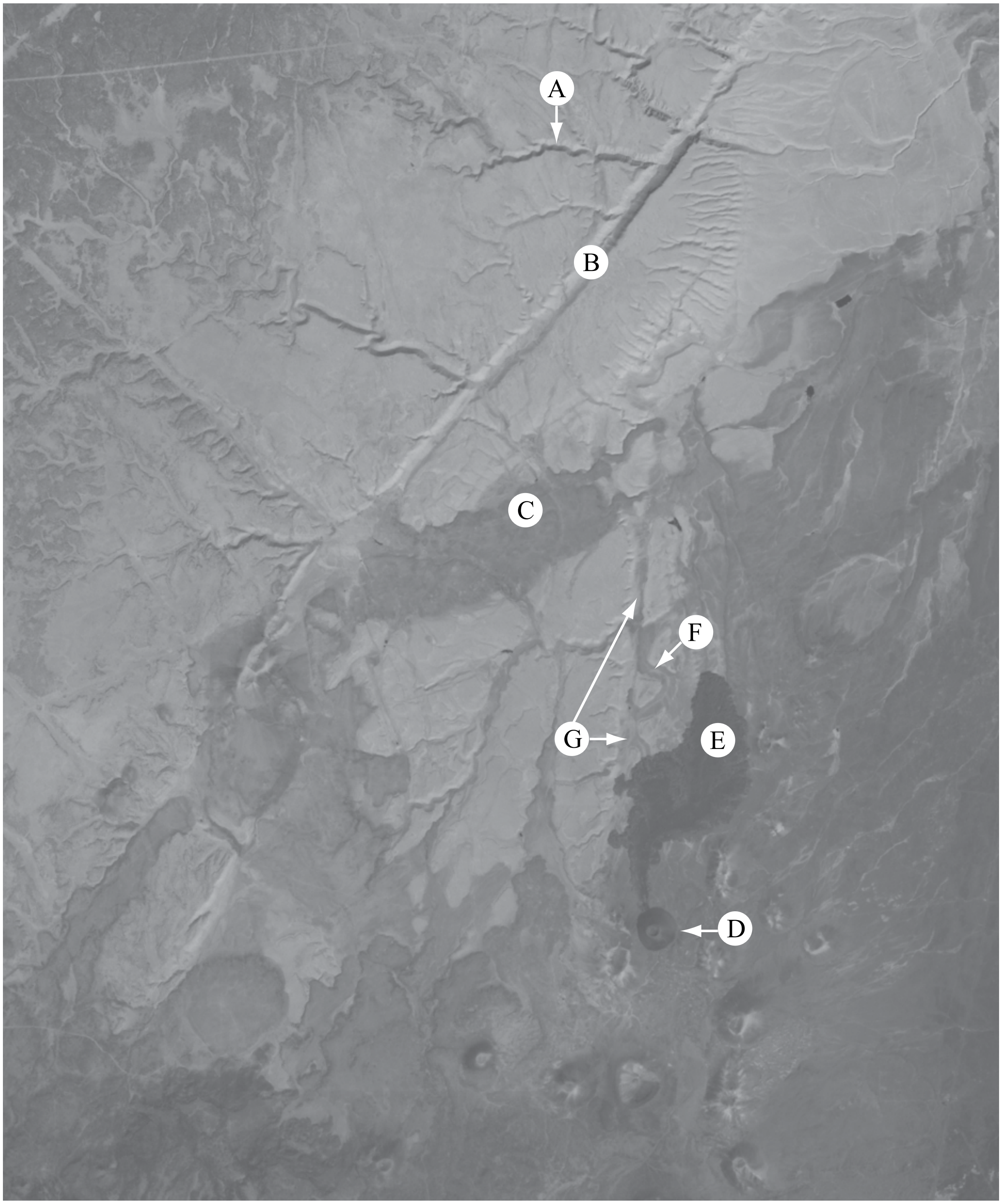


Figure S9. Image of northern Arizona taken by Landsat satellites. Geologically interesting features are marked with the letters A-G. North is to the top of the picture. (Picture credit: NASA/Landsat/U.S. Geological Survey: http://edcsns17.cr.usgs.gov/EarthExplorer)

19. Identify a place in the photograph where a pre-existing graben has affected the behavior of a volcanic flow that took place later. [Hint: look at the behavior of the dark grey feature.]

a. Sketch in the box below what you see in this area:

b. Describe in words what you think happened at this location.

____

____

____

20. Determine the sequence of events that affected the region shown in Figure S9. Mark in the list below the order in which the events occurred, from the first (1) to the most recent (5):

______ river and stream valleys formed

______ dark (black) volcanic materials were deposited

______ medium gray volcanic flows were deposited

______ light gray plains were formed

______ tectonism produced grabens

Explain why you chose this order:

____

____

____

____

21. Large impacting objects such as asteroids have fallen rarely to the Earth in the last few million years, but billions of years ago large impacts were common. It is reasonable to assume that throughout the geologic history of the Earth, as many impacts have occurred on our planet as on the Moon. Why, then, do we see so few craters on the Earth today, while so many remain visible on the Moon?

Photogeologic Mapping

Materials
- ▼ Blank overhead transparency
- ▼ Set of transparency markers
- ▼ Roll of tape

Your team: ______________________________

____

____

____

Date: ______________________________

Introduction

Recognizing geologic processes that formed landforms visible in photographs taken of the surface of another world in the Solar System is the first step in preparing a geologic map of the world. A geologic map is similar to a regular map in the sense that it shows what the features on the surface look like, but it also includes additional information by portraying graphically the different types of rocks and structural features found on the surface. The map also includes interpretation of the basic data, such as information on the processes that created the features, and how the landforms are related to each other. In this manner, a geologic map makes it possible for scientists to record their interpretations of the observations in a form that can be easily understood by other scientists. This makes it possible to compare observations made at different locations to help us understand the geologic history of the world.

The basic component of a geologic map is the *rock unit*, which is defined as a three-dimensional body of rock that has uniform composition and was formed during some specific interval of time. For example, a unit could be a lava plain or an impact crater on top of the lava plain. The map also identifies structural features, such as faults or riverbeds visible on the surface. In essence, photogeologic mapping starts with examining a surface depicted in a photograph, and dividing the surface features into different units and structural features according to their type, composition, origin, and estimated age. Different units can be identified based on their:
- ▼ ***morphology***: the size, shape, texture and other distinctive properties of the landforms;
- ▼ ***albedo characteristics***: the range of brightness from light (high albedo) to dark (low albedo);
- ▼ ***color***: not only visible color differences, but also different types of light not visible to the human eye, such as infrared, ultraviolet, etc.;
- ▼ ***the degree of erosion***: how much the feature has eroded or how well it has been preserved;

and other properties visible in the photograph.

Once the rock units and the structural features have been identified, it must be determined how they were formed; that is, what geologic processes were responsible for creating them (volcanism, tectonism, erosion, impacts.) The next step is to determine how the units and structural features are related to each other; most importantly, determine the order in which the units and features were formed. This is also called determining the stratigraphic relation of the features, since it is an example of stratigraphy, a branch of geology that studies the origin, composition, and distribution of rock layers. The methods used for this step include:

▼ ***the principle of superposition***: for units and structural features that are (even partially) on top of each other, the oldest (the one that formed first) is on the bottom, and the youngest (the one that formed most recently) on top.

▼ ***the law of cross-cutting relations***: for a unit or a structural feature to be modified (via volcanism, impacts, tectonic faulting, erosion, etc.) it must first exist. For example, if there is a fault going through a rock unit, the underlying unit is older than the tectonic event that created the fault.

▼ ***embayment***: if a bay-like feature is formed when one unit "floods into" (embays) another, the flooding unit must be younger than the one being flooded.

▼ ***impact crater distribution***: in general, older units have more craters on them, and the craters are larger and more degraded (eroded) than younger units.

Once the stratigraphic relation has been determined, the units are listed on the side of the map in order from the oldest (at the bottom of the list) to the youngest (at the top) as the stratigraphic column. Finally, using the information gathered during the previous steps, you can write a geologic history of the region. The geologic history describes the events that formed the surface seen in the photograph in a chronological order from the oldest to the youngest.

Figure S10 (on the next page) shows an example of a geologic map. The relative ages of the units marked on the map were determined in the following manner: The cratered terrain has more (and larger) craters than the smooth plains unit, indicating that the cratered terrain unit is older. In addition, fault 1 cuts across the cratered terrain, but does not continue to the smooth plains. This suggests that the faulting occurred after the formation of the cratered terrain and prior to the formation of the smooth plains, indicating that the smooth plains unit is younger than the cratered terrain and fault 1. The large impact crater and its ejecta unit (material ejected from the crater into the surrounding area) are mapped as a separate unit, and since it is on top of the smooth plains unit, the crater and ejecta unit is younger. Finally, fault 2 cuts across all the units, including the crater's ejecta, and is therefore the youngest event

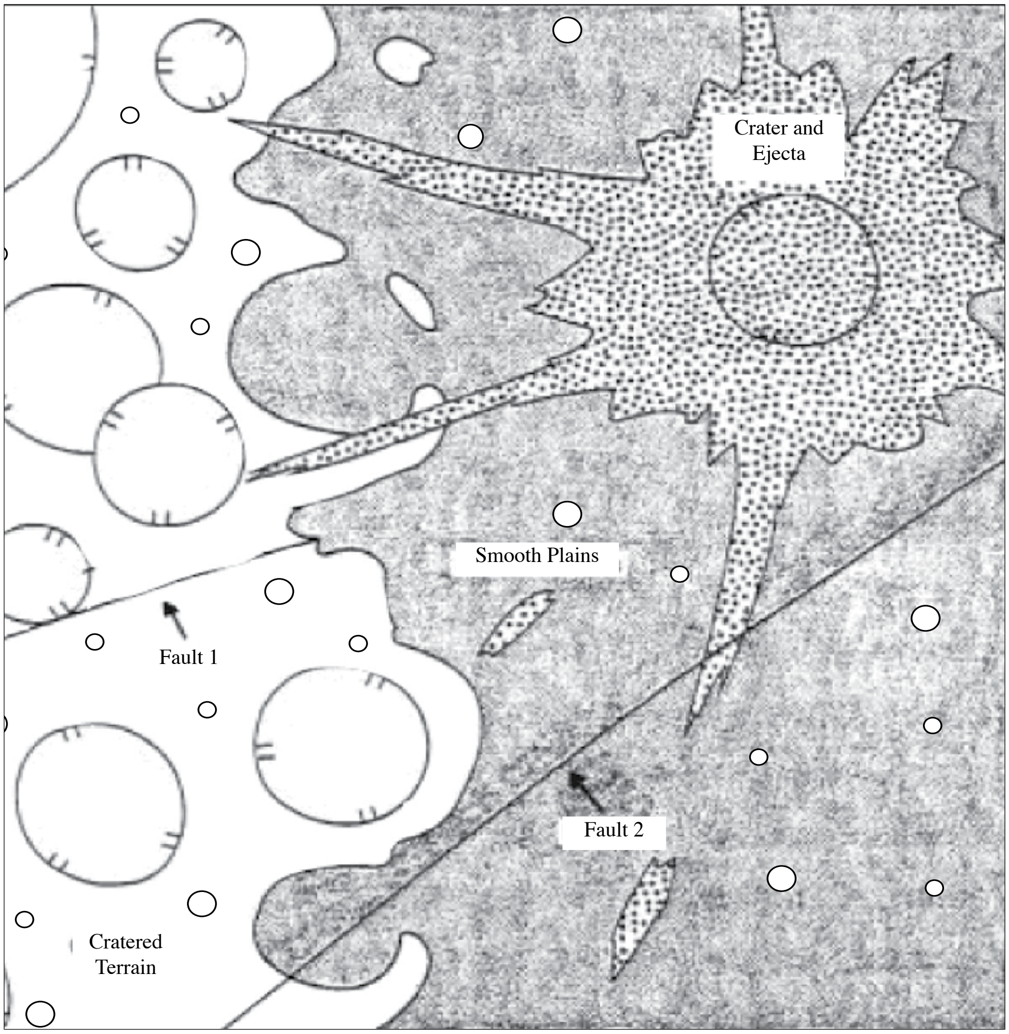


Figure S10. An example of a geologic map of a planetary surface. In addition to the graphical portrayal of the different rock units and structural features (left), the complete map includes a description of the rock units, including observations of their characteristics and an interpretation of their origin (bottom left), and a stratigraphic column describing the age relations between the rock units and structural events identified in the map (bottom right.) (Picture credit: NASA: http://solarsystem.nasa.gov/educ/docs/Intro_Photogeologic_Map.pdf)

Unit Descriptions

Unit Name	Observation	Interpretation
Crater and Ejecta	Rough, blocky surface, high albedo, crater in the middle	Crater and ejecta formed by impact
Smooth Plains	Smooth plains, few craters, low albedo, rounded edges	Volcanic flow
Cratered Terrain	Rugged, heavily cratered plains, high albedo	Old unit, possibly of volcanic origin, has had extensive cratering

Stratigraphic Column

Youngest ↑ Oldest

Geologic Unit	Structural Event
	Fault 2
Crater and Ejecta	
Smooth Plains	
	Fault 1
Cratered Terrain	

in the region. The geologic history that could be derived from this map is the following:

The cratered terrain is the oldest surface in the area. It was cratered by impact activity over time, and then faulted by tectonic activity. After the tectonic activity, a plains unit was created, probably by volcanic activity. Cratering continued after the formation of the smooth plains, as shown by the small craters on top of the smooth plains and the large, young crater (and its ejecta), which is mapped as its own unit. There has been additional tectonic activity after the impact which created the young crater, as indicated by the fault which goes through the crater's ejecta.

Anyone who reviews the map shown in Figure S10 can construct the same geologic history of the region without having to go through all the steps of constructing the map themselves.

Geology of the Planet Mercury

1. Examine Figure S11, a photograph of the surface of Mercury taken by a spacecraft. The area shown in the picture is a great illustration of the complex geologic history of the planet. Let's examine the features visible in the image in greater detail.

a. What types of main terrain can you detect? [Hint: think about the main types of terrain in the sample geologic map, S10] .

b. Which terrain do you think is the oldest? Which is the youngest? Explain your answer.

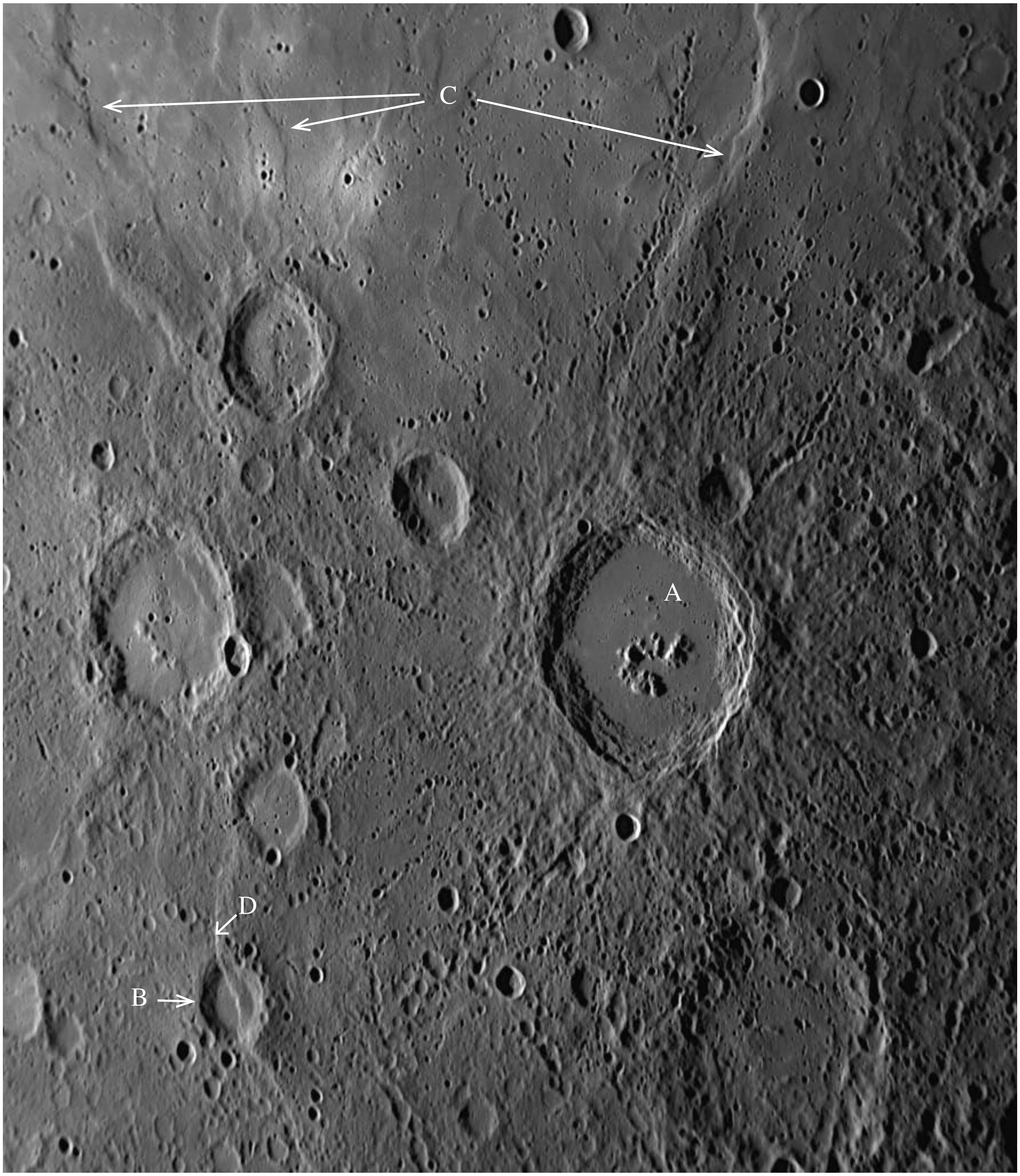


Figure S11. A photograph of the surface of Mercury taken by the MESSENGER spacecraft in 2009. Letters A-D mark geologically interesting features. (Picture credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington: http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?page=1&gallery_id=2&image_id=352)

2. What geologic features and landforms can you see in the picture?

a. Signs of volcanic activity? (Examples: volcanoes, smooth lava plains)

b. Signs of tectonic activity? (Examples: faults, grabens) [Hint: remember that tectonic faults are not always in straight lines but may sometimes have gently curving appearance.]

c. Signs of erosion? (Examples: riverbeds, sand moved by wind, crater walls degraded by the action of rain, wind, ice, or gravity) [Hint: remember which planet the photograph depicts and which agents of erosion are likely to act there.]

d. Signs of impact cratering? (Examples: impact craters, ejecta around craters)

3. Tape a blank overhead transparency over Figure S11. Mark on the transparency the four corners of the photograph as reference points in case the sheet shifts while you are working on it. The transparency will be the basis for your photogeologic map.

4. Draw the boundaries between the main types of terrain you identified in Step 1.

5. Write the mapping unit descriptions of the terrains in the table below. Label the units on your map.

Unit Name	Observation	Interpretation

6. Let's investigate the relationship between the terrains, the craters and a few of the tectonic features visible in the photograph. Trace a few of the largest craters on your map (be sure to include craters marked A and B), and some of the tectonic features (be sure to include at least a couple of the so-called wrinkle ridges marked C and the cliff marked D.)

a. What is the age relation between the terrains you identified? What observations did you use to decide?

b. Note the large crater (A) in the image. A crater this large can have central mountain peaks at the center of the crater, large ejecta blankets around it, and even secondary craters, where material blasted away from the impact site strikes the ground some distance away from the crater. Secondary craters can be recognized as a string or a group of small craters around the main crater. What is the age relation between the large crater (A) and the terrains you identified in Step 5? (That is, is the crater older or younger than the terrains?) Explain your answer.

c. What is the age relation between the wrinkle ridges (C) and the surrounding terrain? (That is, are the ridges older or younger than the terrain?) Explain your answer.

d. What is the age relation between the cliff (D) and the surrounding terrain? Explain.

e. What is the age relation between the cliff (D) and the mid-size crater (B) on it? Explain.

7. Place the geologic units (terrains) and the structural features marked A-D in the correct sequence in the stratigraphic column below. List the oldest at the bottom and the youngest at the top.

	Geologic Unit	Structural Feature
Youngest		
Oldest		

8. Using your unit descriptions and stratigraphic column, write a geologic history for the area you have mapped. Use evidence from the photograph and your map to support your answer.

Answer Key

Please note that in the following, it is assumed that the photographs in the worksheets are not reduced or enlarged during printing/copying.

Student Worksheet 1

1. a. The volcano has a circular base and a circular crater. The sides of the volcano have been affected by erosion. There is a lava flow down the side (marked with A in the photograph.)

   b. A road.

2. a. Scale: 200 m in reality = 1.0 cm in the photograph.

   x = 3.0 cm in the photograph; therefore x = 600 m in reality.

   b. Slope = 334 m / 600 m = 0.56

3. a. The surface is somewhat rugged.

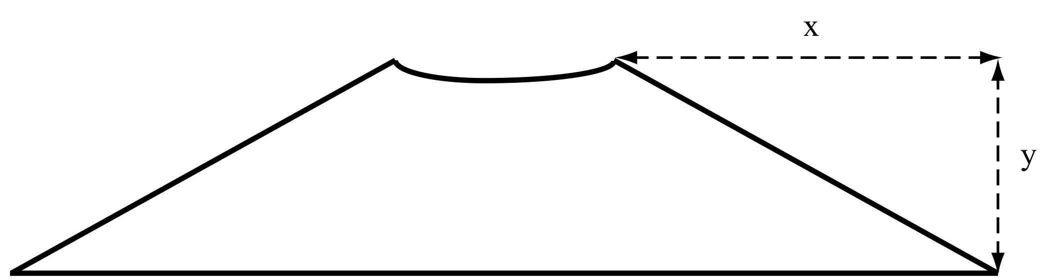
   b. The source of the lava flow is probably at the base of the crater near the road.

4. a. They are similar in shape (conical), with a central depression, the volcanic crater, at the top. They both have old lava flows coming down the sides of the mountain.

   b. The crater of Mt. Tavurvur is more irregular in shape, not quite as circular as the crater on Mt. Capulin.

5. The crater is not perfectly circular but somewhat scalloped, which suggests that it has been reshaped several times by multiple volcanic eruptions.

6. a. The schematic is the same as for Mt. Capulin:



b. Since the edge of the volcano is very irregular, the answers will vary. Here is one example:

Scale: 200 m in reality = 1.5 cm in the photograph.

x = 3.2 cm in the photograph; therefore x = 430 m in reality.

Slope of Mt. Tavurvur = 225 m/430 m = 0.52.

Since the slope of Mt. Capulin (from question 2b) is 0.56, it has a slightly steeper slope than Mt. Tavurvur (but not very different). Mt. Capulin would be harder to climb because it is steeper.

7. Answers may vary but could include the following: Single eruption versus multiple eruptions over time, the type of material (ash versus lava), how viscous the lava was (which depends on its temperature and composition), the amount of time the lava flows from the crater. After the volcano is formed, erosion by wind or rain may affect the slopes.

8. The fault cuts through the mountains and can be seen as a depression. The rocks along the fault were ground together and weakened, so that they were more easily eroded than the rocks away from the fault.

9. a. The road would have been cut and separated.

   b. There are at least two off-set features along the fault: near the middle of the photo, and near the bottom of the photo. (The features in this case are drainage valleys and not roads.)

10. Blocks A and C must move apart and away from block B in the horizontal direction.

11. a. The alluvium is material eroded from the Panamint mountains.

    b. All three agents have acted to produce materials eroded from the mountains, but water probably was the main agent, since there are features that look like drainage valleys on top of the mountains leading to the start of the alluvium fan features. The rivers have brought sediments from the mountain and deposited it on the sides. Material is also brought down the mountain by the action of gravity. One can also see some ripples in the feature probably caused by the wind.

    c. By all three agents but mainly by water carrying sediments from the mountains. Features that look like river beds or drainage valleys come from top of the mountains to the start of the alluvium fans, suggesting that the material was deposited by water.

    d. It would be eroded by the agents of wind, water, and gravity. For example, sand dunes are visible alongside the fans, providing evidence of erosion by the wind.

12. a. The river carries material from one place (glacier) to another (the Pacific Ocean.) Along the way, it deposits material on the river banks to form sandbars. The river also can remove material from its banks.

    b. The river channels change position with time. Dry and semi-dry (ponds present) channels are visible in the foreground of the photo, indicating that they have carried water before but do not do so at the moment.

13. a. It is a roughly circular depression in the ground, with its sides somewhat squared from a perfect circle.

    b. The walls are grooved, indicating erosion by running water. It looks like material from the sides of the crater has falled down to the bottom. The rim of the crater has eroded from a more circular shape it may have had originally.

14. Scale: 400 m in reality = 1.4 cm in the photograph.
    Diameter of the crater = 4.2 cm in the photograph; therefore x = 1,200 m in reality.
    Size of crater / size of asteroid = 48.

15. a. The Meteor Crater is much wider than a volcanic crater compared with the vertical size of the feature. Impact craters excavate (occur at ground level and dig out below ground level), while volcanoes are built up above ground level and have a crater on top of the mountain. A volcano also has material flowing from the crater to the surrounding area; an impact crater may have an ejecta blanket around it, but it is usually not as extensive or complex as lava outflows from a volcano.

    b. They have the same circular shape with a crater in the center.

16. a. It is circular but has a somewhat subdued appearance: the rim looks worn, and not very clearly defined. The center of the crater seems to have been partly filled with sediment, as shown by the presence of sand dunes.

    b. The Roter Kamm crater appears to be more eroded than the Meteor Crater. It appears to have filled with material from the crater sides and the surrounding area, and is therefore probably not quite as deep (compared with the size of the crater), as the Meteor Crater.

17. a. The crater does not appear as high or as steep.

    b. They all are circular and have raised rims.

18. A. Type: River valley; Process: Erosion; Evidence: curving feature carved into rock.

    B. Type: Graben; Process: Tectonism; Evidence: straight-line feature that is lower than the rocks on either side of it.

    C. Type: Lava flow; Process: Volcanism; Evidence: large-scale flow with darker color (medium gray) compared with the surrounding area (light gray.)

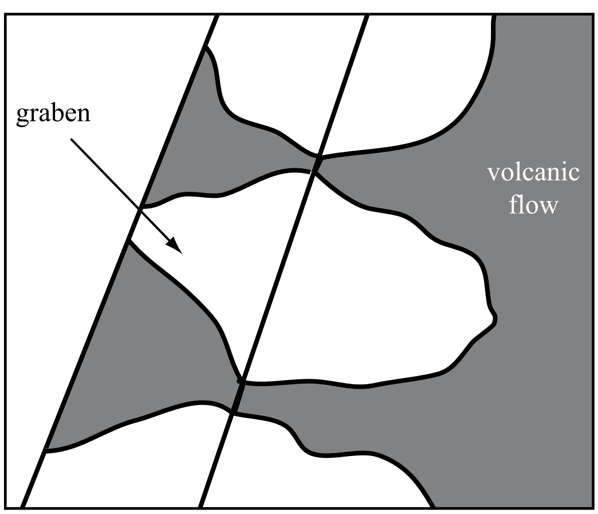
    D. Type: Volcano; Process: Volcanism; Evidence: cone-shaped hill which has a crater on top and which appears to be located in the middle of an area with lava flows.

    E. Type: Lava flow; Process: Volcanism; Evidence: dark material flows in an irregular pattern across the area and seems to have its source on a cone-shaped volcano.

    F. Type: Lava flow in a pre-existing river valley; Process: Erosion followed by volcanism; Evidence: winding feature (similar to A) that seems to be at least partially filled with new medium-gray material from a lava flow.

    G. Type: Graben; Process: Tectonism; Evidence: roughly straight-line feature similar to B.

19. a. Schematic of an area where a volcanic flow interacts with a pre-existing graben (southeast of the location of the letter G):



    b) Volcanic material flowed into the pre-existing graben valley in two separate places. The flows spread out in a fan shape.

20. _3_ river and stream valleys formed

_5_ dark (black) volcanic materials were deposited

_4_ medium gray volcanic flows were deposited

_1_ light gray plains formed

_2_ tectonism produced grabens

Explanation: The light gray plains appear to be the basis on which all other features are formed. The rivers and lava flows flood into the grabens (rather than the grabens cutting across existing rivers and lava flows, for example, as indicated by the fact that the rivers are widest on both sides of the graben just before going into the graben), so the grabens were formed next. At least some of the rivers have been affected by later lava flows, so they were formed after the grabens but before the lava flows. The dark lava flow is on top of the medium gray lava flows (as shown by places where the dark lava appears to flow on top of the medium gray lava), which means that it is younger of the lava flows.

21. On the Earth most craters have been erased by the other active geologic processes: volcanism, plate tectonics, and erosion (especially wind and water.) On the Moon, the effect of these agents has been much less: some of them do not exist at all (plate tectonics, wind and water), while others have not been active for quite some time (volcanism.)

Student Worksheet 2

Answers will vary depending on the students' interpretation of the image. Note that, for this activity, it is not as important for the students to correctly identify all the features in the photograph as it is for them to logically justify their answers.

1. a. Answers will vary. At a minimum students should list the following: Terrain One: smooth plains—smooth, brighter (higher albedo), less cratered areas; Terrain Two: heavily cratered terrain—rough, slightly darker (lower albedo), heavily cratered areas with craters of various sizes. Possible additional terrains include: large young craters with ejecta around them and older, more eroded craters.

   b. Answers will vary depending on the terrains the student identified. For the terrains listed in question 1a, the heavily cratered terrain is older than the smooth plains, because it has more craters, and the smooth plains seem to have formed so that they cover the heavily cratered terrain, rather than the other way around. The young craters are on top of the other terrains.

2. a. Smooth lava plains, but no sign of volcanoes (the craters are impact craters.)

   b. Several faults, especially in the upper part of the image; the faults are gently curving features. Features C and D are examples.

   c. Some of the craters appear to have degraded, probably due to gravity, since wind and water are not candidates for being agents of erosion on Mercury.

   d. Many craters of different sizes in all parts of the image, with craters fewer in the smooth terrain than in the heavily cratered terrain. Features A and B are examples.

5. Unit Descriptions

Unit Name	Observation	Interpretation
Smooth plains (or whatever name the students give to the unit on top)	Smooth plains, fewer (and mostly small) craters, higher albedo	Volcanic flow
Heavily cratered terrain (or whatever name the students give the unit at bottom)	Rougher surface, numerous craters of various sizes, lower albedo	Old, heavily modified surface, possibly of volcanic origin

6a. The smooth plains are younger than the heavily cratered terrain. The latter contains more craters, larger craters (as well as small craters), and more eroded craters. It is overlain by the volcanic smooth plains.

b. The crater is younger than either of the terrains. The main crater is on top of the heavily cratered terrain, and the secondary craters appear to reach all the way to the smooth plains, indicating that the secondary craters were formed after the smooth plains unit.

c. The wrinkle ridges are younger than the smooth plains because they are on top of the unit and are not covered somewhere along their length.

d. The cliff is younger than the heavily cratered terrain because it is completely on top of the terrain and is not covered somewhere along its length.

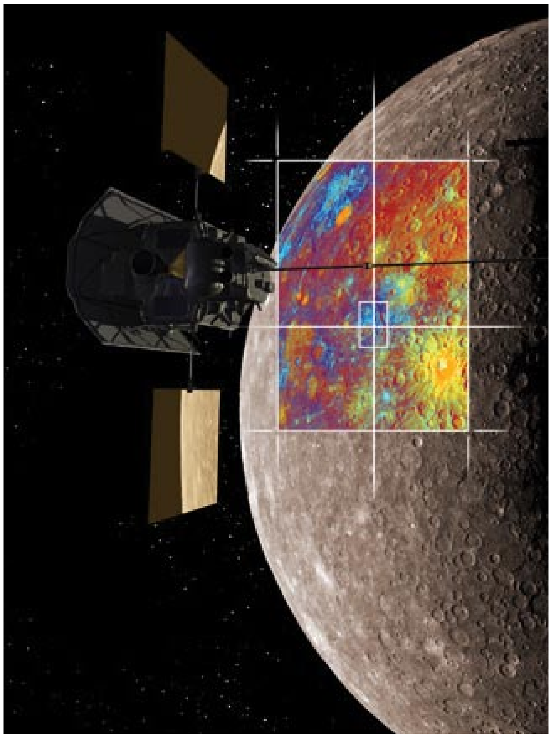
e. The crater is older because the cliff cuts through it.

7. The stratigraphic column:

	Geologic Unit	Structural Features
Youngest		Large young crater (A) Wrinkle ridges (C)
	Smooth plains	
		Cliff (D) Mid-size crater (B)
Oldest	Heavily cratered terrain	

12. This region was initially covered by the heavily cratered terrain unit, which is possibly of volcanic origin. The unit has been modified by continued cratering and tectonism, as evidenced by the cliff (D) that cuts through the mid-size crater (B). Volcanic flows occurred in the map area, represented by the smooth plains unit. No source area of the flows is identifiable within the mapped area. Cratering continued after the formation of the smooth plains unit. There has been a continuation (or reactivation) of tectonic activity in the area, indicated by the wrinkle ridges (C). Finally, cratering has continued, as shown by the presence of the large young crater on top of the two main geologic units, with secondary craters seemingly on top of the wrinkle ridges.

MESSENGER Mission Information Sheet



MESSENGER is an unmanned NASA spacecraft that was launched in 2004 to study the planet Mercury. After three flybys of its target planet in 2008 and 2009, the spacecraft will go into orbit around Mercury in 2011. It will not land but will make detailed observations from orbit. MESSENGER will never return to the 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, who, it was said, wore winged sandals and was somewhat of a trickster.

MESSENGER will be 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 about one Earth year, during which time it will make close-up and long-term observations, allowing us to see the whole planet in detail for the first time.

During its mission, MESSENGER will attempt to answer several questions about Mercury. 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? What is the nature and origin of Mercury's very tenuous atmosphere? Does ice really exist in the permanently shadowed craters near the planet's poles? Mercury is an important subject of study because it is the extreme of the terrestrial planets (Mercury, Venus, Earth, Mars): it is the smallest, one of the densest, it has one of the oldest surfaces and the largest daily variations in surface temperature—but is the least explored. Understanding this "end member" of the terrestrial planets holds unique clues to the questions of the formation of the Solar System, evolution of the planets, magnetic field generation, and magnetospheric physics. Exploring Mercury will help us understand how our own Earth was formed, how it has evolved, and how it interacts with the Sun.

Exploring Solar Systems Across the Universe

Lesson Overview

Lesson Summary

This lesson investigates how exploration of our Solar System provides information on the properties of planetary systems elsewhere in the Universe—and vice versa. In the first activity, the students investigate Solar System data to find clues to how our planetary system was formed. By the end of the activity, the students come to understand that other stars form just like the Sun, and, as a result, many stars could have planets around them. The second activity examines how scientists can find these extrasolar planets. By observing the behavior of a model star-planet system, the students come to understand that it is possible to see the effect a planet has on its parent star even if the planet cannot be seen directly. By comparing the properties of our Solar System with other planetary systems, we can gain a deeper understanding of planetary systems across the Universe. This is a great example of how exploration of similar phenomena can benefit the different strands of investigation.

Grade Level
9–12

Duration
Two 45-minute class periods

Essential Question

Why is it important to explore other planets and other planetary systems?

Lesson 1 of the Grades 9-12 Component of the *Mission Design* Education Module

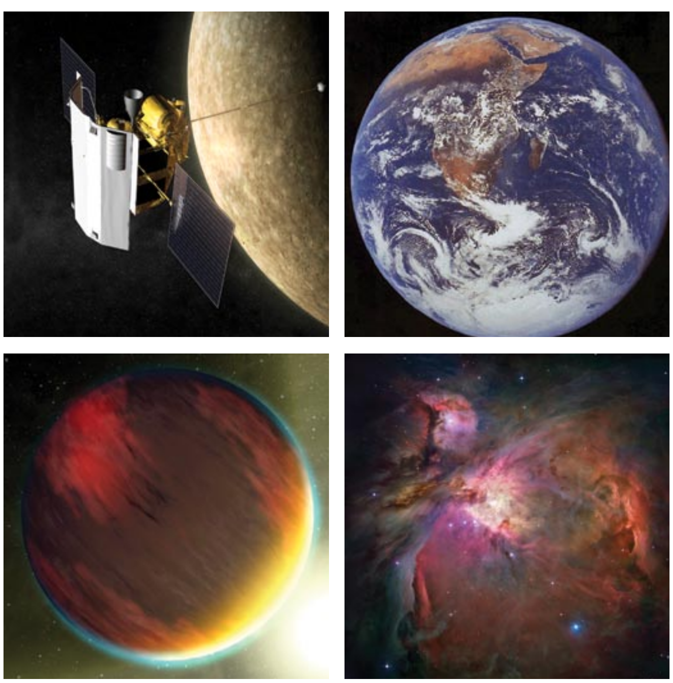


Figure 1. By offering points of comparison, studies of the other planets in the Solar System (e.g., MESSENGER mission to Mercury; top left) help us better understand the properties of other planets, including the Earth (top right), as well as of the whole Solar System. Studies of extrasolar planets (e.g., an artist's impression of a giant extrasolar planet located close to its star; bottom left) and environments in which stars and planets form (e.g. the Orion Nebula; bottom right) help us understand the origin and the evolution of the Solar System better. The reverse is also true: Solar System studies help us understand better the properties, origin, and evolution of planetary systems across the Universe. (Picture credits: NASA/JHU-APL/CIW: http://messenger.jhuapl.edu/the_mission/artistimpression/atmercury_br.html; NASA: http://www.nasa.gov/vision/earth/features/bm_gallery_1_prt.htm; NASA/JPL-Caltech: http://www.nasa.gov/images/content/169779main_A_ArtistConcept_final.tif; NASA/ESA/M.Robberto(STScI/ESA)/Hubble Space Telescope Orion Treasury Project Team: http://hubblesite.org/gallery/album/entire_collection/pr2006001a/)

This lesson was developed by the National Center for Earth and Space Science Education (http://ncesse.org).

Objectives

Students will be able to do the following:

- ▼ Investigate, compare, and describe patterns in Solar System data.
- ▼ Hypothesize about the formation of the Solar System based on data.
- ▼ Explain how extrasolar planets can be discovered.

Concepts

- ▼ Scientists can understand how the Solar System was formed by looking for clues in the properties of the Solar System objects today.
- ▼ The Solar System evolved over time, and it looks different today than when it first formed.
- ▼ Other stars and their planets formed in a similar way to our Solar System.
- ▼ Scientists can detect planets around other stars even though they cannot see them directly; they look for the effects that the planets have on their parent stars.

MESSENGER Mission Connection

MESSENGER will study Mercury, the closest planet to the Sun. Because of the environment in which the spacecraft has to operate, MESSENGER will also learn a lot about the space environment at Mercury's distance from the Sun. It is in this kind of close proximity to their parent stars that many extrasolar planets have been discovered. By learning more about the environment around our own star, the Sun, we can learn about the environment around other stars and the environments in which many extrasolar planets reside. In addition, MESSENGER's studies of Mercury may provide clues to the early history of the Solar System.

Standards & Benchmarks

National Science Education Standards

Standard D3: The origin and evolution of the earth system

- The sun, the earth, and the rest of the solar system formed from a nebular cloud of dust and gas 4.6 billion years ago. The early earth was very different from the planet we live on today.

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.

Standard G2: The nature of scientific knowledge

- Scientific explanations must meet certain criteria. First and foremost, they must be consistent with experimental and observational evidence about nature, and must make accurate predictions, when appropriate, about systems being studied. They should also be logical, respect the rules of evidence, be open to criticism, report methods and procedures, and make knowledge public. Explanations on how the natural world changes based on myths, personal beliefs, religious values, mystical inspiration, superstition, or authority may be personally useful and socially relevant, but they are not scientific.

AAAS Benchmarks for Science Literacy

Benchmark 1A/H1:

- Science is based on the assumption that the universe is a vast single system in which the basic rules are everywhere the same and that the things and events in the universe occur in consistent patterns that are comprehensible through careful, systematic study.

Benchmark 4A/H1:

- The stars differ from each other in size, temperature, and age, but they appear to be made up of the same elements that are found on the earth and to behave according to the same physical principles.

Benchmark 4A/H2:

- Stars condensed by gravity out of clouds of molecules of the lightest elements until nuclear fusion of the light elements into heavier ones began to occur. Fusion released great amounts of energy over millions of years. Eventually, some stars exploded, producing clouds of heavy elements from which other stars and planets could later condense. The process of star formation and destruction continues.

SCIENCE OVERVIEW

Science can be a lot like detective work. Scientists make observations of the phenomenon they are investigating in a similar way that a detective studies a crime scene for clues and evidence. A detective uses the clues and evidence gathered from a crime scene to produce a hypothetical scenario of what happened, and, through questioning of witnesses and interrogation of suspects, gathers enough evidence to prove the case in court. In a similar manner, scientists use observations as a basis for a hypothesis to explain the properties, origin and history of the phenomenon they are investigating. The hypothesis is then tested to see whether it holds true. If the tests are successful, the hypothesis will become part of a larger theory. For both the detective and the scientist, the story of the object of interest is not clearly spelled out; they have to use clues to piece the story together. Oftentimes, even the clues may not be clear, and the investigators have to compare observations from many places or use indirect evidence to arrive at a comprehensive hypothesis.

A great example of this idea—science as detective work—is the discovery of the planet Neptune and the dwarf planet Pluto. When scientists in the 19th century observed the orbit of the planet Uranus around the Sun, they noticed that the orbit did not quite follow the pattern predicted by Newton's laws. They deduced that there must be another planet-size object further out in the Solar System gravitationally disturbing the orbit of Uranus from the predicted path. Scientists started scanning the skies for planets in the places where the calculations suggested the planet would be, and in 1846, Neptune was discovered close to the predicted position. Further observations of the orbits of Uranus and Neptune seemed to suggest that there had to be yet another planet further out in the Solar System. Scientists continued to scan the skies, and in 1930 Pluto was discovered. However, it later turned out that Pluto's mass is too small to cause the observed effects in the orbits of Uranus and Neptune. Instead, Pluto's discovery turned out to be just fortunate happenstance. In reality, the apparent problem with the observed orbits of Uranus and Neptune was caused by the fact that Neptune's mass was not accurately known at the time. The observed orbits now match the calculations made with the proper mass of Neptune, and no massive planet further out in the Solar System is required to explain the behavior of the two planets.

Formation of the Solar System

Another good example of science as detective work is explaining the origin of the Solar System, which has intrigued scientists over centuries and which continues to be a hot topic of research even today. It is a question that has attracted the attention of some of the most prominent philosophers, mathematicians, and scientists over the last few centuries, from Descartes, Kant, and Laplace to the scientists working today. The problem with studying the formation of the Solar System is that it was a one-time event, it happened a long time ago, and there were no scientists around to record what happened. Instead, scientists have observed the properties of the present-day Solar System, as well as the formation of other planetary systems elsewhere in the Universe, to formulate the likeliest scenario of how our planetary system was formed. What follows is the generally accepted theory, though many of the details require further confirmation to provide a complete picture of the origin of the Solar System.

The Solar System was formed about 4.6 billion years ago, when a giant cloud of interstellar gas and dust started to contract under its own gravity. In the central part of the cloud, a precursor of the Sun called a protosun was formed, and around it formed a rapidly spinning disk. The disk fed material onto the growing protosun, while at the same time, small grains of dust within the disk collided, stuck together, and grew. Eventually the dust grains became large chunks, which collided and merged together, until planet-sized objects existed within the disk. The planet-sized objects then "swept up" remaining material, pulling leftover gas and dust toward them, and continued to grow. At the same time, the temperature inside the protosun rose, and eventually the temperature became so high that nuclear fusion, the process that powers the stars, began. At this point, the Sun became a proper star. The energetic, young Sun blew away remnant gas from the disk around it, revealing the Sun's family of planets. Asteroids, comets, and other small objects in the Solar System are thought to be material left over from building the planets—material that did not quite make it to become a planet or a major moon around a planet.

This explanation for the origin of the Solar System is the result of decades of research, including observations of the present-day Solar System, observations of stars and planets forming elsewhere in the Universe, and detailed computer simulations exploring different formation scenarios. The great strength of the standard theory is that it explains the observations quite well. For example, all planets revolve around the Sun in the same direction (counterclockwise, as seen from above the north pole of the Sun), and most of them rotate around their axis in a counterclockwise direction. In addition, all the planets circle the Sun in nearly the same plane. All this can be explained because the planets formed out of the same rotating disk. The scenario can also explain some of the differences between the planets, primarily why the terrestrial planets are small and rocky, while the Jovian ones are gas giants. In the inner part of the Solar System, the Sun made it too hot for much of the gas in the disk to collect onto the growing planets. Only small amounts of high-density materials like rock and metals could be pulled together by gravity to form the small, rocky planets. Farther out in the disk, large planetary embryos were able to pull vast amounts of gases like hydrogen and helium toward them, providing the extensive gaseous atmospheres in these planets.

Another great strength of the scenario is that it connects well with the formation of stars elsewhere in the Universe (see Fig. 2.) In fact, the scenario of the origin of the Solar System is basically the current standard theory of star formation everywhere.

Extrasolar Planets

According to the standard theory of star formation, planets should form as natural byproducts during the birth of stars. Over the last few years scientists have discovered that this, in fact, is the case. The first discovery of a planet around a Sun-like star was made in 1995. The number of observed extrasolar planets (planets outside our Solar System) around Sun-like stars grows all the time; the exact number was 455 in June 2010. It is difficult to see planets around other stars, because the planets appear just as small specks of reflected starlight located very close to the glare of their parent star. Directly observing any planets around even the closest star to the Sun would be similar to trying to see a tiny moth hovering by a small bright spotlight in San Diego by an observer located in Boston. As a result, the vast majority of the extrasolar planets discovered to date have not been seen directly in images taken with a telescope; instead, a variety of methods have been used to detect them indirectly.

Figure 2. A picture of the Orion nebula taken with the Hubble Space Telescope. Stars and planets are being formed inside giant interstellar clouds such as the Orion nebula. The Solar System was born in a similar environment about 4.6 billion years ago. (Picture credit: NASA/ESA/M.Robberto(STScI/ESA)/Hubble Space Telescope Orion Treasury Project Team; http://hubblesite.org/gallery/album/entire_collection/pr2006001a/

Detecting Extrasolar Planets via Stellar Wobble

Two indirect extrasolar planet discovery methods are based on detecting the small gravitational tug that the planets exert on their parent stars. According to Newton's third law, as the star exerts gravitational forces on a planet that keep the planet on its orbit around the star, the planet also exerts a gravitational force (of the same magnitude) on the star. In fact, the planet is not really orbiting the star; rather, the planet and the star are both orbiting around the center of mass of the two objects. The location of the center of mass—the point at which the two objects balance each other—can be calculated from the formula

$$r_1 = r_{tot} * \frac{m_2}{(m_1+m_2)}$$

where r_1 is the distance from body 1 to the center of mass, r_{tot} is the distance between the two bodies, and m_1 and m_2 are the masses of the two bodies. If the masses of the two bodies are similar (e.g., a double star system), the center of mass is between the two bodies, a little from the halfway point toward the more massive object (see Fig. 3.) In this case, it is possible to easily observe the orbits of both bodies around the center of mass. If the masses of the two bodies are very different (e.g., a star and a planet), the center of mass is close to the massive object (the star), and can even be located inside the more massive object. In this case, the orbit of the less massive object around the center of mass can be observed easily, but the orbit of the more massive object around the center of mass can be seen only as a small wobble in its position.

Detecting the Wobble via the Astrometric Method

Scientists can try and directly observe the wobble of the star caused by the presence of a planet. This approach is called the astrometric method. Because the stellar wobble is small and the stars are located far away, scientists have to be able to measure very small motions; in other words, scientists must

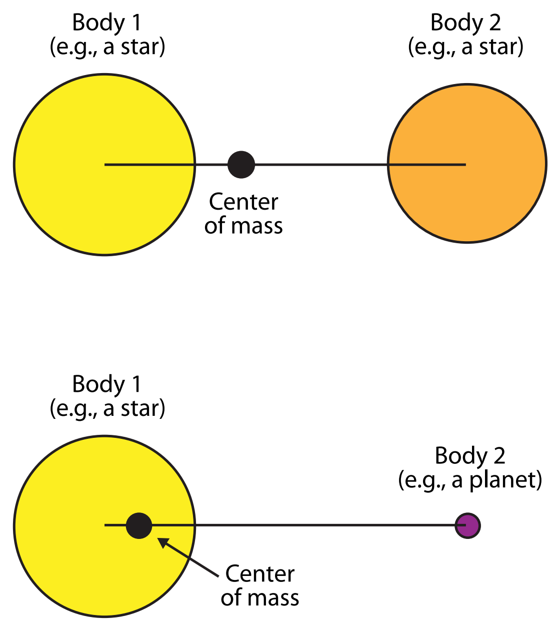


Figure 3. The center of mass in a two-body system where the bodies are similar in mass (top), such as in a double star system, is located in space between the two objects. In contrast, the center of mass in a two-body system where one body is much more massive than the other one (bottom), such as in a star-planet system, is much closer to the center of the more massive body and can even be located inside the large body.

be able to measure the position of the star in the sky very accurately. For example, Fig. 4 shows the wobble of the Sun caused by the presence of Jupiter as could be seen by an observer located at a nearby star. The observable wobble in the sky is minute, and the observing systems (telescopes and measurement devices) have to be accurate enough to see these small changes. Scientists are now starting to have the technology capable of seeing this effect. While no planets have been discovered via this method to date (June 2010), it probably is only a matter of time before the first discovery is made this way. This method is most sensitive to finding massive extrasolar planets, but in the future, it may be possible to detect the presence of Earth-size planets orbiting nearby Sun-like stars.

Detecting the Wobble via Doppler Shift

The second extrasolar planet discovery method that is based on the wobble of the parent star does not observe the wobble directly. Instead, it uses the changes in the starlight coming from the moving star to measure the Doppler shift of the starlight as the star moves along its orbit around the center of mass (see Fig. 5.) As a light source (the star) moves toward an observer, the light waves are shifted slightly toward the blue end of the light spectrum. This is caused by the light waves becoming slightly compressed when the light is coming from a source moving toward the observer, causing an effect called blueshift. When the light source moves away from the observer, the light waves are slightly spread out, and the light is redshifted. The faster the light source is moving toward (or away) from the observer, the larger the blueshift (or redshift). By monitoring the Doppler shift of starlight, we can detect the motion of the star around the center of mass, and from that motion determine the properties of the planet causing the wobble.

Just like the astrometric method, the Doppler shift method can most easily detect massive planets. In addition, the Doppler shift method works well when the light source is moving fast, which is the case for wobbles caused by planets orbiting close to their parent star. Combined, this means that the Doppler shift method is most sensitive to massive planets in close orbits around the central star. The vast majority (more than 90%) of the extrasolar planets discovered to date have been detected first via this method.

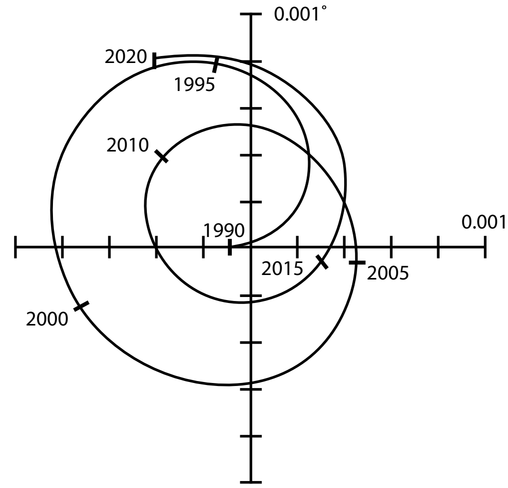
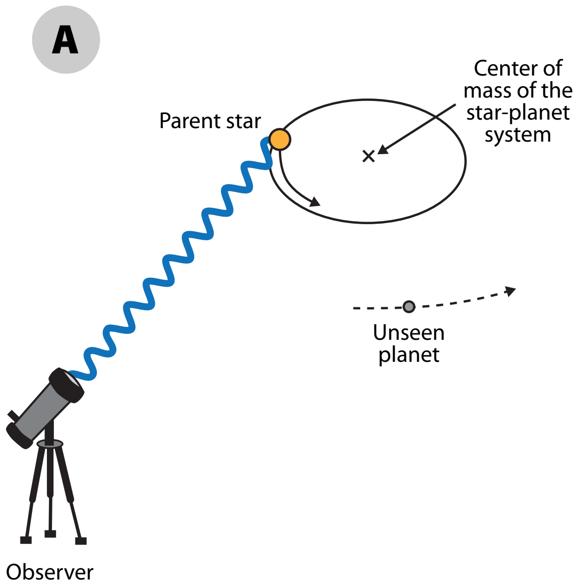


Figure 4. The wobble of the Sun caused by the gravitational tug of Jupiter as could be seen by an observer located at the distance of some of the nearby stars (10 parsecs; 33 light-years; 3.09×10^{14} km; 1.92×10^{14} miles). The wobble is measured in thousandths of an arcsecond (noted as " in the figure above on the axes), which is a way to measure sizes in the sky. Here, the wobble is less than 0.001 arcseconds. For comparison, the size of the full Moon as seen in the sky is 0.5 degrees, or about 1800 arcseconds. In other words, detecting the wobble of a star requires being able to see changes in its position of the size of 1.8 millionth the size of a full Moon. The diagram shows what the wobble of the Sun would look like over 30 years (between 1990 and 2020.) (Picture credit: NASA/JPL; http://planetquest.jpl.nasa.gov/science/finding_planets.cfm)



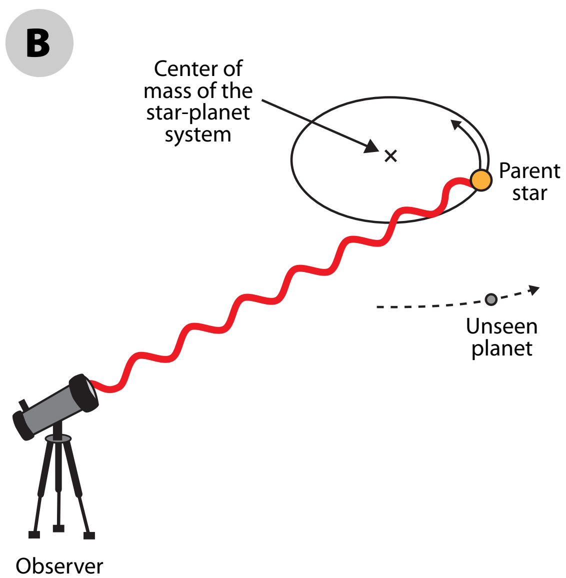


Figure 5. Detecting extrasolar planets via the Doppler shift. The light emitted by a wobbling star is shifted toward the blue wavelengths when the star is moving toward the observer (A), and toward the red wavelengths when the star is moving away from the observer (B), as the star orbits the center of mass (or wobbles.) Analyzing the Doppler shift provides information on the unseen planet.

Detecting extrasolar planets via other methods

Transit method

Sometimes a planet may pass in front of its parent star and block a small portion of the starlight, dimming the star's light as viewed by observers on the Earth. By observing this phenomenon, it is possible to calculate details such as the orbit and the size of the planet. This method is most sensitive to large planets located close to their central star. Some of the extrasolar planets detected through the Doppler shift method have also been seen transiting their parent star.

Microlensing

Einstein's general theory of relativity suggests that gravity can cause stars and planets to act as cosmic magnifying glasses, bending and focusing light much like a lens bends and focuses light in a telescope. Through this effect, the light from a background ("source") star may be bent and focused by the gravity of a foreground ("lens") star (see Fig. 6.) Because objects in space are moving, the foreground object usually passes quickly in front of the source star, as viewed from the Earth, causing the background star to brighten only briefly before its brightness returns to normal—creating the microlensing event observed on the Earth. If the lens star has a companion (such as a planet), it is possible to see complicated spikes in the source star's brightening pattern, and an analysis of the spikes reveals the presence of the otherwise unseen planet. The strength of this method is that it can detect planets of all masses.

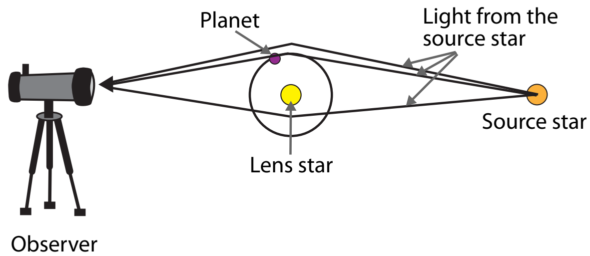


Figure 6. The gravity of a star ("lens star") passing in front of another star ("source star") as seen by an observer on the Earth can cause the light from the source star to be bent and focused much like in a lens of a telescope. If the lens star has a planet, the brightening of the source star exhibits a different pattern than if the lens star does not have a planet.

Direct Detection

The extrasolar planet detection methods described above are indirect methods: the planets are not seen directly. Scientists have been working hard to overcome the technological obstacles of taking direct images of these faint objects, and by June 2010, there are a dozen extrasolar planet candidates detected via direct imaging. However, the detailed properties of the objects remain uncertain and need to be confirmed. With improved observing techniques, refined planet detection methods, and more sensitive telescopes, the number of extrasolar planets observed directly is likely to rise significantly in the future.

Pulsar Planets

The first extrasolar planet ever discovered was actually not found around a Sun-like star (like most of the planets discovered since), but around an object called a pulsar, which is a remnant of a star that died in a massive explosion. Even though they are, in a sense, dead stars, pulsars send out pulses of energy into surrounding space—pulses which can be detected here on the Earth. By monitoring the disturbances in the pulses of a particular pulsar, scientists suggested in 1992 that the observed disturbances could be explained best by the presence of three planets orbiting the pulsar. The interesting property of these pulsar planets is that they are much smaller than the Jupiter-size planets discovered to date around Sun-like stars—in fact, most of the objects discovered to date by this method are Earth-sized or smaller.

Solar System Analogs

The detection methods used to discover most of the extrasolar planets to date are most sensitive to finding large planets close to the stars. The masses of the extrasolar planets around Sun-like stars discovered to date range from about 0.006 to 25 times the mass of Jupiter. While the lower end of the mass limit approaches Earth-size planets (the mass of the Earth is 0.003 Jupiter masses), the vast majority of the extrasolar planets are giant planets. In the Solar System, Jupiter, the closest giant planet to the Sun, is located about 5.2 times as far from the Sun as the Earth. In contrast, the majority of the extrasolar planets discovered around Sun-like stars are located closer to their parent stars than the Earth is located to the Sun. As these comparisons indicate, the extrasolar planetary systems discovered to date are quite different from the Solar System. In the future, improved observational methods may be able to detect Earth-sized planets around other stars, and discover Solar System analogs: planetary systems with small rocky planets near the star and gas giants further out. Once extrasolar Earth-like planets can be detected, scientists can begin to examine whether they could be hospitable for life or even be inhabited. For the most recent discovery data and statistics, see the Web sites listed in the *Internet Resources & References* section; the Web sites are updated almost daily.

Extrasolar Planet Detection Missions

Numerous observers around the world are using ground-based and space telescopes to discover and characterize extrasolar planets, and, in fact, even amateur astronomers can monitor nearby stars to see if their brightness dips enough to reveal the presence of a transiting planet around the star. In addition to making observations using multi-purpose telescopes (that is, telescopes such as Hubble and Spitzer space telescopes, which are designed to observe many different kinds of objects in the Universe), there are a few current projects specifically designed to look for and characterize extrasolar planets. NASA's Extrasolar Planet Observations and Characterization (EPOCh) project used the existing Deep Impact spacecraft to look for transiting extrasolar planets and wobbling stars with planets, and to try and analyze the light reflected off the surfaces of extrasolar planets. NASA's Kepler mission, launched in 2009, and the European Space Agency's Convection Rotation and Planetary Transits (COROT) mission, launched in 2006, are looking for extrasolar planets through the transit method. Since they are observing thousands of stars in their surveys, Kepler and COROT are likely to multiply the number of known extrasolar planets and start to determine how common Earth-like planets might be among the planetary systems across the Universe. Future planned missions, such as the Terrestrial Planet Finder, will help refine these estimates.

Planetary Systems Across the Universe

One of the great scientific success stories of the last few decades has been the increasing understanding of how the Solar System was formed, how planetary systems form elsewhere in the Universe, and the discovery of the first extrasolar planets that confirm the expectation that planetary systems are, in fact, common, as the theory of star formation suggests. The origin of the Solar System and the formation of other stars have interested scientists and philosophers for thousands of years, but it has only been over the last couple of decades that the theory of star formation in general, and the origin of the Solar System in particular, have started to become clear. Essential in all this has been great advances in technology. Advances in observational instruments and techniques have made it possible for scientists to better understand the properties of Solar System objects, as well as the regions in which stars form elsewhere in the Universe. At the same time, computer technologies have enabled detailed theoretical studies and computer simulations of the processes involved in star and planet formation. The same advances have also led to the discovery of extrasolar planets, ushering in the era where scientists can not only compare the properties of different planets in our Solar System, but with those in dozens of planetary systems elsewhere. This work over the last few decades has created a momentous shift in our view of the Universe. We now know that the Solar System is not unique; there are, certainly hundreds, but probably billions of planetary systems out there across the Universe.

The investigations into the origin of the Solar System and the presence of planets around other stars also highlight an important philosophical aspect of exploration. By exploring one phenomenon, we not only learn about that topic but can also gain great insight into other, related phenomena. By studying other planets in the Solar System, we not only learn about the properties of those planets, but we also may gain insight into the Earth, and even the origin and the evolution of the Solar System. By studying other planetary systems, we not only learn about the variety of different worlds across the Universe, but also gain insight into our own Solar System. This rationale for exploration is found everywhere in science—and, indeed, throughout human activity—but it shines especially bright in space exploration, where scientists must gather as much information as they can from usually a limited number of directly observable sources to formulate and refine their theories.

Lesson Plan

Warm-Up & Pre-Assessment

1. Show students a picture. It could be any picture that shows the result of interesting events; for example, a picture of a crime scene works well for this purpose. Ask the students what they can see in the picture. Make sure the students only make observations about what is visible in the picture and do not infer what may have happened to lead up to the scene depicted in the picture.

2. Ask the students: if they only have a picture of the end result of something that happened earlier, how could someone (such as a detective) understand the events that lead up to that point? *(Desired answer: the detective can look for evidence in the scene and in other places to put together a story of how things progressed to the situation shown in the picture.)* The kinds of evidence one would look for depends on the kind of problem that is being solved. Ask the students to identify different types of evidence that someone would look for to determine the events that lead up to the scene depicted in the picture.

3. Draw analogies to the two activities the students will do in this lesson. For the analogy to the first activity, ask the students how scientists might know how the Solar System was formed, even though they were not around to witness the event. The main clues that scientists have to lead their thinking is an understanding of what the Solar System is like right now. For the analogy to the second activity, discuss with the students the discovery of Neptune. Scientists knew that a planetary-size object must be out there based on how it was affecting the orbits of other planets around the Sun (See the *Science Overview* for details.) Similarly, how would astronomers know if there is an unseen object that affects the behavior of another, visible object (such as might be the case with a small planet orbiting a bright star)? Astronomers can look closely at light coming from the visible object to see if there are clues to the existence of an unseen object in the light, just like a detective needs to investigate a crime scene carefully to find clues that may not be immediately clear.

Materials

- ▼ Picture of a crime scene (or similar)

Activity 1: Formation of the Solar System

Students analyze information about the relative positions, sizes, and compositions of the Sun, planets, asteroid belt, comets, and Kuiper Belt Objects to form a hypothesis about the origin of the Solar System based on patterns they discover in the data. The students compare their hypothesis with those of other students to discover strengths and weaknesses of each. By investigating pictures of star-forming interstellar clouds and planet-forming disks elsewhere in the Universe, the students come to understand how scientists have come up with the current theory of Solar System formation based on observations of our Solar System as well as of planetary systems currently being formed elsewhere.

Materials

Per class:

- *Planets and Orbits Transparency* (3 pages)
- *Young Stars Transparency* (2 pages)

Per student:

- Student Worksheet 1

Preparation

1. Make overhead transparencies of the *Planets and Orbits Transparency* and the *Young Stars Transparency* found in the back of the lesson, or make copies of the pictures for each group of students.
2. Place students in groups of two or three.

Procedures

1. Present the *Planets and Orbits Transparency* on an overhead projector or hand out copies to each group of students.
2. Have the students examine at the picture of the planets on the first page, which shows the planets in their correct order from the Sun and at right relative sizes (but not at relative distances from the Sun), and ask the students to describe trends or patterns that they notice among the planets.
3. Have the students investigate the next two pages, which show the orbits of the planets and location of some of the other Solar System objects. Ask the students to describe trends or patterns they may notice among the Solar System objects.
4. Ask the students how they could use this information to think about how the Solar System might have formed. Discuss how the Solar System has not always looked the same way; that it has evolved over time. Ask the students to think back to the Warm-Up and their discussion about how

scientists have to look at the properties of the present-day Solar System and use these clues to determine how the Solar System was formed. Discuss with the students why they might be interested in finding out how the Solar System was formed. Do the students think it is because of basic curiosity about the Universe around them, or something else?

5. Hand out Student Worksheet 1. The students will follow the directions on the Worksheet to come up with more observations on the properties of Solar System objects and eventually create a hypothesis about how the Solar System could have formed.

Teaching Tip

If your students are unfamiliar with any of the details in Table 1 in Student Worksheet 1, be sure to discuss them as a class before starting work. For example, make sure that the students understand that an Astronomical Unit (AU) is the average distance from the Earth to the Sun, eccentricity measures how much an orbit deviates from a perfect circle (the eccentricity of which is 0) toward a more elliptic orbit, and inclination measures the tilt of an object's orbit from the plane of the Earth's orbit around the Sun.

Discussion & Reflection

1. Have each group of students present their hypotheses of how the Solar System was formed. After a group has presented its idea, encourage other groups to challenge the proposal with counter-evidence or to offer supportive evidence that the group may have overlooked.

2. As a class, come up with a coherent story of how the Solar System was formed based on the evidence presented. It is acceptable if the story does not match the actual scientific theory, as long as the students base their explanation on evidence.

3. Discuss the scientifically accepted theory for how the Solar System was formed (see the *Science Overview*). Discuss which components of the students' hypothesis agree with the theory, and which do not. Ask the students to try to explain those parts that are not consistent with their own hypothesis based on the evidence they have seen. Remind the students that in reality, scientists had access to more information than the students had when coming up with the theory of Solar System formation, such as ages of different Solar System objects. Scientists have also been able to refine their hypotheses with the help of computer simulations investigating the processes involved in the formation of the Solar System. A comprehensive

theory requires a lot of data and a lot of work by many people over many years before scientists are able to agree that the theory is comprehensive and correct; that, for example, this is the way that the Solar System was formed.

Teaching Tip

You can have the students look up the scientifically accepted theory of Solar System formation in the library or on the Internet, either as homework or as a class. They could also research and discuss other pieces of evidence scientists have used to derive the theory and which the students may not have had available in formulating their own hypotheses.

4. Discuss with the students how the process they followed in Student Worksheet 1 is how science really works. Observations and experiments are an essential part of a scientific investigation, but a crucial part of the scientific process occurs when the scientists try and interpret the gathered data; that is, when they try to explain the processes involved in creating the situation depicted by the data.

4. Ask the students if they think other stars form the same way as the Sun. *(Desired answer: yes.)* If other stars form like our own, how could we see evidence of this? *(Desired answer: look for planets around other stars, or look to see if there are any places in the Universe where stars are forming right now and where we might be able to see the process in action, for example by seeing disks around other stars that are in the process of forming planets.)* Show the students the *Young Stars Transparency* on an overhead projector or hand out copies to the class. The transparency shows young stars forming in a cloud of gas with disks around them. Planets will eventually form in these disks, if what happened in our Solar System happens around other stars (as scientists think is the case.) By learning how the Solar System was formed and by comparing it with stars forming today, the students can understand that other stars are born in the same manner as the Sun. Similarly, scientists know more about how other stars form by understanding how our Solar System was formed. But the reverse is also true: scientists can use their observations of how other stars are born to refine the theory of how our Solar System formed. The two strands of investigation feed off of one another: if we learn more about one, we are likely to learn more about the other, as well. Have the students discuss whether the connection between the formation of the Solar System and the birth of stars elsewhere in the Universe means that other stars may have planetary systems of their own.

ACTIVITY 2: TUGGING THE STAR

Students construct a model of a star and planets orbiting the star by using a grapefruit to represent the star and a variety of smaller objects to represent the planets. The students connect the two objects with a tube, hang the model from its center of mass, and monitor it as it rotates. The students discover that by observing the rotation of the model star around the system's center of mass, they could detect the presence of the model planet even if they were not able to see it. As a result, the students come to understand that using this principle, scientists can learn about the presence and properties of planets around their parent stars even if the planets cannot be seen directly. The students also find out that it is easiest to observe massive planets like Jupiter around other stars using this method of extrasolar planet detection.

Materials

Per group of 3:

- Grapefruit
- 3 balls of different masses; we suggest a softball, a baseball, and a golf ball
- Binder clip (medium-size)
- Black marker
- Cardboard tube
- Laboratory scale
- Paperclip (small)
- Ruler
- Scissors
- Sheet of white paper at least 50 cm (about 1.5 ft) long; two sheets of 11" x 17" of paper taped together length-wise will suffice
- 4 short pieces of string (each about the length of your hand)
- 2 long pieces of string (each at least 1 m; 3.3 ft long)

Per student:

- Student Worksheet 2

PREPARATION

1. Make sure the students are familiar with the general concept of the center of mass (see the *Science Overview*). This is a very important concept to understand in order to conduct the activity.
2. Locate cardboard tubes for students to use in the activity. For example, the cardboard tubes found on wire hangers used by drycleaners work well, but any narrow tube of roughly 30 cm (12") length works. Make sure that one of the long pieces of string can be threaded through the tube, and that the strings are strong enough to carry the weight of the apparatus (see Student Worksheet 1 for details on how to construct the apparatus.)
3. Divide the students into groups of three.

Teaching Tip

The materials list includes suggestions for the different balls to use as the model planets. However, you can use any balls of different masses you can find. In fact, if you can find a large, low-mass ball and a small, high-mass ball to use as two of the planets, you can use them to illustrate that the center of mass and therefore the wobble of the host star depends on the mass of the planet, and not the size.

Procedures

1. Remind the students of Activity 1. They should have come to the conclusion that there may be other planets around other stars that could have formed the same way that the planets formed around our star, the Sun. These planets are called extrasolar planets because they are outside of our Solar System. Ask the students why they might be interested in finding out whether there are planets around other stars. What reasons do the students think scientists have to look for the planets?

2. Ask the students to imagine looking at other stars and trying to detect planets around them. Do any problems come to mind? *(Desired answer: other stars (and their planets) are very far away. In addition, planets do not shine their own light; they reflect the light of their parent star. As a result, planets are very dim compared to the stars they orbit because the light from the star washes out dim objects around it.)* Planets are very difficult to see directly, even with powerful telescopes. One to-scale analogy you can give the students is that looking for a planet around another star would be like standing in Boston and trying to detect a moth that is hovering near a small, bright spotlight that is located in San Diego.

3. Ask the students: if scientists cannot see extrasolar planets directly, what can they do? *(Desired answer: they can look for other kinds of evidence that the planets exist; refer to the Warm-Up where the class discussed how detectives have to determine who committed a crime even if not all evidence is clearly visible in the crime scene.)*

4. Have the students brainstorm in their groups for a few minutes about how scientists could detect planets without being able to see them directly. Come together as a class and review the ideas. If the students need help coming up with the idea of celestial bodies affecting the movements of each other, remind them about the discovery of Neptune discussed in the Warm-Up. [Reminder: Scientists knew that a planetary-size object must be out there based on how it was affecting the orbits of other planets around the Sun (see the *Science Overview* for details.)] Similarly, how would astronomers know if there are planets around other stars when the planets are too dim to see directly?

5. Remind the students that a planet does not just orbit its parent star; in fact, the planet and the star both orbit the center of mass of the system of the two bodies. Because the star is so much more massive than the planet, the center of mass is much closer to the star; in fact, sometimes it is inside of the star. Even in this case, scientists can tell that a planet is orbiting

a star because the star will appear to "wobble" around the center of mass of the star-planet system.

6. Ask the students how they could experiment with different types of star-planet systems in the classroom. Discuss the ideas as a class and lead the discussion toward the experiment the students will perform. Be sure to have the students discuss that if they experiment with model planets of different masses, they might be able to see what kind of planets are easiest to detect this way.
7. Hand out Student Worksheet 2, and have the students follow the instructions to conduct the experiment and answer the questions.

Discussion & Reflection

1. Have the groups share which situation was best for detecting the wobble of the model star. They should have discovered that the system with a massive model planet works best, because in this case, the model star has a bigger, more easily detectable wobble.
2. Discuss the extrasolar planet detection methods based on the principle of stellar wobble. Discuss the differences between the purely astrometric method (detecting the wobble directly) and the Doppler shift method (detecting the wobble through changes in starlight.) (See the *Science Overview* for an overview of the methods.)
3. Discuss the types of planets that have been found using these detection methods thus far (see the *Science Overview*.) They are massive planets that are located close to their parent star. Discuss with students how the extrasolar planetary systems compare with the Solar System. Point out that since the detection methods are most sensitive to massive planets located close to the parent star, this is exactly what scientists have found. Most of the extrasolar planets discovered are giant planets similar to Jupiter but located very close to the parent star, as close to or even closer than Mercury is to the Sun.
4. Ask the students what is the likelihood of finding life on the detected extrasolar planets. *(Desired answer: it is not very likely, because the planets do not resemble the Earth, which is the only planet that we know has life. The detected extrasolar planets are gas giants, which probably do not have a solid surface on which life forms could live. Most of the detected extrasolar planets are located close to the parent star, which means that they are very hot and probably not suitable for life for that*

reason, either. However, the giant extrasolar planets could have large moons, and perhaps life could survive on those moons. There are many extrasolar planetary systems where the giant planets are at the same distance of their parent star as the Earth is from the Sun, perhaps making any large moons they might have very habitable by some kind of life forms.)

5. Discuss the other methods of detecting extrasolar planets; a brief description of them can be found in the *Science Overview*. Be sure to point out the difference between the purely astrometric method, where the wobble of the star is detected directly, and the Doppler shift method, where the wobble is detected through details in the wobbling star's light.

6. Discuss with the students the idea of a "Solar System analog": a planetary system that looks more like the Solar System than the planetary systems discovered so far. Point out that the technology has not been good enough to detect true Solar System analogs until now. Do the students think scientists will discover planetary systems just like our own one day?

Extensions

- Have the students research alternate hypotheses of how the Solar System was formed. There used to be many ideas for Solar System formation, but they have fallen out of favor because of the evidence that supports the current standard theory.
- Amateur astronomers have become a part of the search for extrasolar planets, because even small telescopes equipped with sensitive detectors can monitor nearby Sun-like stars to see if any planets might transit over them. If the students have access to a suitable telescope, either through school, a local observatory or by partnering with local amateur astronomers, you can have the students start an extrasolar planet transit observation campaign. Visit http://www.transitsearch.org/ for more details.
- NASA's Kepler mission searches for extrasolar planets using the transit method. If you want to have your students explore the concepts behind this approach in greater detail, visit the Kepler education activities Web site http://kepler.nasa.gov/education/

Curriculum Connections

- *Social Studies*: Have the students research how ancient cultures believed the Solar System (or the Earth) was formed. How do the ancient creation myths compare with the current theory of Solar System formation?

- *Literature*: Find science fiction books or stories that describe planets around other stars, and have the students write an essay on how well the author's description of the planets matches the properties of known extrasolar planetary systems.

- *Math*: Have the students research exactly how scientists can determine the properties of the extrasolar planets using the different detection methods. For example, the Doppler shift method tries to fit the observed data to mathematical descriptions of planetary orbits and requires a lot of computing to solve the mathematical problem. The extrasolar planet Web sites listed in the *Internet Resources & References* section describe the mathematical process.

Closing Discussion

- Discuss with the students what motivations scientists may have for examining the origin of the Solar System and the existence of extrasolar planets. Do the students think it is just basic human curiosity? Perhaps scientists hope to learn more about the Solar System today (or in the future) by understanding how our Solar System was formed and how it compares with other planetary systems elsewhere in the Universe?

- Discuss how scientists have been able derive the standard theory of star formation and a good explanation of the origin of the Solar System over the last couple of decades. Discuss how modern technology has been essential for the progress by making it possible to conduct detailed observations of Solar System objects and star-forming regions elsewhere and to perform large-scale computer simulations that help distinguish between different scenarios.

- Discuss how the view of our place in the Universe has changed with the discovery of extrasolar planets. Until the 1990s, scientists knew of only one planetary system in the Universe: the Solar System. We now know there are at least hundreds, and probably billions, other planetary systems out there. Even though the extrasolar planetary systems discovered so far have been a little different from the Solar System—with giant planets located close to their parent star instead of a bit farther out as in the Solar System—the discoveries have shown that planetary systems are common in the Universe. How do the students think this affects our view on the possibility of finding life somewhere else in the Universe?

- Discuss how scientists have to explain why so many planetary systems appear to be at least a little bit different from the Solar System. Did they form in a slightly different way from the way our Solar System formed, at least in some details? Or do the exact properties of the environment in which stars and planets form determine what they end up looking like in the end? Right now, scientists do not know. The answers to these questions will provide information on the formation of planetary systems across the Universe, and it will also give us insight into the formation and evolution of our own Solar System. Similarly, by studying the environments in our own Solar System at various distances from the Sun, we can understand the environments in which extrasolar planets exist. This is a great example of how exploring one phenomenon can provide important information on other, related topics. This is, in fact, an important reason for exploration in general.

▼ Hand out copies of the *Mission Information Sheet* and the *Mission Science Goals* located at the back of the lesson. Discuss with the students how the mission connects with the topics discussed in this lesson.

Assessment

4 points

▼ Student identifies patterns in the Solar System data that could help explain the formation of the Solar System in Activity 1.

▼ Student uses evidence to come up with a reasonable hypothesis for the formation of the Solar System in Activity 1.

▼ Student finds that more massive planets affect their parent stars more than less massive planets in Activity 2.

▼ Student completes both Worksheets.

3 points

▼ Student meets three of the four above criteria.

2 points

▼ Student meets two of the four above criteria.

1 point

▼ Student meets one of the four above criteria.

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/publications/bsl/online/bolintro.htm

National Science Education Standards

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

COROT Mission Web Site

http://smsc.cnes.fr/COROT/

Exoplanet Data Explorer

http://exoplanets.org/

Extrasolar Planets Encyclopaedia

http://exoplanet.eu/

Hubble Space Telescope Gallery of Nebulae (Note that the collection includes images of other nebulae besides star-forming clouds, since nebula is a more general term)

http://hubblesite.org/gallery/album/nebula_collection/

International Astronomical Union Minor Planet Center's Transneptunian Object List

http://cfa-www.harvard.edu/iau/lists/TNOs.html

Kepler Mission Web Site

http://kepler.nasa.gov/

NASA National Space Science Data Center's Planetary Fact Sheets

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

NASA/JPL Small Body Database

http://ssd.jpl.nasa.gov/sbdb_query.cgi

The Nine Planets Web Site

http://www.nineplanets.org/

PlanetQuest: Extrasolar Planets website at NASA/JPL

http://planetquest.jpl.nasa.gov/

ACKNOWLEDGEMENT

Activity 2 has been adapted from the activity "The Mathematics of Rotating Objects (Extra-Solar Planets)" (http://planetquest.jpl.nasa.gov/documents/Math_ExS.pdf) from NASA's PlanetQuest Educator Resources.

PLANETS AND ORBITS TRANSPARENCY #1

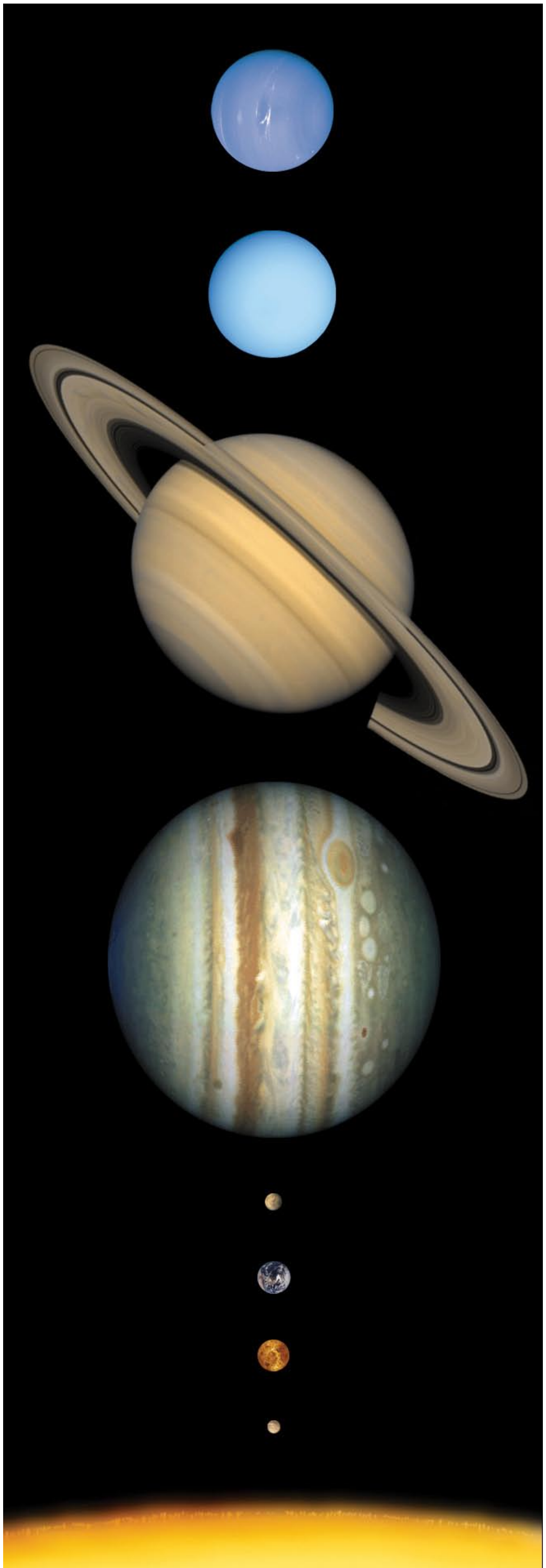
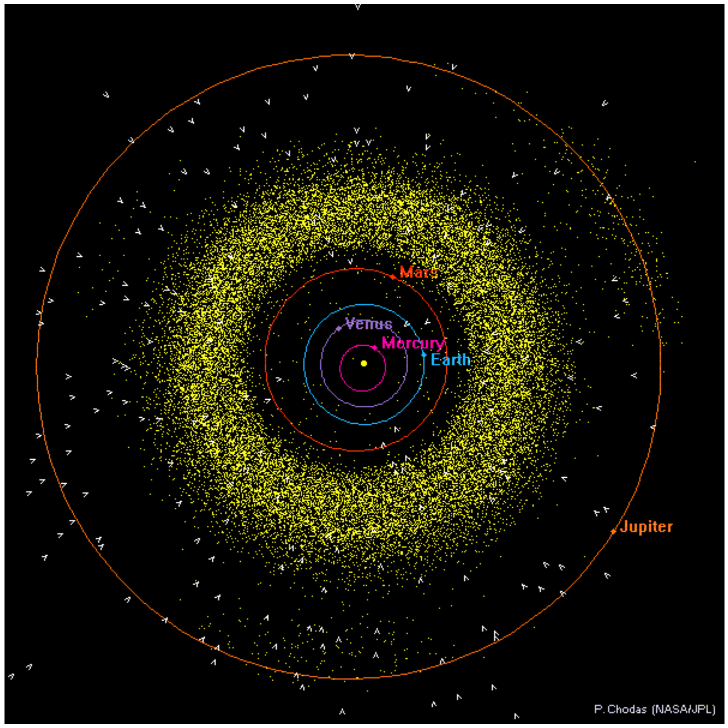
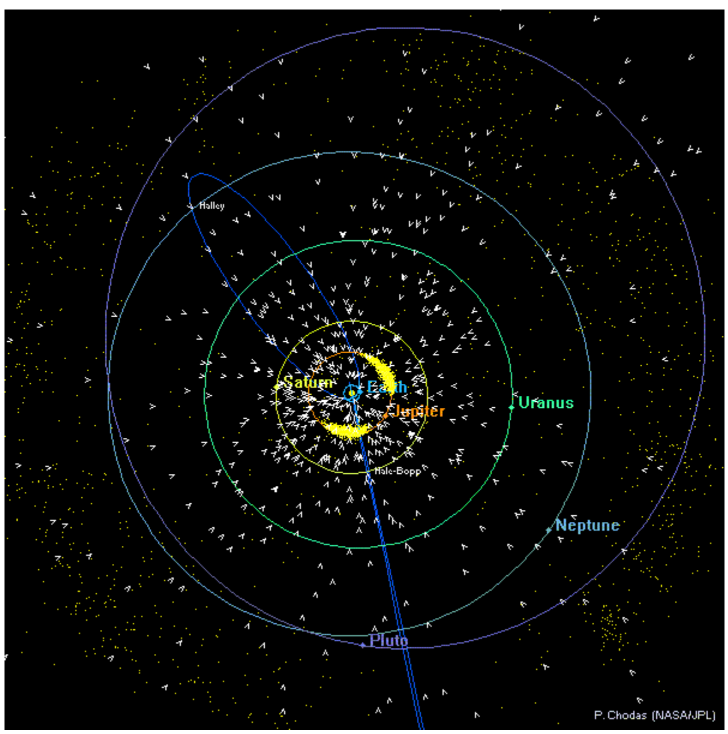


Figure P1. The Sun and the planets shown at the right relative sizes but not at the right relative distances from each other. (Picture courtesy of Calvin J. Hamilton; http://www.solarviews.com/cap/misc/ss.htm)

Planets and Orbits Transparency #2



A



B

Figure P2. Diagrams showing planets (in different color circles), asteroids (yellow dots) and comets (wedges) in the inner Solar System (A), and in the outer part of the planetary realm of the Solar System (B) on October 1, 2009. Also shown in the picture are the orbits of the planets Mercury, Venus, the Earth, Mars, and Jupiter (A) and the Earth, Jupiter, Saturn, Uranus, and Neptune, as well as the orbits of the dwarf planet Pluto and the comets Halley and Hale-Bopp (B). These views of the Solar System are from above the north pole of the Sun, high above the plane of the Earth's orbit around the Sun. (Picture credit: Paul W. Chodas, NASA/JPL; http://ssd.jpl.nasa.gov/?orbits)

Planets and Orbits Transparency #3

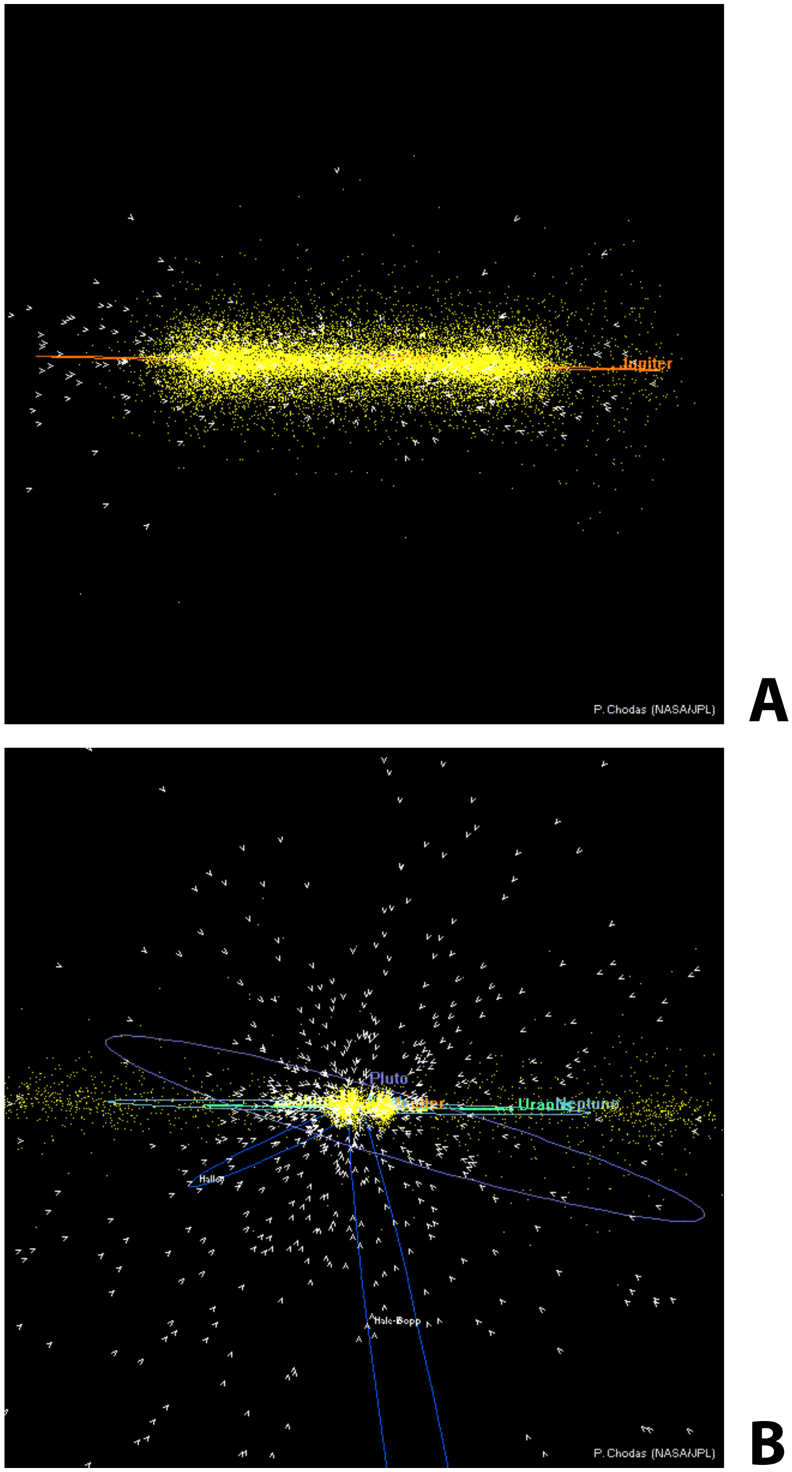


Figure P3. Diagrams showing the planets (in different color circles), asteroids (yellow dots) and comets (wedges) in the inner Solar System (A), and in the outer part of the planetary realm of the Solar System (B) on October 1, 2009. Also shown in the picture are the orbits of the planets Mercury, Venus, the Earth, Mars, and Jupiter (A) and the Earth, Jupiter, Saturn, Uranus, and Neptune, as well as the orbits of the dwarf planet Pluto and the comets Halley and Hale-Bopp (B). These views of the Solar System are from the edge of the plane of the Earth's orbit around the Sun; the viewing angle is rotated 90° from the pictures in Fig. P2. (Picture credit: Paul W. Chodas, NASA/JPL; http://ssd.jpl.nasa.gov/?orbits)

Young Stars Transparency #1

Figure Y1. A picture of the Orion Nebula taken with the Hubble Space Telescope. Stars are being formed inside these kinds of nebulae: interstellar clouds made of massive quantities of gas and dust spread over a large area. Over millions of years, the gas molecules and dust particles come together and start to form stars. Each side of the picture above is about 4 parsecs, or 13 light years, or 1.2×10^{14} km; or 7.6×10^{13} miles; or 8,000 Solar Systems wide (if the size of the Solar System is estimated as 100 times the average distance from the Earth to the Sun.) There is enough material in the cloud to form hundreds of thousands of stars as massive as the Sun; about 3,000 young stars of various sizes can be found in the picture. (Picture credit: NASA/ESA/M.Robberto (STScI/ESA)/Hubble Space Telescope Orion Treasury Project Team; http://hubblesite.org/gallery/album/entire_collection/pr2006001a/)

YOUNG STARS TRANSPARENCY #2

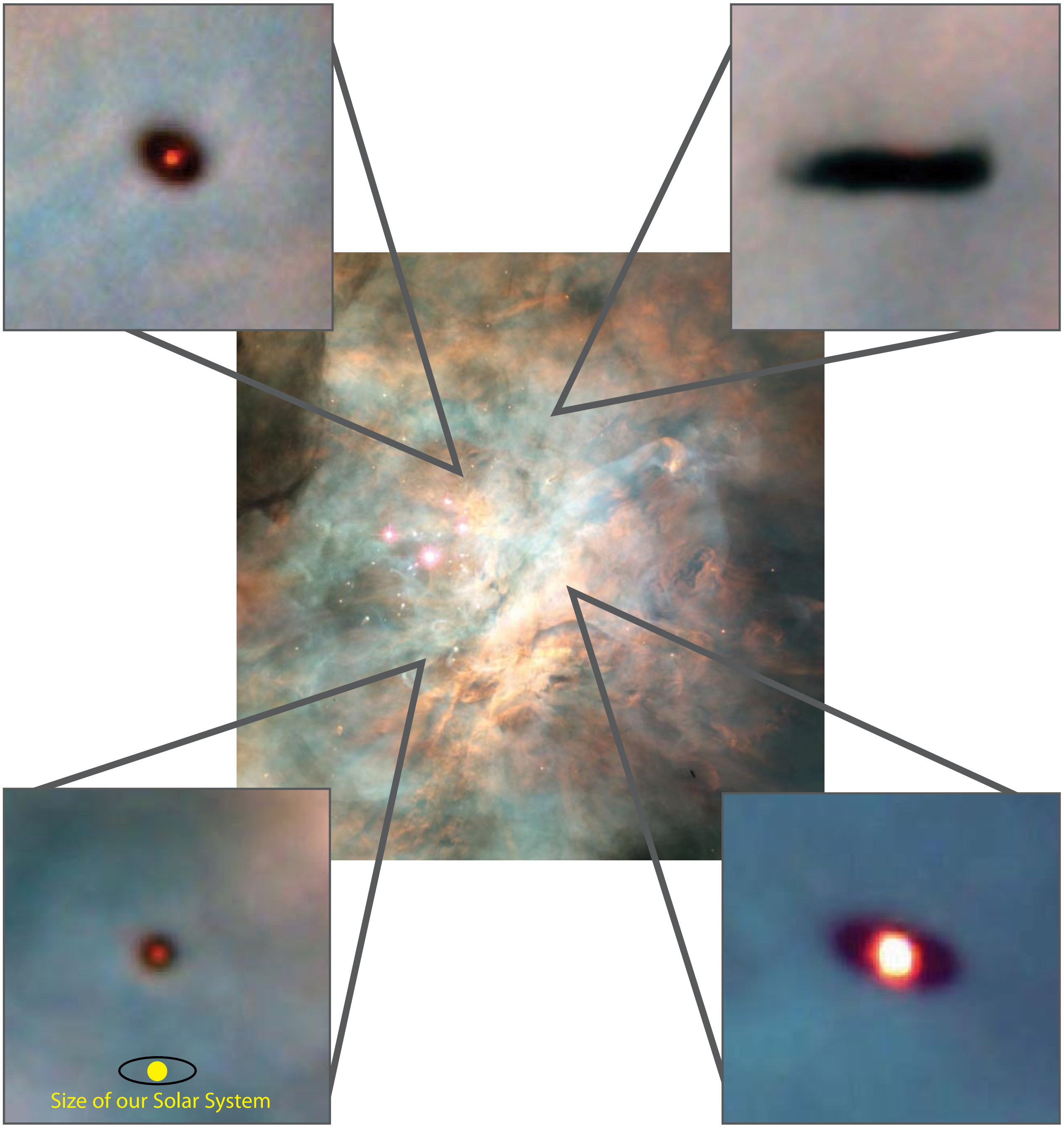


Figure Y2. A closeup view of the Orion Nebula shows that there are objects inside it where young stars (bright/red points in the callout boxes) are surrounded by a dark, disk-like patch of material. In some cases (the upper right-hand box), the disk is seen edge-on, and the star is hidden from our view by the disk material, while in others, the system is seen from the top or from an angle (the other three callout boxes.) The lower left-hand box shows that the disk structures are about the size of the Solar System. Many objects like this have been discovered in interstellar clouds where stars are being born. (Picture credit: NASA/ESA; http://hubblesite.org/gallery/album/entire_collection/pr1995045a/; http://hubblesite.org/gallery/album/entire_collection/pr1995045b/; http://hubblesite.org/gallery/album/entire_collection/pr1995045c/;)

Formation of the Solar System

Name: ______________________ **Date:** ______________________

Introduction

You will look for patterns in Solar System data to create a hypothesis for the formation of the Solar System.

I. Describe, Compare, and Search for Patterns

Examine carefully the *Planets and Orbits Transparency* and Table S1. Discuss within your group any patterns you detect among the objects in the Solar System in terms of size, shape, composition, distance from the Sun, orbital inclination, orbital direction, etc. Come up with at least five general trends or patterns and write them down below. The patterns may cover all Solar System objects, or just a subgroup. The patterns may also cover just most of the objects in the subgroup, not always all of them. For example: There seems to be two categories of planets in terms of size; the innermost four can be grouped together as small inner planets, the other four can be grouped together as giant outer planets.

Pattern 1: ______________________

Pattern 2: ______________________

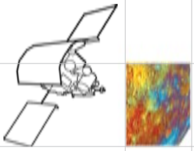
Pattern 3: ______________________

Pattern 4: ______________________

Pattern 5: ______________________

Table S1. Properties of Solar System objects. The table includes the actual values for the Sun and the planets, and ranges of values for asteroids, comets and Kuiper Belt Objects. Please note that the numbers for the three group entries may change as new objects are discovered and more accurate measurements are made. The distances from the Sun are given in terms of Astronomical Unit (AU), which is the average distance between the Earth and the Sun, or 150 million km (93 million miles). *(Data from NASA National Space Science Data Center's Planetary Fact Sheets http://nssdc.gsfc.nasa.gov/planetary/planetfact.html; International Astronomical Union Minor Planet Center's Transneptunian Object List http://cfa-www.harvard.edu/iau/lists/TNOs.html; NASA/JPL Small Body Database http://ssd.jpl.nasa.gov/sbdb_query.cgi; Nine Planets web site http://www.nineplanets.org/, and references therein.)*

	The Sun	Mercury	Venus	Earth	Mars	Jupiter	Saturn
Mean Distance from the Sun (Astronomical Units, AU)	N/A	0.387	0.723	1.000	1.524	5.204	9.582
Mass (Earth masses)	333,000	0.055	0.815	1.000	0.107	31.8	95.2
Orbital Period; or Length of One Year	N/A	88 days	225 days	365.3 days	687 days	11.86 Earth years	29.46 Earth years
Diameter (kilometers)	1,390,000	4,880	12,300	12,800	6,790	143,000	121,000
Rotation Period	25 Earth days	59 Earth days	244 Earth days retrograde[1]	23 hours, 57 min	24 hours, 37 min	9 hours, 56 min	10 hours, 39 min
Main Composition	Gas	Rocky	Rocky	Rocky	Rocky	Gas	Gas
Atmosphere (main components)	Hydrogen, Helium	Virtually a vacuum	Carbon Dioxide	Nitrogen, Oxygen	Carbon Dioxide	Hydrogen, Helium	Hydrogen, Helium
Orbital Eccentricity	N/A	0.21	0.0067	0.017	0.095	0.049	0.057
Orbital Inclination (degrees)	N/A	7.0	3.4	0.0	1.9	1.3	2.5
Orbital Direction (as seen from the Sun's north pole)	N/A	Counter-clockwise	Counter-clockwise	Counter-clockwise	Counter-clockwise	Counter-clockwise	Counter-clockwise
Number of Moons	N/A	0	0	1	2	63	61



	Uranus	Neptune	Pluto (dwarf planet)	Asteroids	Comets	Kuiper Belt Objects
Mean Distance from the Sun (Astronomical Units, AU)	19.201	30.047	39.482	Most between 1.1 - 3.0; some 14	2.2 – 1,170; perhaps up to 50,000	30-50; maybe up to 135
Mass (Earth masses)	14.5	17.1	0.00021	Much less than one-billionth to 0.00015	Much less than one-billionth	Varies; possibly up to 0.00021 or slightly more
Orbital Period; or Length of One Year	84.01 Earth years	164.79 Earth years	247.68 Earth years	Most between 1.1 and 5.2 Earth years; some 51 Earth years	3.3 – 40,000 Earth years; maybe more for very distant objects	Typically 200-300 Earth years; maybe up to 770 Earth years
Diameter (kilometers)	51,100	49,500	2,390	1 to 960	A few to 20	37-200; maybe up to 2,400
Rotation Period	17 hours, 14 min retrograde[1]	16 hours, 7 min	6 days retrograde[1]	2.3 to 418 hours	3 to 70 hours	3 hours to a few Earth days
Main Composition	Gas, ice and rock	Gas and Ice	Ice and rock	Rocky	Ice and rock	Ice and rock
Atmosphere (main components)	Hydrogen, Helium, Methane	Hydrogen, Helium, Methane	Methane, Nitrogen	None	None (except as material blown off the nucleus when near the Sun)	Probably none
Orbital Eccentricity	0.046	0.011	0.25	0.1-0.8	0.5 – 0.9998	0.01 – 0.37
Orbital Inclination (degrees)	0.77	1.8	17	0.9 - 35	4 - 162	0.2 - 48
Orbital Direction (as seen from the Sun's north pole)	Counter-clockwise	Counter-clockwise	Counter-clockwise	Counter-clockwise	Varies	Mostly counter-clockwise
Number of Moons	27	13	3	0 to 1	Unknown	0 to a few

[1] Note on the Rotation Period row in Table 1: One can imagine looking down on the Solar System from high above the Sun's north pole. From this vantage point, most of the planets are seen to rotate on their axes counterclockwise. However, Venus, Uranus, and the dwarf planet Pluto (as well as many other small objects), are seen to rotate clockwise and are said to be rotating 'retrograde'. On the surface of an object with retrograde rotation, the Sun would appear to rise from the west and set in the east.

II. Explain Similarities and Differences

Come up with an explanation for each pattern you identified in Part I: what could have caused it? Provide one explanation per pattern:

Explanation for Pattern 1: ______________________________

____

____

____

Explanation for Pattern 2: ______________________________

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Explanation for Pattern 3: ______________________________

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Explanation for Pattern 4: ______________________________

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Explanation for Pattern 5: ______________________________

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III. Hypothesis for the Formation of the Solar System

Write a paragraph about how you think the Solar System was formed, based on your observations of and explanations for the trends or patterns in the Solar System. Be sure to include why you think that the Solar System formed the way you think it did. Be prepared to present your hypothesis to the whole class and to defend it with your observations.

Tugging the Star

Materials

- Grapefruit
- 3 small balls of different masses
- Binder clip (medium-size)
- Black marker
- Cardboard tube
- Laboratory scale
- Packaging tape
- Paperclip (small)
- Ruler
- Scissors
- Sheet of white paper at least 50 cm long (about 1.5 ft)
- 4 short pieces of string (each about the length of your hand)
- 2 long pieces of string (each at least 1 m; 3.3 ft long)

Name: ______________________________

Date: ______________________________

Introduction

You will construct an apparatus with a model star (grapefruit) and a model planet (small ball) to see how the presence of a planet around a star can affect the star.

Preparation

1. Measure the length of the cardboard tube:

   Length of tube: ____________________ cm

2. Measure the masses of the three small balls. These represent three planets of different masses.

   Mass of model planet 1: ____________________ g

   Mass of model planet 2: ____________________ g

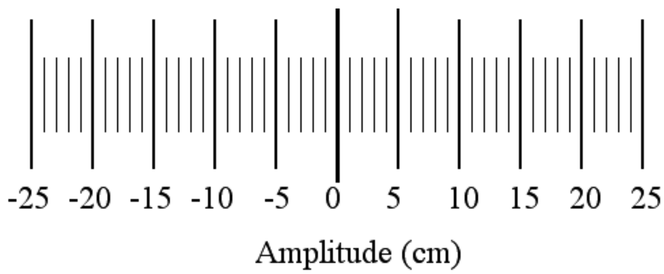
   Mass of model planet 3: ____________________ g

3. Measure the mass of the grapefruit. This is your model star.

   Mass of model star: ____________________ g

Constructing the Apparatus

1. Use a black marker to draw an amplitude scale similar to the one below on a sheet of paper. Make sure that the scale is at least as long as your cardboard tube in both positive and negative directions. For example, if your tube is 25 cm long, draw the amplitude scale at least from -25 cm to 25 cm.



2. Tape a short piece of string (about the length of your hand) to the model star (see Figure S1.) Tape the three other short pieces of string to the model planets. Make sure the strings are secure enough that the model star and planets can hang from them.

3. Thread a long piece of string through the tube by taping a paper clip to the end of the string, and then dropping the paper clip through the tube. The clip will pull the string through. (Tip: You may have to straighten the paper clip to fit it through the tube. You also may have to shake the tube slightly to make the clip slide through.) Remove the paper clip from the string. Tie the ends of the string together, leaving a little slack, so that you have a triangle shape with the tube at one side.

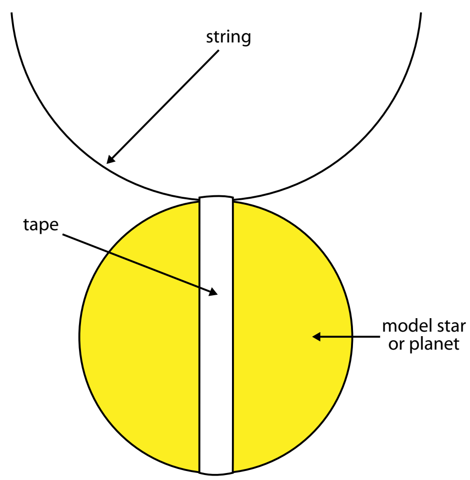


Figure S1. Setup for the model star and the model planets. Tape a short piece of string to the model star and the model planets and make sure the strings are securely attached.

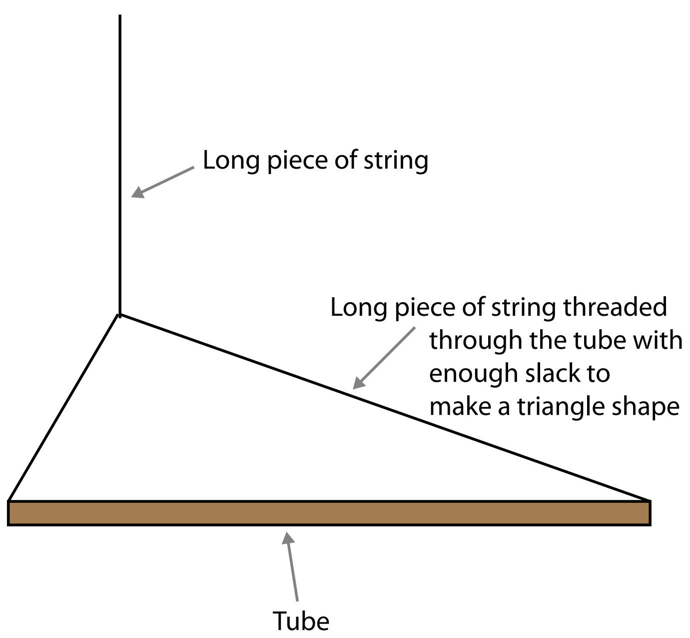


Figure S2. The setup for the basic experiment apparatus: thread a long piece of string through the tube, and tie the ends of the string together to form a triangle shape with the tube on one side. Loop a second long piece of string around the first.

4. Take the second long piece of string, loop it around the first, and tie its ends together (see Figure S2). NOTE: this second loop must be able to slide freely along the first string.

5. Hang the second long string from the ceiling close to a wall (but far enough away from the wall that the apparatus can rotate without hitting the wall), so that the apparatus is at about eye level.

Experiment

1. Attach the amplitude scale you made earlier to the wall behind the apparatus at eye level, so that when you step a couple of feet away, you can see the scale right behind the model star and the model planet, with the center of mass of the system (the point where the strings come together under the binder clip) is right over the zero line of the amplitude scale.

2. Tie the string attached to the model star to one end of the tube. Select the lowest mass ball as your first model planet and tie the string attached to it to the other end of the tube (see Figure S3.)

3. Find the center of mass of the model star-planet system. To do this, slide the loop hanging from the ceiling back and forth along the loop threaded through the tube until you find the spot where the tube hangs horizontally. You can slowly rotate the apparatus around the string hanging from the ceiling to make sure the tube remains horizontal as it rotates. At this point, the two-body system

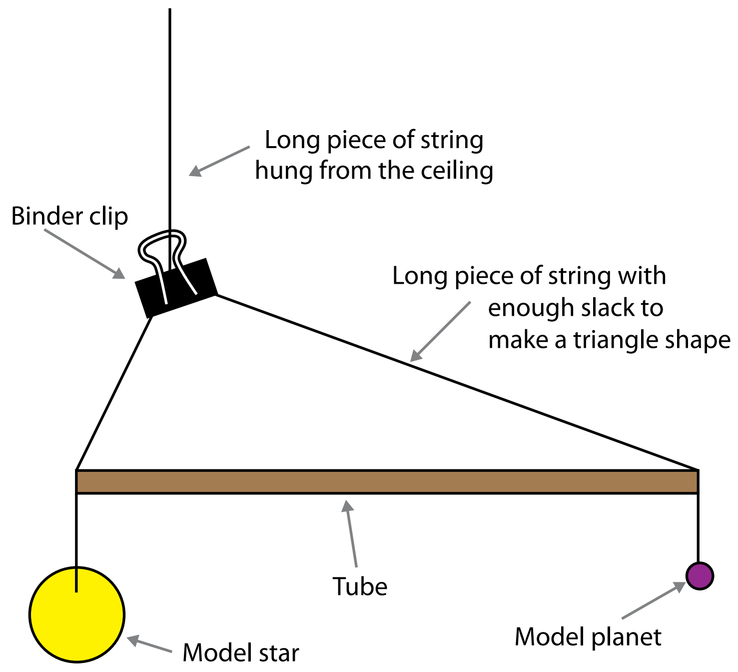


Figure S3. The setup for the apparatus. One long piece of string is threaded through the tube. A second long piece of string is looped through the first and hung from the ceiling so that the apparatus is roughly at eye level. The model star and the model planet are attached to the ends of the tube by the strings attached to the models. A binder clip is used to secure the apparatus once the center of mass of the system is located.

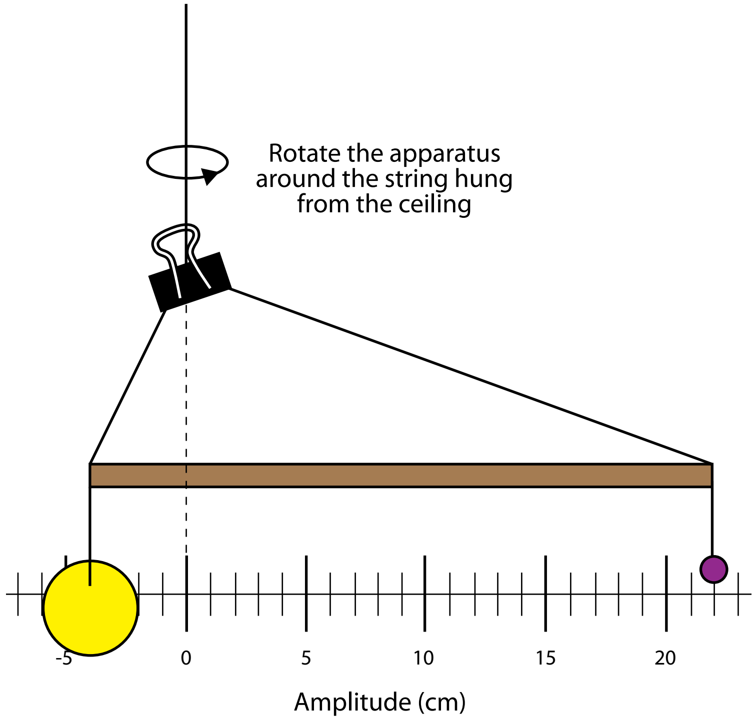


Figure S4. As the apparatus rotates around its center of mass, the amplitudes of the rotation (that is, the maximum distances from the 0 mark) for the model star and the model planet can be observed.

(model star-planet) is balanced; you have located the center of mass of the system. Use a binder clip to secure the point where the two long loops of string connect so that when you let go of the strings, they do not slide and the tube still hangs horizontally.

4. Have one member of your team slowly rotate the apparatus around its center of mass, making sure that the tube stays horizontal (see Figure S4). Another member stands a couple of feet away to monitor the apparatus as it rotates to make sure the center of mass remains at the zero mark of the amplitude scale. This person can then observe the amplitudes of the rotation for the model star and the model planet as they rotate around the center of mass of the system; that is, observe the maximum distances of the model star and planet from the 0 mark during their rotation. [For example, in Figure S4, which shows a sample system at a time when both the model star and the model planet have rotated to their maximum distances from the 0 mark, the model star is at the -4 mark, and so its amplitude is 4 cm, while the model planet is at the +22 mark, making the amplitude of its rotation 22 cm.] Have the third member of your team record the amplitudes for your model star and model planet in the Data Table on the next page.

5. Remove the model planet from the apparatus by cutting the string connecting it to the apparatus. Replace it with another model planet with a different mass. Repeat the experiment (Steps 1-4) with the second and third model planets to fill in the Data Table.

Data Table

Mass of the model planet (g)	Amplitude of rotation of the model star (maximum distance from the model star to the center of mass) (cm)	Amplitude of rotation of the model planet (maximum distance from the model star to the center of mass) (cm)

Questions

1. What does the tube represent in the model? (Hint: what is the connection between the real star and the real planet?)

____

____

2. What is the trend you observe in the Data Table between the mass of the model planet, and the resulting amplitude of the model star's rotation?

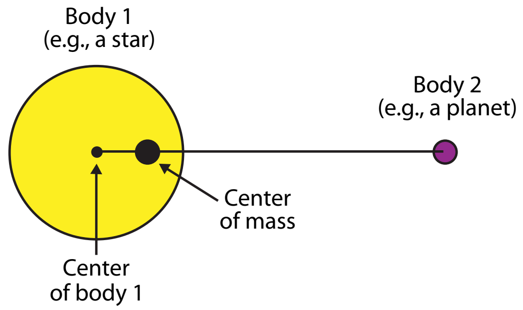
____

____

3. The situation you investigated in the experiment is a model of a two-body system (see illustration below), in which case the center of mass can be calculated from the formula

$$r_1 = r_{tot} * \frac{m_2}{(m_1+m_2)}$$

where r_1 is the distance from the center of body 1 to the center of mass, r_{tot} is the distance between the two bodies, and m_1 and m_2 are the masses of the two bodies.



Let's designate the model star as body 1 and the model planet as body 2 in your experiment. Calculate the location of the center of mass (the distance from the center of body 1) for each case:

a) model planet 1: r_1 = ______________________________ cm

b) model planet 2: r_1 = ______________________________ cm

c) model planet 3: r_1 = ______________________________ cm

4. In your experiment, the masses of the model star and planets are more similar than is typically the case for a real planet and a real star. Using the formula on the previous page and the data in Table S2, and assuming body 1 = the Sun and body 2 = the planet, calculate the center of mass for:

a) the Sun – Jupiter system:

b) the Sun – the Earth system:

c) the Sun – Mercury system:

For each case, also determine whether the center of mass is inside or outside the surface of the Sun by comparing the value you calculated (that is, the distance from the center of the Sun to the center of mass) to the radius of the Sun. Write your answers next to to the numerical values above.

Table S2. Properties of a few Solar System objects.

	The Sun	Mercury	Earth	Jupiter
Mean Distance from the Sun (km)	0.0	5.79×10^7	1.50×10^8	7.79×10^8
Mass (kg)	1.99×10^{30}	3.30×10^{23}	5.97×10^{24}	1.90×10^{27}
Diameter (km)	1,390,000	4,880	12,800	143,000

5. Imagine that we modify the experiment so that the model planet is not visible (for example, if the model planet was a clear glass ball which you cannot see from a few feet away) and you could only observe the behavior of the model star. Imagine another case where there is no model planet in the system at all, just the model star. How could you tell the difference between the two systems from a distance based on just what you can observe of the behavior of the model star?

6. Since planets around other stars are very difficult to see directly, scientists are searching for these so-called extrasolar planets by trying to detect the rotation of the star around the center of mass caused by the presence of a planet; this effect is often called stellar wobble. This is exactly what you modeled in your experiment. [One big difference is that instead of an amplitude scale against which to measure the wobble, the scientists have to use the positions of other, background stars which do not move (or at least do not move as rapidly as the observed star wobbles) as the basis for measuring the effect.] Based on the experiment and your calculations, what kind of planets are most likely to be detected this way?

Answer Key

Student Worksheet 1

I. Describe, Compare, and Search for Patterns

Answers will vary. Note that the patterns may cover all Solar System objects, or just a subgroup. The patterns may also cover just most of the objects even in the subgroup, not always all of them. All answers that are supported by data given to the students are acceptable. Some examples of patterns include:

1) Sizes: There appear to be two categories among planets: small planets close to the Sun and large planets farther away. Among other Solar System objects, there are small bodies throughout the Solar System: asteroids mostly between the orbits of Mars and Jupiter; Kuiper Belt objects in the outer parts, and comets throughout (but mostly in the outer parts.)

2) Compositions: There appear to be two main categories among the planets: rocky, Earth-like planets close to the Sun and gaseous, Jupiter-like planets farther away (sometimes mixed with rock and ice). The students may also find three planet categories, such as rocky planets, gas giants and gas-ice giants. Among other Solar System objects, rocky asteroids are located mostly between the orbits of Mars and Jupiter; icy Kuiper Belt objects in the outer parts, and icy comets throughout (but mostly in the outer parts.) The amount of ice in the objects seems to increase as one goes further away from the Sun.

3) Orbits: Planets orbit the Sun in almost circular orbits, except for Mercury. The small bodies in the Solar System (including the dwarf planet Pluto) seem to have a variety of orbital shapes.

4) Orbital direction: All objects orbit the Sun in the same direction (except for comets, some of which orbit in the opposite direction.)

5) Orbital distances: Inner planets orbit the Sun with smaller average distances between them; outer planets are further apart.

6) Orbital inclination: The planets orbit the Sun in pretty much the same plane. Dwarf planets (such as Pluto), asteroids and Kuiper Belt objects orbit the Sun close

to but not quite on the same plane. Comets can have large orbital inclinations.

7) Moons: The giant planets have lots of moons, while the smaller planets have fewer moons; the closest planets to the Sun, Venus and Mercury, have none. The dwarf planet Pluto, some asteroids and Kuiper Belt objects also have moons.

8) Atmospheres: A lot of variety for planetary atmospheres, except for the giant planets, which have atmospheres made of mostly hydrogen and helium (same as the Sun.)

9) The Sun seems to be in a category all its own. It is by far the biggest and most massive object, and it is located near the center of the Solar System. [Note: The Sun is near but not exactly at the center of the Solar System, since that is located at the center-of-mass of the whole system, and so slightly offset from the center of the Sun; this effect will be discussed in Activity 2 but is not important for the present purposes.]

II. Explain Similarities and Differences

Answers will vary. All explanations that could explain the patterns the student observed in Part I are acceptable. The possible explanations for the patterns described above include:

1) There may have been more material from which to make planets in the regions where the giant planets formed. There may have been less material both close to the Sun and in the outer parts of the Solar System.

2) Heat from the Sun may have made it difficult for gas and ice to exist in the inner Solar System; that is why the small inner planets are rocky. There may have been more gas in the region where the gas giants formed. Even further out, more ice existed, and the composition of the objects becomes increasingly icy.

3) Planets may have formed in circular orbits, but perhaps the other objects did not. Or perhaps all objects formed in circular orbits but the orbits of the smaller objects changed over time to become more eccentric. (Scientists now think that the latter explanation is the correct one, but either is an acceptable answer to this question based on the data available to the students.)

4) Planets (and other objects) may have formed from a structure that was rotating

around the Sun in the same direction.

5) Massive planets may have needed more space from which material was gathered to form their bulk, making it necessary for large gaps to exist between the planets. Perhaps the smaller planets needed less space from which the material came to form the planets, so they could form closer together. (Scientists now think that the gravitational interactions between the forming planets also have made the distances between the planets to what they are today, but the students cannot be expected to know this based on the data given to them.)

6) Planets may have formed from a structure that was very thin, like a disk. Maybe the other objects formed some other way. (Scientists think that all objects in the Solar System formed from a thin disk that later dissipated, leaving the currently observed objects behind. The objects that no longer orbit the Sun in the plane of the former disk were probably scattered into their present orbits by gravitational interactions with planets during the early history of the Solar System. However, the data provided to the students is not sufficient to make this determination.)

7) Large planets may have had a lot of material left over from when they formed; maybe this material became the many moons they have today. Smaller planets may have had less material from which to make the moons. (Scientists now think that many moons of the smaller Solar System objects were either captured through gravitational interaction or formed after a massive collision, but the students cannot be expected to know this based on the provided data.)

8) Hydrogen and helium may have been the main gases in the forming Solar System. The larger objects were able to hold onto these light gases while smaller objects were not.

9) The Sun may have formed near the center of the Solar System (and maybe formed first) and the planets formed from the material around the young Sun.

III. Hypothesis for the Formation of the Solar System

Answers will vary. All answers are acceptable as long as they can be supported by the observations of the Solar System data and the explanations the students have for the patterns. See the *Science Overview* for the description of the current standard theory for the formation of the Solar System.

Student Worksheet 2

Data Table

Answers will vary. Example values below are based on a 39-cm long tube, a 540-g grapefruit as the model star, and a 180-g softball, a 145-g baseball and a 50-g golf ball as the model planets.

Mass of the model planet (g)	Amplitude of rotation of the model star (maximum distance from the model star to the center of mass) (cm)	Amplitude of rotation of the model planet (maximum distance from the model star to the center of mass) (cm)
50	5	34
145	10	29
180	12	27

Questions

1. The tube represents the gravitational force between the real planet and the real star.

2. The results should be similar to the sample data table and show that the more massive the model planet, the larger the resulting amplitude of the model star's rotation.

3. Answers will vary; example answers based on the system shown in the Data Table above:

   a) 3.3 cm

   b) 8.2 cm

   c) 9.8 cm

4. a) 743,000 km (462,000 miles) from the center of the Sun; the center of mass is outside the Sun.

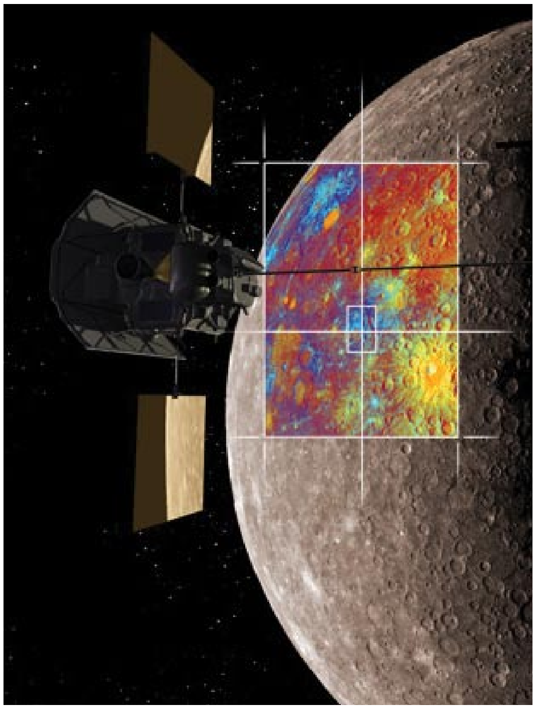
   b) 450 km (280 miles) away from the center of the Sun; the center of mass is inside the Sun.

   c) 9.6 km (6.0 miles) away from the center of the Sun; the center of mass is inside the Sun.

5. In the system with a model planet, the model star would rotate around the center of mass of the model star-planet system, while in the system without a model planet, the model star would not be observed moving against the amplitude scale.

6. A massive planet (such as Jupiter). If the student analyzes the formula for the location of the center of mass, it is possible to conclude that the planet at a greater distance is easier to see (since the effect is more pronounced), but this conclusion is not required.

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.

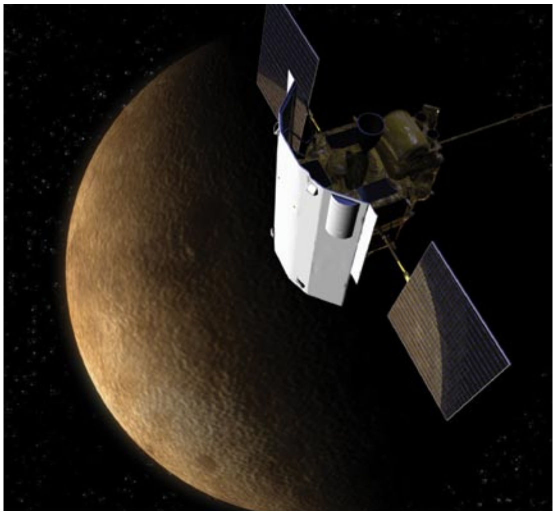
MESSENGER will be only the second spacecraft ever to study Mercury: In 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for one Earth year; its close-up observations will allow us to see the entire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

Additional Science Topics
In addition to improving our understanding of Mercury today, MESSENGER will also give a lot of information on the formation and later evolution of the planet, which in turn will provide clues to the formation and the early history of the whole Solar System, and especially of Earth-like planets. MESSENGER will also investigate the space environment close to the Sun, in this manner helping scientists gain a better understanding of the Sun's influence at a close distance. Since most of the extrasolar planets discovered to date are at similar distances from their parent stars as Mercury is from the Sun, MESSENGER's investigation will provide a unique perspective on comparing the properties of planetary systems across the Universe.

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 will explore the physical conservation laws by observing the behavior of balls colliding with other objects. In Activity 2, the students will 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

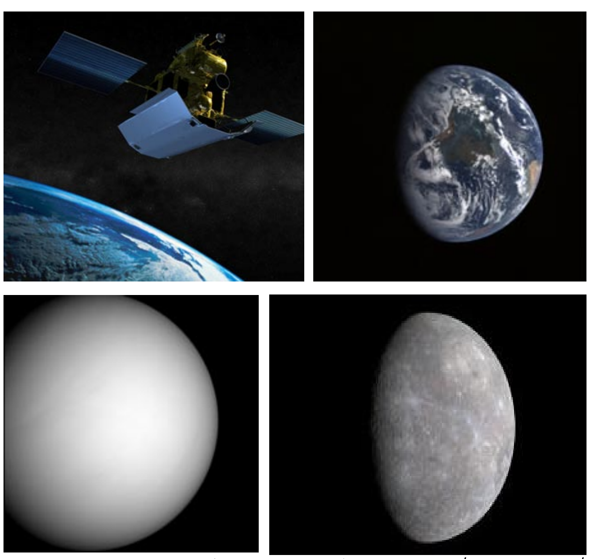


Figure 1. Gravity assists are an important part of spacecraft mission design today. Not only can they speed up the journey to explore distant worlds, but they also make it possible to conduct missions otherwise considered impossible. For example, after the launch of the MESSENGER spacecraft in 2004 (an 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)

This lesson was developed by the National Center for Earth and Space Science Education (http://ncesse.org).

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

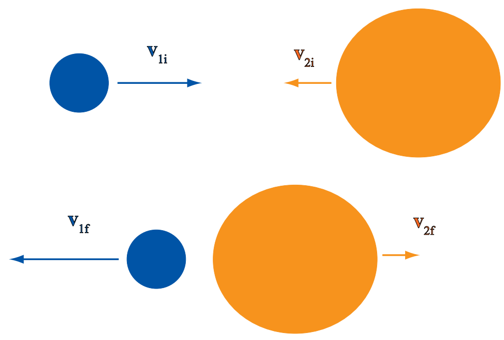


Figure 2. Momentum is conserved in an elastic collision of objects with masses m_1 and m_2. The sum of the mass times the initial velocities ($\mathbf{v}_{1i}$, $\mathbf{v}_{2i}$) of the two objects is equal to the sum of the mass times the final velocities ($\mathbf{v}_{1f}$, $\mathbf{v}_{2f}$) of the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

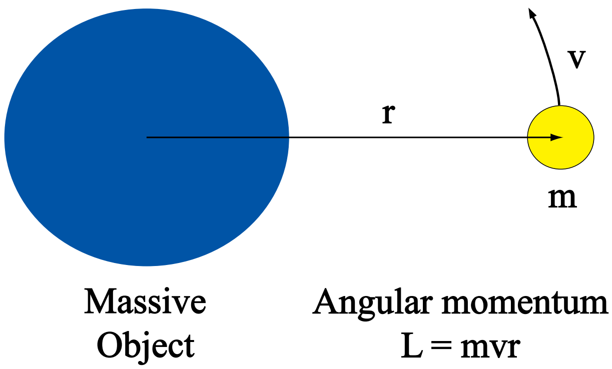


Figure 3: A small mass (m) orbiting a larger massive object at a distance r with a velocity v has an angular momentum of magnitude L = mvr.

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.

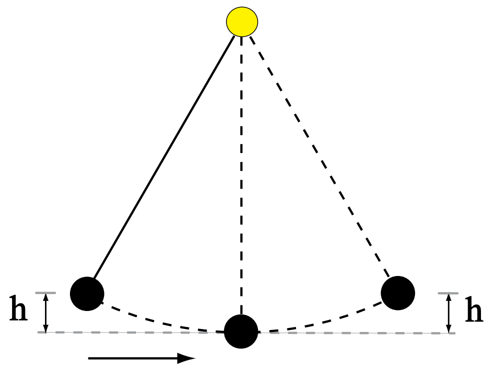


Figure 4. When a pendulum swings back and forth, potential energy changes to kinetic energy and back again, but the total amount of energy remains constant (if no energy is lost due to friction.)

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

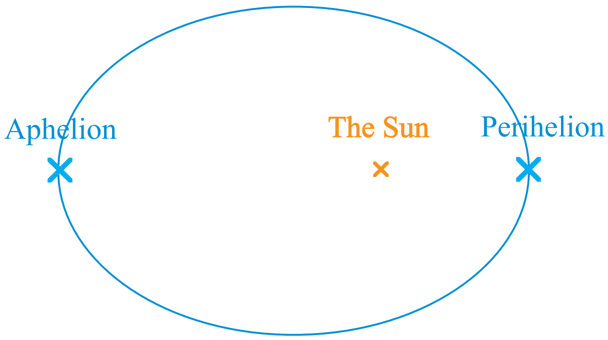


Figure 5. The orbit of a planet around the Sun. During an orbit, the planet's orbital velocity changes from the minimum at aphelion (the furthest point from the Sun) to the maximum at perihelion (the closest point to the Sun), as the potential energy is converted to kinetic energy and back again. The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

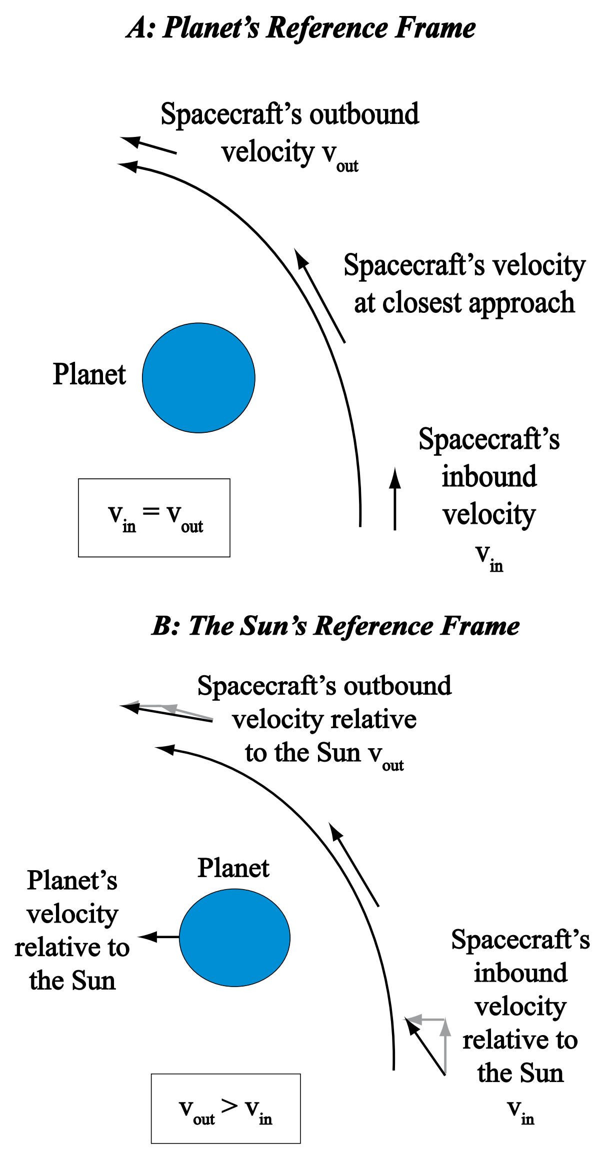


Figure 6. Schematic of the interaction during a gravity-assist maneuver. Case A (top) shows the interaction with respect to the planet. The magnitudes of the inbound and outbound velocities of the spacecraft (v_{in} and v_{out}) are the same (though the direction a little different) relative to the planet 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 ($\boldsymbol{F} = m\boldsymbol{a}$), 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

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

Name: ______________________________

Date: ______________________________

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.

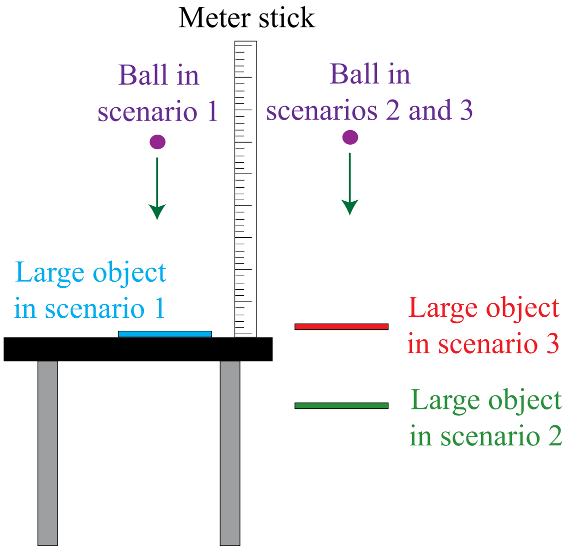


Figure S1. Setup for the experiment. Place a meter stick on the table so that it is standing perpendicular to the surface, close to the edge of the table, and so that the 0 cm mark is at the table's surface (except in scenario 1, where you place the meter stick on top of the large object.) Have one person 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?

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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:

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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?

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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.

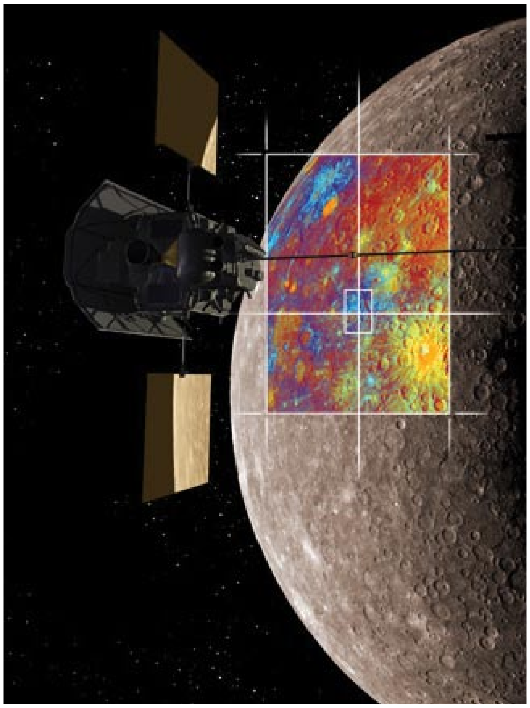
    c) The gravitational force is greater closer to the planet, so in the "1 million km" trajectory the force is the greatest. We know this because the speed increases the most in this trajectory and the path changes the most.
12. a) In the closest trajectory (1 million km) the speed of the spacecraft changed 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.

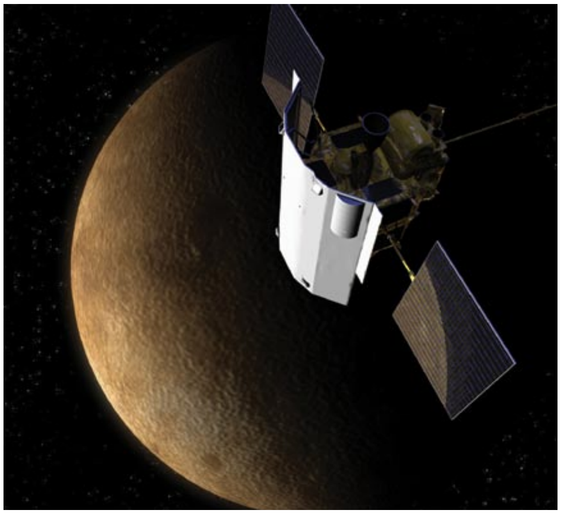
MESSENGER will be only the second spacecraft ever to study Mercury: In 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for one Earth year; its close-up observations will allow us to see the entire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

Can You Hear Me Now?

Communicating with Spacecraft

Lesson Overview

Lesson Summary

In this lesson, students examine the essential role of computers and communications in space exploration: scientists must tell robotic spacecraft how to operate, gather data, and send the data back to the Earth for analysis. The students investigate various ways to improve mission design to maximize the scientific return. In the first activity, the students examine how the use of flowcharts can help make computer programs error-free and efficient, in this way making the spacecraft more reliable. In the second activity, the students investigate how data can be compressed for transmission over limited bandwidth. By the end of the lesson, the students come to realize that the wealth of data gathered by spacecraft is useless if it cannot be transmitted safely and efficiently to the scientists on the Earth.

Grade Level
9–12

Duration
Two 45-minute class periods

Essential Question

Considering the vast distances in space, how is data transmitted from spacecraft to scientists on the Earth?

Lesson 3
of the Grades 9-12
Component of the
Mission Design
Education Module

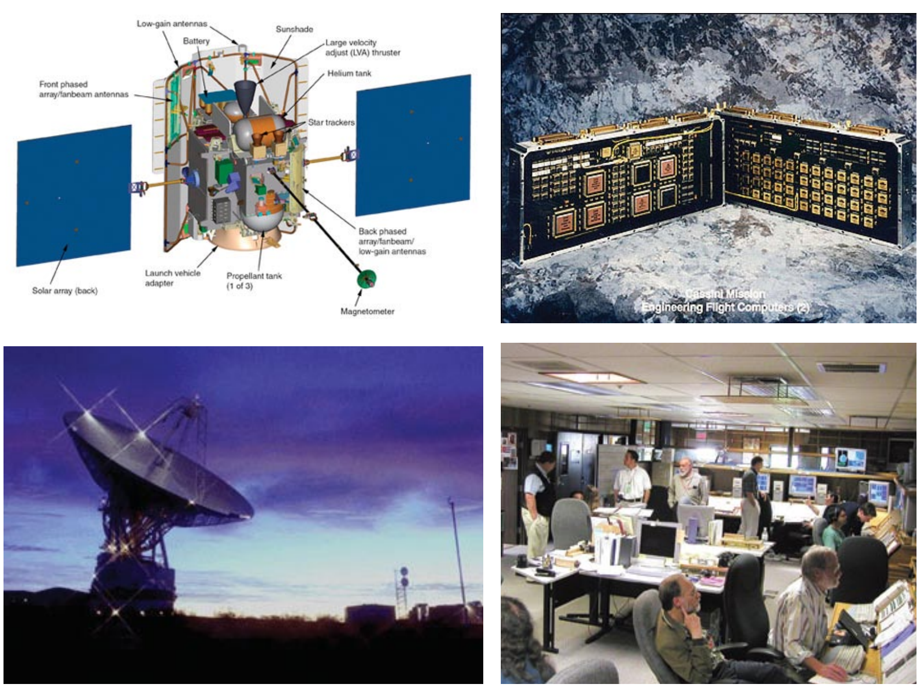


Figure 1. Robotic spacecraft cannot operate without reliable computers and communication protocols with ground control on Earth. Careful planning of these aspects is essential for all spacecraft mission designers, from planning the basic structure of the spacecraft (schematic of the MESSENGER spacecraft, top left), to constructing computer systems capable of operating in the harsh space environment (command and data subsystem from the Cassini spacecraft, top right), scheduling communication times with the spacecraft through NASA's Deep Space Network (a Deep Space Network antenna in Goldstone, CA; bottom left), and having a Mission Operations Center monitor the behavior of and communicate with the spacecraft (Mission Operations Center of the Gravity Probe B spacecraft at Stanford University; bottom right.) (Picture credits: NASA/ JHU-APL/CIW: http://messenger.jhuapl.edu/spacecraft/overview.html; NASA/JPL: http://saturn.jpl.nasa.gov/spacecraft/images/subsys-command.jpg; NASA: http://deepspace.jpl.nasa.gov/dsn/gallery/images/goldstone7.jpg; NASA/LM/SU: http://einstein.stanford.edu/Library/images/MOC-Mar05-1.jpg)

This lesson was developed by the National Center for Earth and Space Science Education (http://ncesse.org).

Objectives

Students will be able to do the following:

- Describe why careful design and implementation of computer programs is essential for spacecraft operations.
- Design a flowchart to describe the operation of a computer program.
- Explain how scientists select the optimum way for a spacecraft to compress and transmit data.

Concepts

- The vast distances between the planets make communication between spacecraft studying other worlds and the ground control on Earth difficult.
- Efficient, reliable computer programs are essential for making spacecraft missions to other worlds possible.
- Advances in computer technology have made more complicated missions possible and have enabled spacecraft to send more data back to the Earth.

MESSENGER Mission Connection

MESSENGER gathers data of Mercury, Venus, the Earth, and the environment around the Sun, and sends the data back to ground control. The long distances between the planets made it necessary for the MESSENGER scientists and engineers to consider the problems addressed in this lesson as they were designing the mission. This lesson shows students the basic principles behind the solutions that the mission design team came up with to make the MESSENGER mission to Mercury possible.

Standards & Benchmarks

National Science Education Standards

Standard A1: Abilities necessary to do scientific inquiry

USE TECHNOLOGY AND MATHEMATICS TO IMPROVE INVESTIGATIONS AND COMMUNICATIONS.

- A variety of technologies, such as hand tools, measuring instruments, and calculators, should be an integral component of scientific investigations. The use of computers for the collection, analysis, and display of data is also a part of this standard. Mathematics plays an essential role in all aspects of an inquiry. For example, measurement is used for posing questions, formulas are used for developing explanations, and charts and graphs are used for communicating results.

Standard A2: Understandings about scientific inquiry

- Scientists rely on technology to enhance the gathering and manipulation of data. New techniques and tools provide new evidence to guide inquiry and new methods to gather data, thereby contributing to the advance of science. The accuracy and precision of the data, and therefore the quality of the exploration, depends on the technology used.
- Mathematics is essential in scientific inquiry. Mathematical tools and models guide and improve the posing of questions, gathering data, constructing explanations and communicating results.

AAAS Benchmarks for Science Literacy

Benchmark 8E/H1:

- Computer modeling explores the logical consequences of a set of instructions and a set of data. The instructions and data input of a computer model try to represent the real world so the computer can show what would actually happen. In this way, computers assist people in making decisions by simulating the consequences of different possible decisions.

Benchmark 8D/H2:

- The quality of communication is determined by the strength of the signal in relation to the noise that tends to obscure it. Communication errors can be reduced by boosting and focusing signals, shielding the signal from internal and external noise, and repeating information, but all of these increase costs. Digital coding of information (using only 1's and 0's) makes possible more reliable transmission, storing, and processing of information.

Science Overview

Designing and constructing a spacecraft to study other worlds in the Solar System is a challenging process. The equipment onboard must operate in harsh surroundings: in the vacuum of space, in microgravity, in high or low temperature, and often in intense radiation environments. In addition to mechanical considerations, mission designers must make sure that the spacecraft is able to operate reliably on its own during much of the mission, communicate with the operators on the Earth—ground control—when needed, and transmit the gathered data safely to scientists for analysis.

Advances in telecommunications and computer technology have had a significant impact on space exploration. Before proper image capturing technology, scientists gathered data of other planets by drawing or writing down features of planets seen through a telescope. The results were dependent on what the scientists saw—or in some cases thought they saw—with their own eyes. Photographic plates increased the objectivity of astronomical observations, and further advances leading up to the development of modern digital camera systems have increased the reliability as well as the sheer amount of data that can be analyzed. These techniques, important for astronomical observations made through telescopes here on Earth, are also important for spacecraft sent to study other worlds in the Solar System.

Well-designed computers and communication tools are essential for the proper operation of spacecraft and therefore one of the most crucial subsystems in a spacecraft (e.g., Fig. 2.) Computers have been used in spaceflight since the early days of space exploration and in all aspects of the missions, from navigation to communications. Computers control much of the basic functions of the spacecraft, such as monitoring its direction, firing its engines, checking for equipment failure, and pointing its instruments in the desired direction. The basic operating software is stored in onboard computers before launch, and it guides the routine operation of the spacecraft. New commands and even new software can be transmitted to the spacecraft from ground control. Basic communication consists of

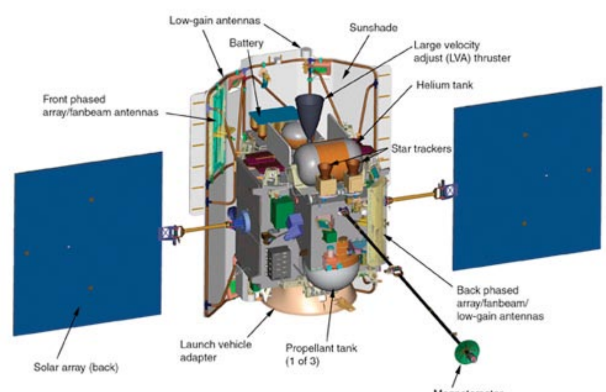


Figure 2. Schematic of the MESSENGER spacecraft. In designing a spacecraft mission such as the MESSENGER mission to Mercury, it is important to consider not only the instruments, power generation and engines, but also reliable computers and communication tools that are essential for robotic spacecraft. (Picture credit: NASA/ JHU-APL/CIW: http://messenger.jhuapl.edu/spacecraft/ overview.html)

either sending commands from the ground control to the spacecraft (uplink) or of the spacecraft transmitting data back to the Earth (downlink). Both are transmitted via radio waves. Since most spacecraft do not return to the Earth, they must be able to transmit the data back to Earth as accurately as possible. As a result, reliable communications with the spacecraft is one of the crucial aspects of planning successful space exploration.

Spacecraft venturing out to explore other worlds in the Solar System communicate with ground control on the Earth usually via the NASA Deep Space Network (DSN), which is an international network of antennas providing communications support for interplanetary spacecraft and even some Earth-orbiting missions. At present, DSN consists of three facilities located approximately 120 degrees apart in longitude around the world, so that spacecraft can be monitored constantly as the Earth rotates: at Goldstone, in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. Each facility includes several large parabolic dish antennas (see Fig. 3), which listen for the faint signals arriving from deep space. Data sent by a spacecraft and received by the DSN is sent to the mission control that is in charge of the spacecraft. The signals may contain information on the status of the spacecraft, in which case mission control may need to send instructions back to the spacecraft via DSN, or the data may be scientific data, in which case it is forwarded to scientists for analysis.

Figure 3. A radio antenna in Goldstone, CA; one of three NASA's Deep Space Network sites around the world. Spacecraft exploring the Solar System communicate with ground control using these kinds of large radio antennas. The antennas are used to both send commands to the spacecraft and receive gathered data. (Picture credit: NASA; http://deepspace.jpl.nasa.gov/dsn/gallery/images/goldstone7.jpg)

Data Transmission

Satellites operating near the Earth can receive commands almost continuously, but spacecraft venturing farther into the Solar System must be able to operate autonomously in-between receiving commands from ground control. This is because communication can only travel at the speed of radio waves; that is, the speed of light. Signals need to travel only a fraction of a second to reach near-Earth satellites, but it takes much longer to get to and from spacecraft exploring other worlds in the Solar System. For example, it takes radio signals over five hours to travel to the distance of

Pluto. As a result, robotic spacecraft need to be able to operate on their own long periods of time, since there may be situations where problems need to be solved immediately, and waiting for a reply is not feasible. In addition to the slow pace of communications, there are other difficulties in communicating with spacecraft traveling in deep space. For example, spacecraft operate within a limited power budget, whether they are solar-powered or use a nuclear power source. This causes the transmitted signals to be faint, and large radio antennas on the ground are needed to receive them. All these considerations require data transmission to be as efficient as possible.

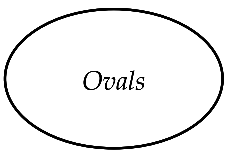
The basic unit of data in computer operations and communications is called a "bit." A bit is like a light switch: it can be either on or off. A single bit is represented as a one or a zero, and data is composed of long strings of ones and zeros. For example, the ASCII (American Standard Code for Information Interchange) encoding system uses eight-bit strings to represent text characters; e.g., "0110 0001" for the letter "a," "0100 0001" for the letter "A," "0110 0010" for the letter "b." This way text can be transmitted easily in digital format.

The rate of data transmission can be expressed in how many bits are sent in a second: the bit rate can be given as bps (bits per second), kbps (kilobits or thousands of bits per second) or mbps (megabits or millions of bits per second.) The bit rate of a typical home dial-up modem is about 56,000 bps (or 56 kbps). The typical download bit rate of a DSL ("Digital Subscriber Loop," or "Digital Subscriber Line") modem is between 128 kbps and 24,000 kbps (or 128,000 and 24,000,000 bps). The typical download speeds for residential cable modems are between 3 and 15 mbps (or 3,000,000 and 15,000,000 bps), and can reach speeds up to 1,000 mbps. The rate at which data is transmitted is often referred to as bandwidth.

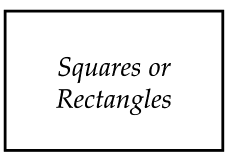
Flowcharts

Because of the long communication times between spacecraft exploring other worlds in the Solar System and ground control on the Earth, the computer programs operating the spacecraft must be reliable and well-designed. An important tool in designing efficient computer programs is the use of flowcharts. A flowchart is a visual representation of steps that need to be taken to complete a task. For example, one could write a flowchart to provide instructions on how to assemble a bookshelf, how to complete a tax form, or how to write a computer program to solve a problem. Flowcharts describe the individual steps that need to be taken to complete the task and the connections between the steps. In this manner, they help the person designing the task to understand the flow of the process better, to identify areas that could pose problems, and to communicate the process to others. Flowcharts are especially helpful in describing situations where there are repetitive steps or situations where different steps must be taken according to decisions made earlier (e.g., if '*abc*' happens, do '*def*', otherwise do '*ghi*'). A comprehensive flowchart can easily be converted to a computer program code and later be used in identifying problems that may be encountered during debugging—the testing of the program to eliminate mistakes.

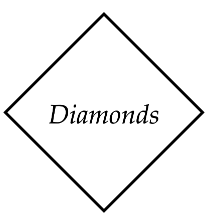
There are four basic symbols used in flowcharts:



are at the beginning and at the end of a flowchart. They indicate the starting and stopping points of the process.



represent an individual step or activity in the process.



represent a decision point. Questions must be answered in order to know which way to proceed next. The activity branches to different directions depending on the answer.

indicate the direction of the flow of information, or the sequence of activity.

A loop is created when the flow of the process returns to a point where it has been already, as a result of a decision to redo something, for example. For an example of a flowchart describing an everyday activity, see Fig. 4.

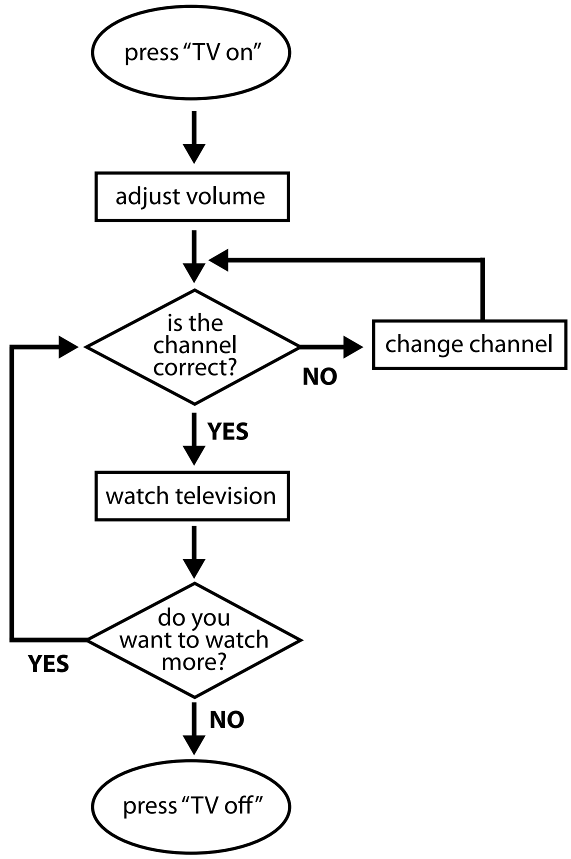


Figure 4. An example of a flowchart: how to watch television.

An example of a problem that benefits from the use of a flowchart is the determination of whether a given year is a leap year. Leap years are necessary because one Earth year in astronomical sense is not exactly 365 days long, but, rather, 365.24 days. If every year on the calendar only had 365 days, astronomical events (such as equinoxes and solstices) as well as seasons eventually would drift to other times of the year. To correct for this effect, the Gregorian calendar, the current standard calendar used in most parts of the world, adds an extra, 29th, day to the month of February every few years; the year in which this occurs is then called a leap year. The rules of exactly when a leap year occurs state that a given year is a leap year if:

- the year is evenly divisible by 4
- except if the year is evenly divisible by 100 (that is, it is a century year such as 1800, 1900, etc.)
- but, these century years are leap years if they are evenly divisible by 400 (such as 2000, 2400, etc.)

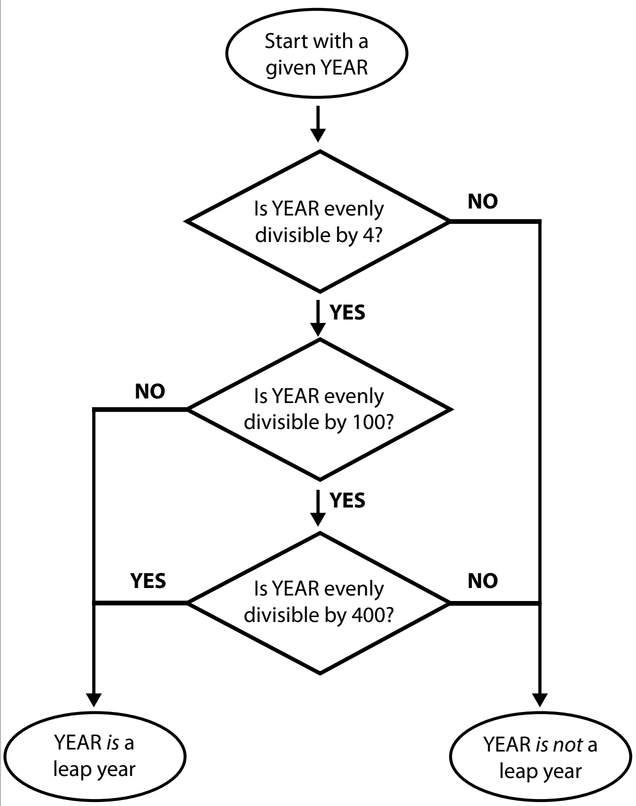


Figure 5. Flowchart to determine if a given year is a leap year.

The rule is complicated, because the actual length of the year is not even an exact fraction of a day (such as exactly 365 and 1/4 days.) A flowchart (Fig. 5) illustrates the flow of the decision-making to determine whether a given year is a leap year, and it makes the rule easier to understand. The flowchart can then be converted easily to a computer program to perform the leap year determination.

Making sure that computer programs operating a spacecraft are reliable and free of errors is an important part of designing a mission to explore other worlds in the Solar System. If an error in a computer program were to cause the spacecraft to malfunction, the mission may be lost (which, in fact, has happened in the past.) Using tools such as flowcharts is essential in making sure that the mission designers can rely on the computer programs not to fail. The typical way to protect a spacecraft in situations where it does not know how to proceed by itself is to have the spacecraft go into "safe mode"—a state where the spacecraft ceases all but essential operations and waits for further instructions from ground control. Safe mode allows spacecraft operators to analyze the situation and devise a solution to the problem. Once the problem is solved, the spacecraft can return to normal operations. Ensuring proper switch to (and from) safe mode is another aspect of careful software programming necessary for spacecraft mission designers.

Data Compression

Another challenge in designing spacecraft missions to other worlds in the Solar System is to provide the spacecraft with the capability of sending back as much data as possible in as compact form as possible. This is not a problem unique to spacecraft: data transmission and storage concerns are of great importance for all computer-related activities, even such familiar tasks as the determination of how large a hard drive or how fast an Internet connection to get for a home computer.

One way to maximize the amount of data that can be stored or transmitted is to use data compression, a technique that reduces the amount of space needed to carry information. A compression program changes data from an easy-to-use format to one optimized for compactness, while an uncompression program returns the information to its original form. In some applications, compression of data is an integral part of the process of gathering information. For example, digital cameras usually compress the image data as they store the picture in the camera's memory. Compression is especially important for pictures, because they contain so much data.

Computer pictures are made of pixels (picture elements), single points in a graphical image. The number of pixels tells how high the resolution of the image is: the more pixels in an image, the better it looks to the human eye. That is why digital cameras, for example, express their resolution in megapixels (millions of pixels.) Each pixel contains several bits of data, and the more bits are used to describe a pixel, the more color depth the image has. But, as a result, the amount of data that needs to be stored or transmitted becomes large, and the need to compress the data becomes even more important. There are many different compression techniques, but there are two basic categories based on how they operate: lossless and lossy.

When using a lossless compression technique, the size of a computer file is reduced without losing any of the information in the file. This means that the compressed file will take up less space, but when it is uncompressed, it will have the exact same information as the original file. This is necessary for many types of data, such as executable computer codes, word processing files, or especially important images. In these cases, not even a single bit of information can be lost, but the data still needs to be stored or transmitted as efficiently as possible. Using this method, the size of a data file is typically compressed up to roughly half its original size. Examples of image file types using lossless compression methods include GIF (Graphics Interchange Format), PNG (Portable Network Graphics), TIFF (Tagged Image File Format; compression optional) and PostScript.

In contrast, there are files that do not have to be in perfect condition for storage or transmission and, therefore, can use a compression technique where some of the information may be lost. All real world measurements—such as captured images or sounds—always contain some amount of noise. In this case, noise can be thought of as parts of the captured image or sound that do not carry additional information (and sometimes may even distort the actual information) but still take up space. For example, a recording of an outdoor concert may include background traffic noise. If a compression technique removes tiny bits of information from the file, it would be similar to just adding a bit more noise to the file. If the changes are not large, no significant harm is done. Compression techniques that allow this type of degradation are called lossy, since they lose some information (even if the information is considered insignificant). Lossy compression methods are much more effective at compression than lossless techniques, and they are widely used today. An example of a popular use of a lossy compression technique is JPEG (Joint Photographers Experts Group) image files. This technique can compress files by a large fraction, up to 1/20th its original size, without significantly sacrificing the image quality. Another popular lossy mechanism is MPEG (Moving Pictures Experts Group), which has become the compression method of choice for digital videos, such as computer videos, digital television networks, and DVDs (Digital Video Discs.) Another form of the MPEG compression standard is used to produce MP3 audio files.

There are hundreds of compression programs available today. Most of them combine several techniques. For example, JPEG compression methods usually use some of the lossless techniques in some of the compression steps in addition to lossy compression. The wide range of digital data transmitted around the world today would be impossible without the use of some kind of compression. The same is true for the sophisticated spacecraft exploring other worlds.

Reliable Communications with Spacecraft

In addition to solving many of the challenges of keeping spacecraft safe while they operate in the hazardous space environment, technology is essential for operating the spacecraft remotely, and for transmitting the gathered data back to the Earth for analysis. Tools such as flowcharts make it possible to design computer programs that are effective and robust. This allows the robotic spacecraft to operate at least somewhat autonomously when immediate contact with ground control is not possible. Gathering massive amounts of data with the spacecraft's instruments is just the first step in the sequence that brings the data from the target to the scientists' computers for detailed analysis. Tools such as compression techniques make it possible for large amounts of data to be transmitted using limited data transmission rates over interplanetary distances. Advances in science and the development of new technologies go hand in hand as scientists reach new milestones in their exploration of the Universe.

Lesson Plan

Warm-Up & Pre-Assessment

1. Ask students to imagine that they are sending a spacecraft to study another planet. The spacecraft carries a variety of instruments to gather data of the planet. What do students think the spacecraft does with the data? *(Desired answer: record and send it back to Earth.)* How does the spacecraft send the data to Earth? *(Desired answer: via radio signals.)* How fast do radio signals travel? *(Desired answer: the speed of light.)* How long does it take for the signals to travel from the explored planet to the Earth? *(Desired answer: depends on the distance.)* How can we figure out how long it takes for signals to travel from different planets to the Earth? *(Desired answer: divide distance from the planet by the speed of light; 300,000 km/s (186,000 miles/s) in the vacuum.)*

2. Draw a table with three columns on the blackboard (or whiteboard) like the one below (but without the data). Fill in the rows one at a time; for each row, write in the data for the first two columns, and then have the students calculate the signal travel time using calculators or scratch paper before filling in the last column. Note that the "Distance from the Earth" given for the planets is the difference between the average distances of the Earth and the planet from the Sun. In reality the distance is different when the two planets are on the same side of the Sun and when the two planets are on the opposite sides of the Sun. The distance between the Moon and the Earth is also the average distance between the two objects.

Object	Distance from the Earth	Signal Travel Time
The Moon	384,000 km (239,000 miles)	1.28 s
Mercury	92 million km (57 million miles)	307 s (5 min 7 s)
Venus	41 million km (26 million miles)	137 s (2 min 17 s)
Mars	78 million km (49 million miles)	260 s (4 min 20 s)
Jupiter	630 million km (390 million miles)	2,100 s (35 min)
Neptune	4500 million km (2800 million miles)	15,000 s (4 hrs 10 min)

3. Ask the students if, considering the distances between the planets and the resulting lengthy signal travel times, there are any concerns they might have when designing a mission to explore other worlds in the Solar System? Write down suggestions. Make sure you get ideas stating that you would like to make sure the spacecraft (including its computer programs) is reliable, as well as issues such as the difficulty of transmitting data across large distances. Ask the students if they can think of ways to solve the problems.

Activity 1: Crafting a Flowchart

In this activity, students examine one way engineers can make sure computer programs operating spacecraft are reliable: using flowcharts as the first step in writing a computer program. A flowchart is a pictorial outline of a process that gives a quick and convenient way to see what the program is designed to accomplish. As an example, the students design a flowchart to determine whether a given year is a leap year or not.

Materials

Per student:

- Student Worksheet 1
- Computer access (Optional)

Preparation

1. Make copies of Student Worksheet 1 (one per student).
2. For computer or design classes, you may want to have students use diagram-drawing software that may be available on their computers (see the *Internet Resources & References* section for examples) to design and draw their flowcharts instead of drawing them by hand. In this case, be sure to reserve the computer lab or media center in advance.

Procedures

1. Remind the students of the Warm-Up where they came up with a list of challenges a spacecraft may face in interplanetary exploration. Explain that they are going to concentrate on one of the challenges: how to make computer programs that run the spacecraft as reliable as possible. You can use the following introduction to lead the students to the idea of using flowcharts in designing computer programs. Ask the students to come up with ideas of how computer programs can be made as foolproof as possible. *(Desired answers include: careful design of the program, paying attention to not making mistakes while actually writing the programs, and repeated testing and debugging of the program.)* Ask if the students know of any tools that could help in making sure that the design of a computer program is as efficient and error-free as possible. *(Desired answer: flowcharts, or some way of visually representing the program.)*
2. Introduce the concept of flowcharts to the students. You can use Fig. S1 in Student Worksheet 1 as an example. Be sure to point out the different

symbols and their meaning.

3. Hand out copies of Student Worksheet 1 and have the students complete the Worksheet.

Discussion & Reflection

1. Ask the students how their flowcharts could be changed to include more features. For example, what if the students needed to print out a table of all leap years in the 21st century? What are the advantages and disadvantages of more or less complicated flowcharts?

2. Ask the students how they think flowcharts are used when designing computer programs for spacecraft, especially in the context of the long communication times discussed during the Warm-Up. *(Desired answer: effective computer programs make it possible for spacecraft to not need having every command given individually. Otherwise, communicating with spacecraft would be similar to having a conversation where one can say only one sentence every few minutes or even hours. If spacecraft are programmed to know what to do in a certain situation, it can save a lot of time.)* Discuss how comprehensive programs created with the help of flowcharts would be particularly useful if something goes wrong with the spacecraft when it is operating in space. Be sure to bring up the point that if there is a problem, it is important for the computer program to have been designed to cover as many situations as possible.

3. Discuss the advantages and disadvantages of an autonomous spacecraft: a robotic spacecraft that is not continuously controlled by humans. For example, one advantage could be that the spacecraft does not have to be constantly watched; we have some confidence that it can take care of itself. But on the other hand, the scientists and engineers lose a certain amount of control over the spacecraft when it has already been programmed to react in a certain way in a given situation. One solution is to have a spacecraft that can operate autonomously much of the time but is able to receive instructions from the Earth before or during critical operations, which is, in fact, how most modern spacecraft operate.

Activity 2: Data Compression

In this activity, students examine one of the big concerns of spacecraft exploring other worlds in the Solar System: how to transmit as much data as possible back to the Earth. The students investigate how image data can be compressed so that the meaning of the information stays the same, but the size of the transmitted data is smaller. Students compare how compression changes the quality of the data and decide what degree of loss of information is acceptable when transmitting data over limited bandwidth.

Materials

Per class:

- Book (or magazine)
- Stopwatch

Per student:

- Student Worksheet 2

Preparation

1. Make copies of Student Worksheet 2 (one per student).
2. Choose a book (or a magazine) that the students will use to count data information rate. Count the number of words on one page of your choice.

Procedures

1. Ask the students to come up with a list of different ways to send a message to a friend living 100 km (62 miles) away (e.g., letter, telegraph, phone call, fax, email, instant message, text message). Which ways are the fastest? Which are the slowest? How can we measure how fast each of these methods sends the data, or which sends the most data in the least amount of time?
2. Explain to the students that computer engineers (and spacecraft engineers), talk about "bit rate," which measures how many bits of information can be sent each second. Tell the students that the class will examine what this term really means. Take out a book, and have a student read a page out loud at a regular speed while another student uses a stopwatch to time how long it takes to read the page. Have the student read the page a second time, this time as fast as possible, while making sure that the other students can understand what the reader is saying. You can have different students read as fast as they can to find out what is the maximum reading rate in your class. (The typical maximum is a few words per second.) You can calculate how long it would take to read the entire book by multiplying the time it took to read one page by the number of pages in the book.

3. Tell the students that you are going to change the reading rate to a bit rate. In computer operations and communications the basic unit transmitted, a "bit," is like a light switch: it can be either "on" or "off." A single bit has a value of "one" or "zero", and by combining several bits together, you can transmit larger pieces for information. For example, the ASCII encoding system uses eight-bit strings to represent text characters; e.g., "0110 0001" for the letter "a," "0100 0001" for the letter "A," "0110 0010" for the letter "b." Using this system, let's assume it takes 8 bits to code each letter in the book, and that there are 5 letters per word, so that there are 40 bits per word. If the reading rate in your class is 4 words per second, for example, this translates to a bit rate of 160 bits per second. For comparison, the bit rate of a typical home dial-up modem is about 56,000 bits per second (bps), or 56 kbps (kilobits per second). The typical download bit rate of a DSL modem is between 128 and 24,000 kbps (or 128,000 and 24,000,000 bps). The typical download speeds for residential cable modems range from 3 mbps (megabits per second) to 15 mbps (or 3,000,000 and 15,000,000 bps) and can reach speeds up to 1,000 mbps. The rate at which data is transmitted is often referred to as bandwidth.

4. You can make the problem harder by introducing background noise. You can go outside near a noisy street, or in front of a loud fan, or turn on background music fairly loud, and have the students read the page out loud again. Point out to the students that if the page is read very quickly, the words can get lost in the noise. The reader has to be careful and make sure that each word is clearly pronounced, which makes it necessary to slow down. Time the reading again and calculate what the bit rate is with background noise. As a further complication, explore with the class how the bit rate changes if the reader moves 3 m (10 feet) away from the person who is listening.

5. Explain to the students that spacecraft face similar problems when they are sending signals across the vastness of space. Just as the students' "bit rate" drops when the reader moves further away, or when there is background noise, a spacecraft's effective bit rate drops when its radio signal weakens with distance, or when it has to overcome interference (such as when its signal has to pass near the Sun, which can generate a great deal of radio noise). For example, the MESSENGER spacecraft will communicate from its orbit around Mercury with ground control on the Earth at a peak data transmission rate of 400 bits per second (when averaged over peak transfer rate and times when the spacecraft cannot communicate at all due to its position.) At this rate, how long would it take for MESSENGER to read the book the students used?

6. Have the students brainstorm ways to overcome the problem of low bit rate. Make sure to bring out the idea of somehow compressing the data. How could the students rewrite the page to compress the information? *(Desired answer: possibilities include removing spaces between words or paragraphs, using shorthand for common words, such as "&" instead of "and", etc.)*

7. Explain to the students that compression is especially important for pictures, because they contain so much data. Computer pictures are made of pixels (picture elements), single points (or, rather, tiny squares.) The number of pixels in an image tells how high the resolution is: the more pixels in an image, the better it looks to the human eye. That is why digital cameras, for example, express their resolution in megapixels (millions of pixels.) Each pixel contains several bits of data, and the more bits used to describe a pixel, the more color depth the image has. But, as a result, the size of the data that needs to be stored or transmitted becomes larger, and the need to compress the data becomes even more important.

8. Hand out copies of Student Worksheet 2, and explain that the students will investigate how picture data can be compressed. You may want to show the first picture of the asteroid in the Worksheet (Fig. S2) and have the students brainstorm ways to somehow compress the picture data before handing out the Worksheet. Have the students work individually or in pairs to complete the Worksheet.

Teaching Tips

- Question 9 of Student Worksheet 2 asks the students to compare images of different resolutions. Some of the details may be lost during photocopying, so you may want to either print the pages with the images directly from the file (rather than photocopying these pages from a printout) or instruct the students to look at the images in the PDF version of this lesson, rather than in the printout.

- Question 11 of Student Worksheet 2 asks the students to obtain a copy of Fig. S6 to compress using image manipulation software. You may want to download the image before class and give it to everyone instead of having the students download the image individually. Most computers include basic image manipulation software that can be used for the purpose of compressing the image using different methods; the *Internet Resources & References* section includes some suggestions. If your class does not have access to any image manipulation software, the students can skip Question 11.

Discussion & Reflection

1. Spacecraft need to send enormous amounts of data back to the Earth once they have gathered it. If communication between the spacecraft and ground control on Earth is not efficient and reliable, the gathered data is useless. Transmitting the data may take a long time because the data transmission rate is limited. Data compression makes it possible to transmit more data in a given time. The students now understand how spacecraft and ground control on the Earth can communicate with one another in a reasonable amount of time without losing the data gathered by the spacecraft. Discuss with the students how the data is received on the Earth through the Deep Space Network (see the *Science Overview* for more information.)

2. Ask the students which type of data compression they think would work best for spacecraft: lossy or lossless. Have the students write down and explain the basis for their answer. There are no right or wrong answers, as long as the explanations for the choices are logical. Whether a spacecraft uses lossy or lossless compression depends on the specific situation, and spacecraft often combine both methods. For example, if there are no bandwidth concerns, lossless method might be preferable, while if the bandwidth is limited, it might be better to transmit data in as compact form as possible, leading to the choice of a lossy compression method.

3. Discuss with the students the different ways that scientists have gathered data of other planets over the history of planetary studies, from drawing features of planets seen through a telescope, to capturing pictures on photographic plates, and to using modern digital camera systems. What kind of communication and data capture devices might be possible in the future?

Lesson Adaptations

For vision-impaired students, you may want to use sound files created/modified using different levels of compression instead of the three image files in Student Worksheet 2. The same principles apply for sound files as for image compression: one can choose a smaller file size for some loss in quality. Most computer audio software gives the option of copying a sound file at different types and levels of compression.

Extensions

- Using a computer programming language of your (or the students') choice, have the students write a program based on their flowchart determining whether a given year is a leap year.
- To explore the kind of data that the spacecraft send to scientists for analysis using the communications strategies discussed in this lesson, adapt the *Mission Design* Middle School Lesson 3: "Look But Don't Touch" for your students. Even though the lesson is targeted toward grades 5-8, it can be adapted easily for use at the high school level.
- Have the students research spacecraft missions that have failed due to computer malfunctions. Can the students think of ways the malfunctions could have been prevented? A good place to look for information for lost spacecraft is to go through the "Chronology of Lunar and Planetary Exploration" web pages at the NASA's National Space Science Data Center (see the *Internet Resources & References* section), and look for the word "attempted" in the mission description.
- Have the students research how current spacecraft solve communications problems. Which strategies are common among different missions, and which solutions may be unique to a particular spacecraft?
- Have the students research different components of modern spacecraft. There are many pieces of hardware that take part in handling gathered data and transmitting it to the Earth, but there are other important components, as well. Whatever the purpose of the component, they are controlled by onboard computers, either autonomously by preloaded operating software or after receiving commands from ground control. Have the students use the Web sites listed in the *Internet Resources & References* section to examine components aboard different spacecraft.
- If the students came up with intriguing communication problems during Warm-up that were not discussed during the lesson, have students research how those problems are addressed in modern spacecraft.

Curriculum Connections

- *History*: Have the students research how the Gregorian calendar became the calendar of choice. What other calendars are in use? How do they differ from the Gregorian calendar? What are the advantages and disadvantages of each?
- *Technology*: Have the students research the data transmission methods used in Internet technology today. What is the bottleneck for transmitting information? How are engineers trying to overcome these problems?
- *History of science*: Have the students research data collection and analysis methods in different kinds of exploration throughout history. How did ancient scientists and explorers bring back their data back to their laboratories and offices? What about during the industrial age before computers? How have advances in computer and communications technology changed the process of gathering, transmitting and analyzing data?
- *Sociology*: Have the students research and discuss how advances in computer and communications technology have changed human behavior and culture. How would the students' daily lives be different if they did not have access to computers and modern communication technology?

Closing Discussion

- In Activity 1, the students learned how spacecraft can be programmed effectively so that they can operate in deep space, gather data of their target, and send the data back to the Earth. In Activity 2, the students learned how the gathered data can be compressed before sending it to the Earth for analysis. Discuss with the students how these two issues are related, whether there are any other communication barriers between spacecraft and ground control, and how we might solve them. Revisit the list of possible communication issues the students came up with during Warm-Up, and make sure all the entries have been discussed.
- Hand out 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 designed an appropriate flowchart to determine whether a given year is a leap year.
- Student completed the compression of image data on Student Worksheet 2 and used logical reasoning to support his or her observations of the quality of images at different resolutions.
- Student answered the questions on the Student Worksheets thoughtfully and used reasoning and evidence to support his or her answer.
- Student completed all Worksheets and participated in the lesson.

3 Points

- Student met three of the four above criteria.

2 Points

- Student met two of the four above criteria.

1 Point

- Student met one of the four above criteria.

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/

Astronomy Picture of the Day: Leap Years (from February 29, 2004)

http://antwrp.gsfc.nasa.gov/apod/ap040229.html

NASA/Jet Propulsion Laboratory Deep Space Network Web Page

http://deepspace.jpl.nasa.gov/dsn/

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

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

NASA Sun-Earth Connection: Calendars

http://sunearth.gsfc.nasa.gov/eclipse/SEhelp/calendars.html

Wikipedia.org: Data Compression

http://en.wikipedia.org/wiki/Data_compression

Web sites discussing communications issues for current spacecraft missions:

Cassini (Mission to Saturn)

http://saturn.jpl.nasa.gov/mission/navigation/missionnavigationuplinkdownlink/

New Horizons (Mission to Pluto and the Kuiper Belt)

http://pluto.jhuapl.edu/spacecraft/commEarth.html

Mars Express (Mission to Mars)

http://mars.jpl.nasa.gov/express/mission/sc_comm.html

Mars Reconnaissance Orbiter (Mission to Mars)

http://mars.jpl.nasa.gov/mro/mission/sc_telecomm.html

MESSENGER (Mission to Mercury) Mission Operations Center

http://messenger.jhuapl.edu/moc/

Venus Express (Mission to Venus)

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=33877&fbodylongid=1438

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=33877&fbodylongid=1439

Web sites for a few commonly used flowcharting software:

Dia

http://live.gnome.org/Dia/

OmniGraffle

http://www.omnigroup.com/applications/omnigraffle/

OpenOffice.org Draw

http://www.openoffice.org/product/draw.html

SmartDraw

http://www.smartdraw.com/

Visio

http://office.microsoft.com/en-us/visio/FX100487861033.aspx

Web sites for a few commonly used image/photograph manipulation software:

Adobe Photoshop and Photoshop Elements

http://www.adobe.com/

Corel Paint Shop Pro (and Other Photo Editing Programs)

http://www.corel.com/servlet/Satellite?pagename=CorelCom/Layout&c=Product_C1&cid=1152105040688&lc=en

GIMP – GNU Image Manipulation Program (for Unix, Windows, MacOS X)

http://www.gimp.org/

iPhoto (for MacOS X)

http://www.apple.com/ilife/iphoto/

IrfanView32 (for Windows)

http://irfanview.com/

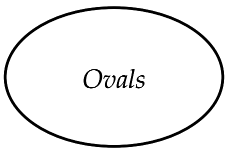
Acknowledgement

Activity 2 was adapted from the activity "Data Handling Techniques" from NASA's *Galileo Curriculum Module* (http://www2.jpl.nasa.gov/galileo/curric_mod/vol1/curr_module.pdf).

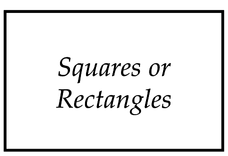
To Leap or Not to Leap?

Name: ______________________________ **Date:** ______________________

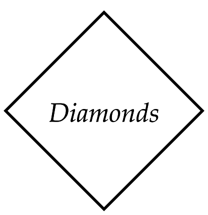
Flowcharts are a great tool in designing efficient computer programs. A flowchart is a visual representation of steps that are necessary to complete a task. It describes the individual steps to be taken, as well as the connections between them. A comprehensive flowchart can easily be converted to a computer program code and later be used in identifying problems that may be encountered during debugging—the testing of the program to eliminate mistakes. There are four basic symbols used in flowcharts:



Ovals are at the beginning and at the end of a flowchart. They indicate the starting and stopping points of the process.



Squares or rectangles represent an individual step or activity in the process.



Diamonds represent a decision point. Questions must be answered in order to know which way to proceed next. The activity branches to different directions depending on the answer to the question.

Arrows indicate the direction of the flow of information, or the sequence of activity.

A loop is created when the flow of the program returns to a point where it has been already, as a result of a decision to redo something, for example. Flowcharts are not only useful for designing computer programs; they can be made for almost any process. Figure S1 shows an example of a flowchart describing an everyday activity.

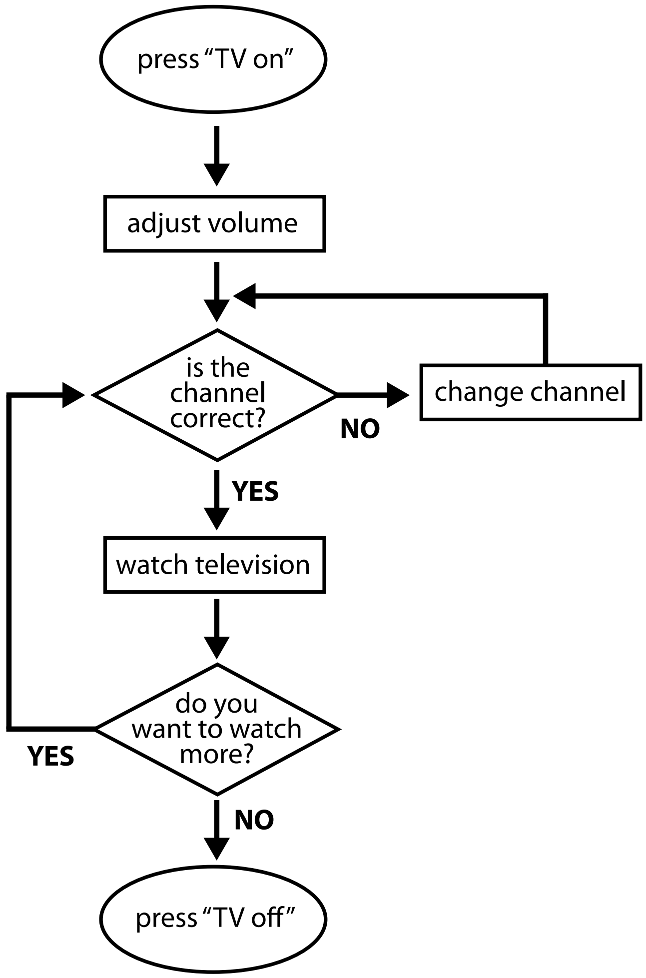


Figure S1. An example of a flowchart: how to watch television.

A great example of a problem that benefits from the use of a flowchart is the determination of whether a given year is a leap year. Leap years are necessary because one Earth year in the astronomical sense is not exactly 365 days long, but, rather, 365.24 days. If every year on the calendar only had 365 days, astronomical events (such as equinoxes and solstices) as well as seasons would drift over time to other times of the year. To correct for this effect, the Gregorian calendar, the current standard calendar used in most parts of the world, adds an extra, 29th, day to the month of February every few years; the year when this occurs is called a leap year. The rules for leap years state that a given year is a leap year if:

- the year is evenly divisible by 4
- except if the year is evenly divisible by 100 (that is, it is a century year such as 1700, 1800, 1900, etc.)
- but, these century years in fact are leap years if they are also evenly divisible by 400 (such as 1600, 2000, 2400, etc.)

Task

Design a flowchart to determine whether a given year is a leap year. Use the symbols and procedures described in this Worksheet.

Compressing Data

Name: ______________________ **Date:** ______________________

Introduction

When robotic spacecraft venture out to explore other worlds in the Solar System, one of the big challenges the mission designers have to consider are ways for the spacecraft to send as much data as possible back to the Earth. However, transmitting data across the vast distance of space can be done only at a limited rate. One way to overcome this problem is to edit and compress the data aboard the spacecraft to reduce the total size of transmitted data that is sent to the Earth.

Let's examine how pictures taken by spacecraft can be compressed in different ways. Digital pictures—such as those taken by spacecraft or by everyday digital cameras—are made of a large number of small pieces (squares) of data called picture elements or pixels. Each pixel contains information about its part of the image, such as brightness and color. The more pixels in an image—the higher its resolution—the better the image looks to the human eye.

The data in the pixels is contained in individual "bits" of information. A bit is the basic unit of data in computer operations and communications. A bit is like a light switch; it can be either "on" or "off." A single bit has a value of "one" or "zero," and by combining several bits together, you can transmit larger pieces for information. The number of bits that make up a pixel tells you the quality of the image; especially the number of colors that can be portrayed in the image. For example, if there are 8 bits per pixel, the picture may include 256 different shades of colors, while if there are 24 bits per pixel, the picture may portray almost 17 million different colors. But the more bits there are in a pixel, and the more pixels that make up an image, the larger the size of the image, and the longer it takes to transmit it.

Example image: Asteroid

Let's imagine that a spacecraft captures an image of an asteroid with a camera that takes pictures at a resolution of 16×16 pixels (see Figure S2.) In this case, the asteroid image is made of 256 pixels. Since the image is black and white—that is, it only contains two colors—we can assign a certain value (for example, "1") to the filled (black) pixels and another (for example, "0") to the unfilled (white) ones. In this case, if we transmit the image as a string of pixels, starting from the top left corner, going left-to-right and then each row top-to-bottom, the data string would be

1-1-1-1-1-1-1-1-1-0-1-1-1-1-1-1-1-1-1-1-1-1-1-1-0-0-0-0-1-1-1-1-1-1-1-1-1-1-0-0-0-0-1-1-1-1-1-1-1-1-
1-0-0-1-1-0-0-1-1-1-1-1-1-0-0-0-0-0-0-0-1-1-1-1-1-0-0-0-0-0-0-0-0-1-1-1-1-0-0-0-0-0-0-0-1-
0-1-1-1-1-1-0-0-0-1-0-0-0-1-0-0-0-1-1-1-0-0-0-0-0-0-0-0-0-0-1-1-1-1-0-0-0-0-0-0-0-1-0-0-1-1-1-1-
0-0-0-0-0-0-0-0-0-0-1-1-1-1-0-0-0-0-1-0-0-0-0-1-1-1-1-1-1-0-0-0-0-0-0-1-1-1-1-1-1-1-1-1-1-0-
0-0-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1

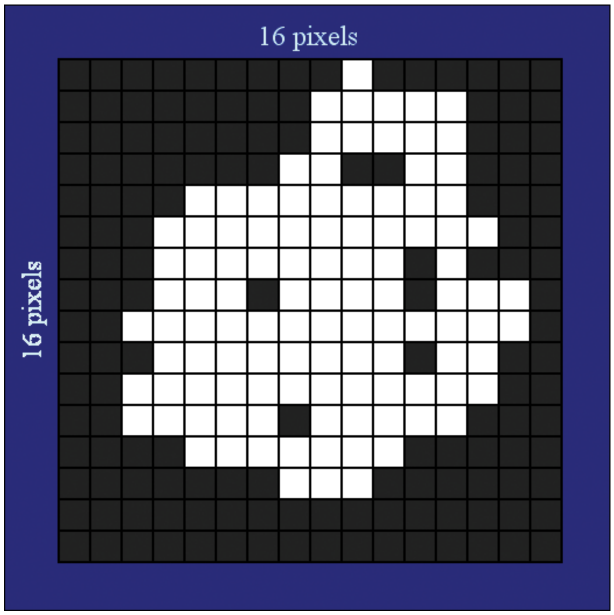


Figure S2. A picture that could be of an asteroid at the resolution of 16 × 16 pixels.

If we know the resolution of the image—how many pixels the image contains in each direction—we can use the string of numbers above to reconstruct the image (in a real situation we would also need to know how many bits each pixel contains, since the “0”s and the “1”s above each could contain several bits of information.)

1. Let’s imagine that you need to compress the image somehow before sending the data to the Earth. Are there ways you can think of that the information in the picture could be presented with fewer pixels? Without 1) losing any data (called a “lossless” compression method), or 2) with losing some data but not a lot of important data (called a “lossy” compression method)? Write down at least one suggestion for each.

Lossless compression

When using a lossless compression technique, the size of the image file is reduced without losing any of the information in the file. This means that the compressed file will take up less space, but when it is decompressed, it will have the exact same information as the original file. Let's see how we could use a "lossless" compression technique to recreate the asteroid image with a smaller number of pixels. Since the asteroid image (Figure S2) is composed of a string of "1"s and "0"s, instead of listing the value for each pixel, we can sum up strings of pixels of the same value. In this case (see Figure S3), the first filled pixel (upper left corner), has the value "1." However, instead of repeating the value "1" several times in the next few pixels, we can instead assign to the following pixel the number of pixels that follow the first one and are identical to it. In this case, the number is 8. As a result, instead of using 9 pixels of data you only use 2. To mark the fact the we no longer need the next seven pixels in the image, we can mark them with an "X." The 10th pixel in the original image is unfilled (equal to "0"), so we mark it again with a "0." This pixel is now followed by a series of 14 filled pixels (6 on the first pixel row of the image, and eight on the second), so we mark the first of these pixels with a "1", the second with "13" to mark the number of pixels that repeat the same value, and the rest of the filled string with "X," etc.

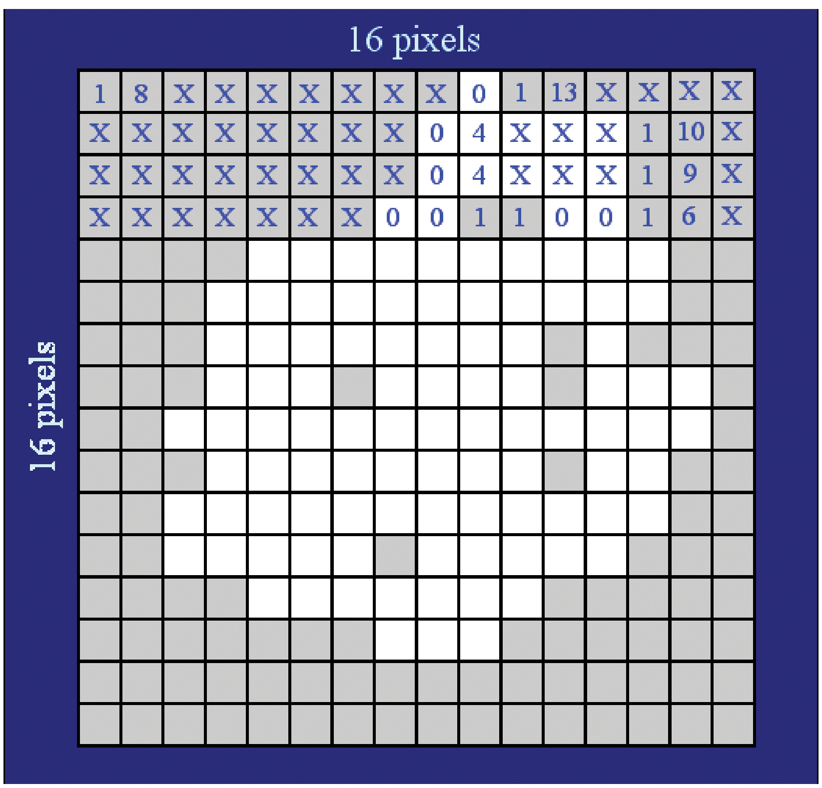


Figure S3. Using a lossless compression method to reduce the size of an asteroid image. (Note that the black pixels have now been shaded grey compared with Figure S2, so that the numbers in the squares are easier to see.)

2. Continue the process of summing up similar pixels and fill the pixels in Figure S3 with the appropriate values.

3. Note that on the fourth row of the image, the two unfilled pixels are given values “0” and “0” instead of “0” and “1” as the procedure described above would instruct. Why is this the case?

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4. Write down the string of pixels (without line breaks) that result from summing up the strings of pixels (remember to leave out the “X”s.)

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5. How does this compare with the pixel string for the original image? How many pixels do you save by summing up the strings of pixels with the same value? How did you come up with this number?

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Lossy compression

In a lossy compression method, the size of the data file is reduced by removing small pieces of information from the file. If the changes are not large, no major harm is done but the reduction in the file size can be significant. In fact, lossy compression methods are much more effective at reducing data file sizes than lossless techniques, and they are widely used today. One simple way to compress the asteroid image (Figure S2) using a lossy compression method is by averaging data over pixels. The original asteroid image is 16×16 (256 total) pixels. Let’s say we want the size of the new, compressed image to be 8×8 (64 total) pixels. We can compress the original image to the new size by taking groups of four adjacent pixels in the original image and replacing them in the new image with a pixel the value of which is the mathematical average of the four original pixels. For example, the first group of 4 pixels in the original image have a value of “1;” that means that the value of the pixel in the compressed image is (1+1+1+1)/4 = 1 (see Figure S4.) This is the case for the first four pixels of the compressed image. The fifth pixel in the compressed image is averaged from original image pixels that contain both "1"s and "0"s. That means that the value of the fifth pixel is (1+0+0+0)/4 = 1/4. Likewise, the value of the sixth pixel in the compressed image is (1+1+0+0)4 = 1/2, etc.

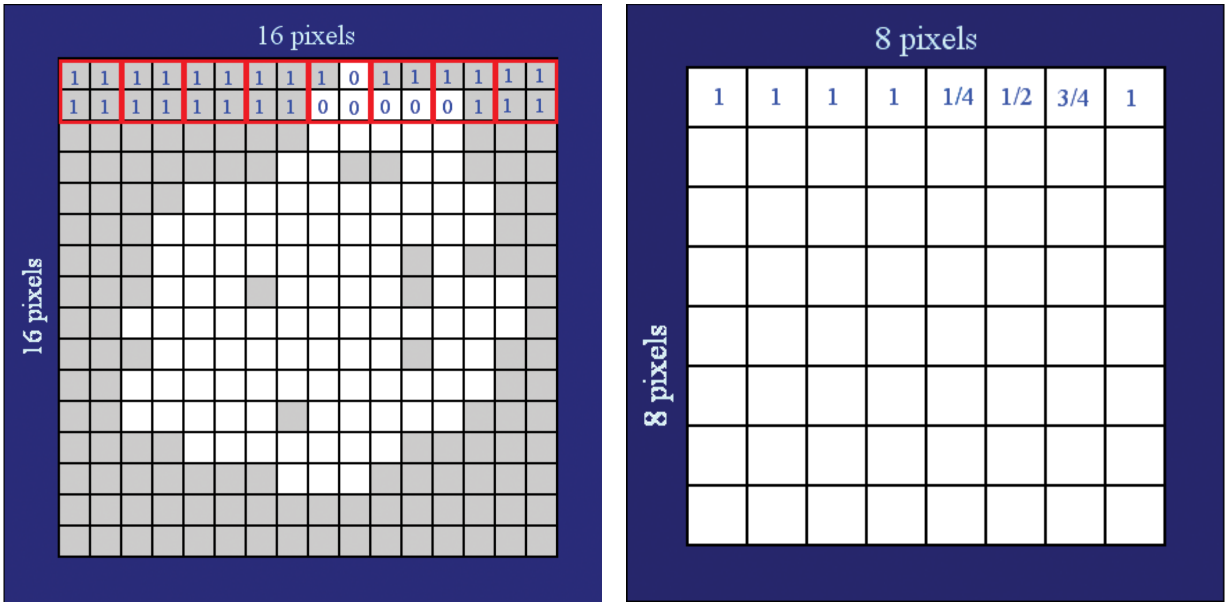


Figure S4. Using a lossy compression method to reduce the size of the original asteroid image through mathematical averaging. In this example, groups of four pixels in the original 16×16 image (left) are averaged to produce the values for pixels in the compressed 8×8 image (right.) The grouped pixels and their values are shown for the first two lines in the original image, resulting in the values on the first line in the compressed image.

6. Continue averaging the pixels in the original image (Figure 3 which you completed in Step 2) and fill Figure S4 with the resulting values for each pixel of the compressed image.

7. You can now use the calculated values (from 0 to 1) to indicate how dark the pixel is. That is, if the value of the compressed pixel is "1," it is black (or dark grey.) If the value of the pixel is "0," it is white (unshaded.) A pixel with a value of 1/2 is shaded halfway between the two end colors, a pixel with a value of 3/4 halfway between the shade of pixels with values "1" and "1/2," etc.

   a) Shade the pixels in Figure S5 according to the values you marked in Figure S4.

   b) How does the compressed image compare with the original (Figure S2)? Are some features lost? Are any artificial features (features not in the original image) introduced? Write down at least two points of observation about the images.

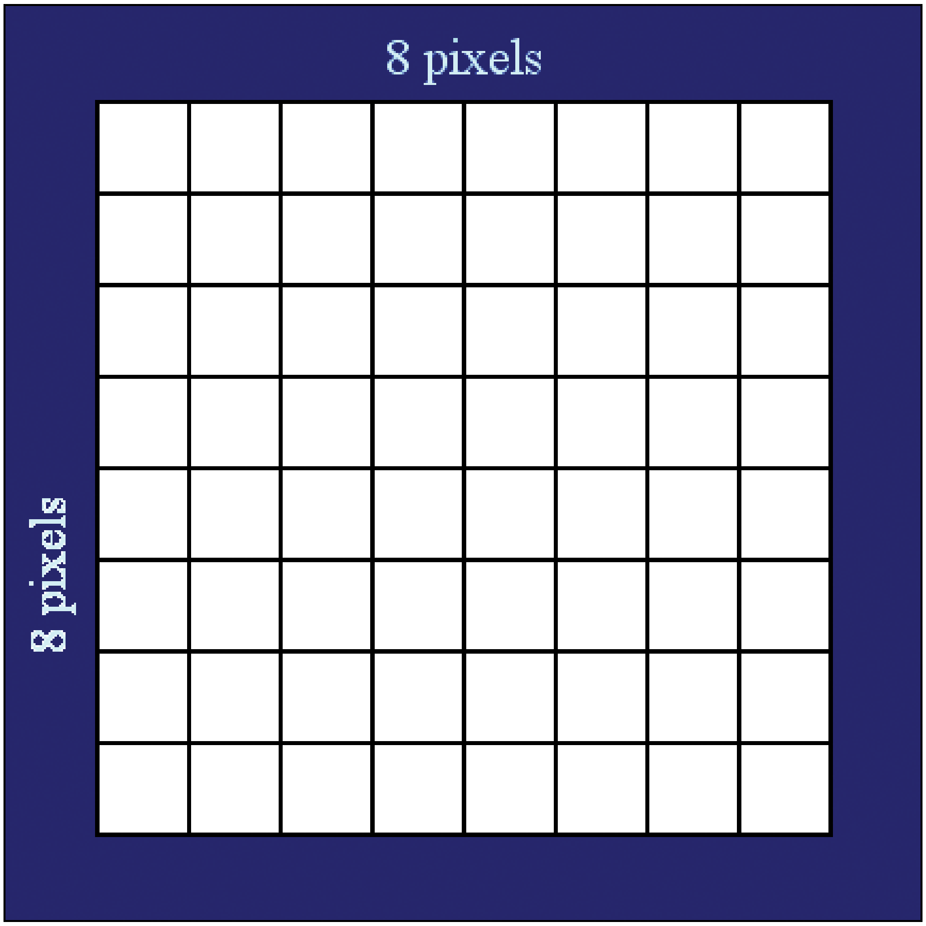


Figure S5. Compressed asteroid image. Shade the pixels based on the values you calculated in Figure S4.

8. How does the number of pixels in the compressed 8×8 image compare with the number of pixels of the image compressed using a lossless compression method (calculated in Step 4)?

File size versus picture quality

Unlike the asteroid picture in Figure S2, which only has 16 pixels in each direction, most images taken by a spacecraft have a lot of pixels. Figure S6 shows an image of the surface of the planet Mercury taken by the MESSENGER spacecraft. Figure S7 shows the same image, but with the number of pixels reduced to 1/4 the original number in each direction using a lossy compression method, while Figure S8 shows an image where the number of pixels is reduced to another 1/4 in each direction.

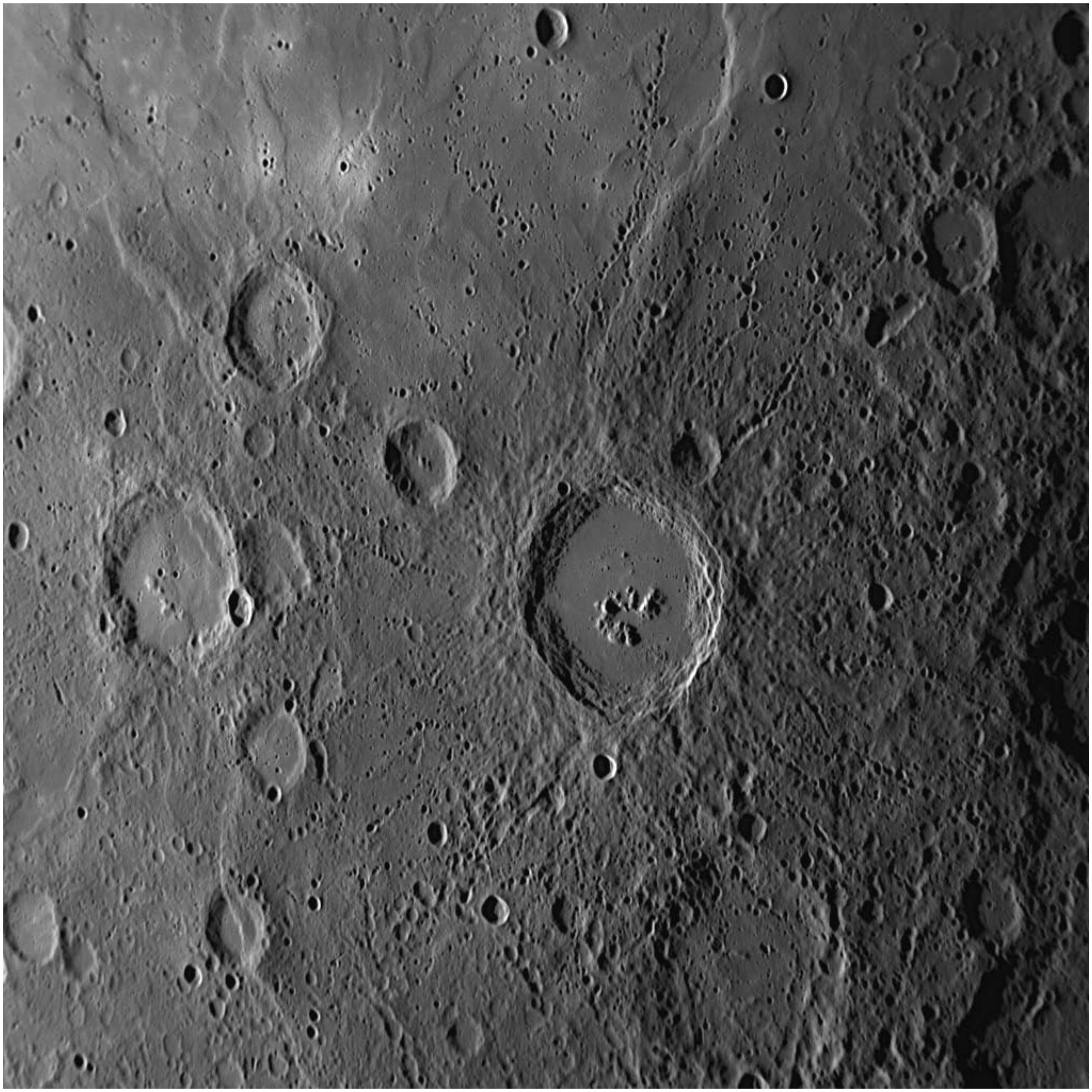


Figure S6. A picture of the surface of Mercury taken by the MESSENGER spacecraft in 2009. The image shows examples of the many geologic processes that have shaped Mercury's surface. There are impact craters of all sizes, down to the smallest craters barely visible in the image. Near the center of the image there is a large, young crater with a smooth floor, central peak structures, terraced walls, and many associated small secondary craters and crater chains created when material blasted off the surface by the impact that created the large crater rained back down to the ground. At the top of the image, smooth plains, common throughout Mercury and possibly volcanic in origin, extend over a large area. Several tectonic features are also visible: ridges cut through the plains, while in the lower left, a cliff cuts through a deformed impact crater. It is thought that these kinds of cliffs are the surface expressions of large faults that formed in the past as Mercury's interior cooled and the surface consequently contracted slightly. The image, about 410 km (250 miles) across, was taken when the spacecraft was about 15,300 km (9,500 miles) above the surface. The resolution of the image is 1018 × 1024 pixels, and the size of the image file 1,020 KB. (Picture credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington: http://photojournal.jpl.nasa.gov/catalog/PIA12313)

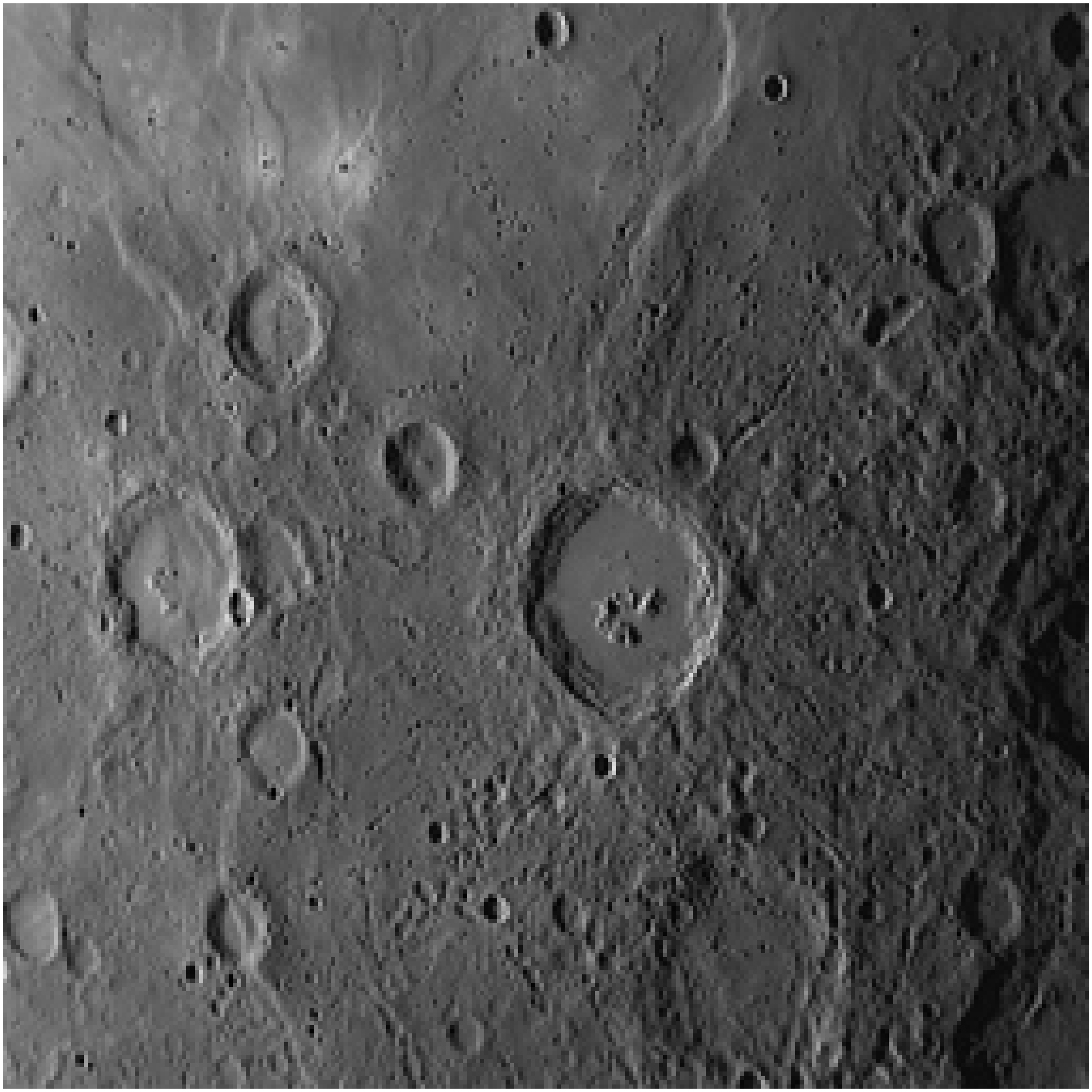


Figure S7. Same as Figure S6, but the image has been compressed so that the number of pixels in each direction is 1/4 of the original. The resulting resolution of the image is 255 × 256 pixels, and the size of the image file 48 KB.

Figure S8. Same as Figures S6 and S7, but the image has been compressed so that the number of pixels in each direction is 1/4 of the number of pixels in Figure S7, or 1/16 of the original in Figure S6. The resulting resolution of the image is 63 × 64 pixels, and the size of the image file 8 KB.

9. How do Figures S6-S8 compare with each other? For example, what is the overall quality of the pictures? Can you see all craters that are visible in Figure S6 in the other pictures? Pay special attention to how craters of different sizes appear in the images. Do you see the tectonic ridges in all three pictures the same way? Make at least four observations of the changes in the quality of the images.

10. Let's imagine the MESSENGER spacecraft can send images to the Earth at a rate of 400 bits per second, and that each pixel in the image is 8 bits in size.

a) How long would it take to transmit the image shown in Figure S6?

b) How long would it take to transmit the image shown in Figure S7?

c) How long would it take to transmit the image shown in Figure S8?

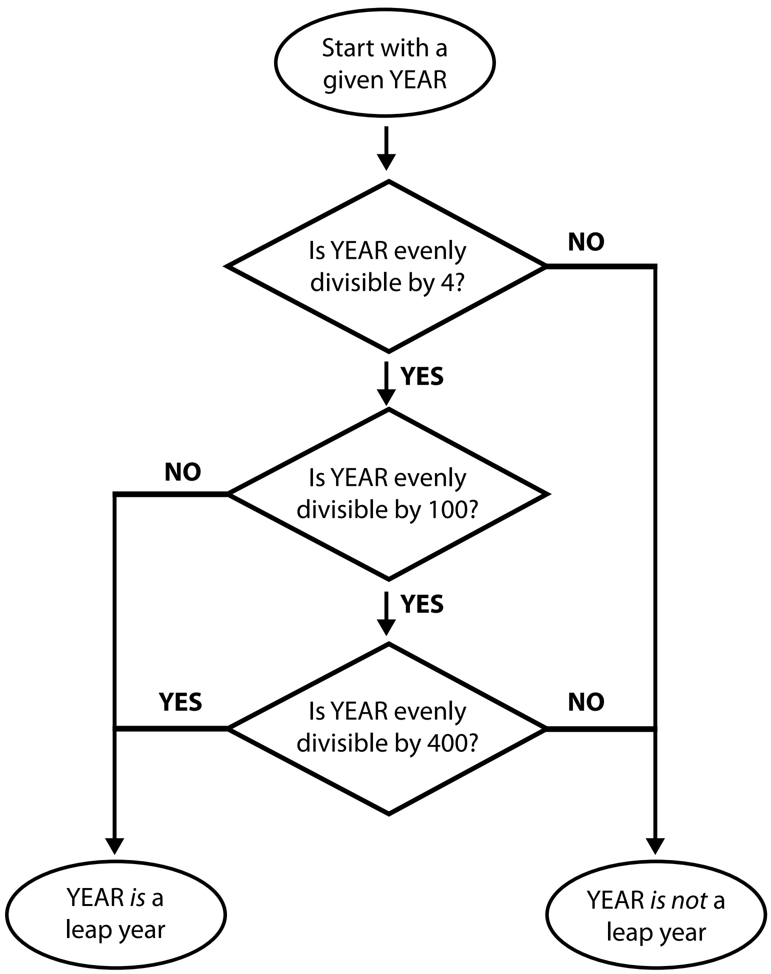
d) What if there was a limit to the total amount of data you can receive from the spacecraft? Would you be willing to spend enough time to receive a couple of images similar to Figure S6, or would you rather have many images similar to Figure S7 or S8? Why or why not?

11. Obtain a copy of the TIFF image in Figure S6 from the Web site listed in the figure caption. Use image manipulation software of your choice to compress the file so that you keep as much of the original information contained in the picture as possible, but the size of the file is as small as possible. The size of the TIFF file is about 1,020 kilobytes (KB; the unit “byte” is used commonly to describe sizes of files; it is composed of a fixed number of bits, usually 8.) What is the size of your compressed file in KB? Compare your results with those of the other students.

Answer Key

Student Worksheet 1

Flowchart to determine if a given year is a leap year or not.



Student Worksheet 2

1. Answers will vary. Since it is up to the students' imagination how to reduce the size of the image, there are no wrong answers, as long as the lossless method truly does not lose any of the information in the image.

2. Completed asteroid image:

16 pixels

16 pixels

1	8	X	X	X	X	X	X	X	0	1	13	X	X	X	X
X	X	X	X	X	X	X	X	0	4	X	X	X	1	10	X
X	X	X	X	X	X	X	X	0	4	X	X	X	1	9	X
X	X	X	X	X	X	X	0	0	1	1	0	0	1	6	X
X	X	X	X	0	9	X	X	X	X	X	X	X	X	1	4
X	X	X	0	10	X	X	X	X	X	X	X	X	X	1	4
X	X	X	0	7	X	X	X	X	X	X	1	0	1	5	X
X	X	X	0	2	X	1	0	3	X	X	1	0	2	X	1
2	X	0	12	X	X	X	X	X	X	X	X	X	X	X	1
3	X	X	0	7	X	X	X	X	X	X	1	0	0	1	3
X	X	0	11	X	X	X	X	X	X	X	X	X	X	1	3
X	X	0	4	X	X	X	1	0	4	X	X	X	1	6	X
X	X	X	X	0	5	X	X	X	X	X	1	11	X	X	X
X	X	X	X	X	X	X	0	2	X	1	37	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

3. If the two pixels were given as "0" and "1," the second pixel could be thought of as being filled. In this case, since "0" and "1" are reserved for describing the color of the pixel, they cannot be used to denote the number of pixels with the same color.

4. The pixel transmission string is

   1-8-0-1-13-0-4-1-10-0-4-1-9-0-0-1-1-0-0-1-6-0-9-1-4-0-10-1-4-0-7-1-0-1-5-0-2-1-0-3-1-0-2-1-2-0-12-1-3-0-7-1-0-0-1-3-0-11-1-3-0-4-1-0-4-1-6-0-5-1-11-0-2

5. The compressed pixel string is much shorter than the original string. It also contains numbers other than "0" or "1." 181 pixels are saved. The number can be calculated by counting the number of "X"s in Figure S3, or by comparing the number of pixels in the original transmission string (16×16 = 256 pixels) and the reduced pixel transmission string in Step 4 (75 pixels.)

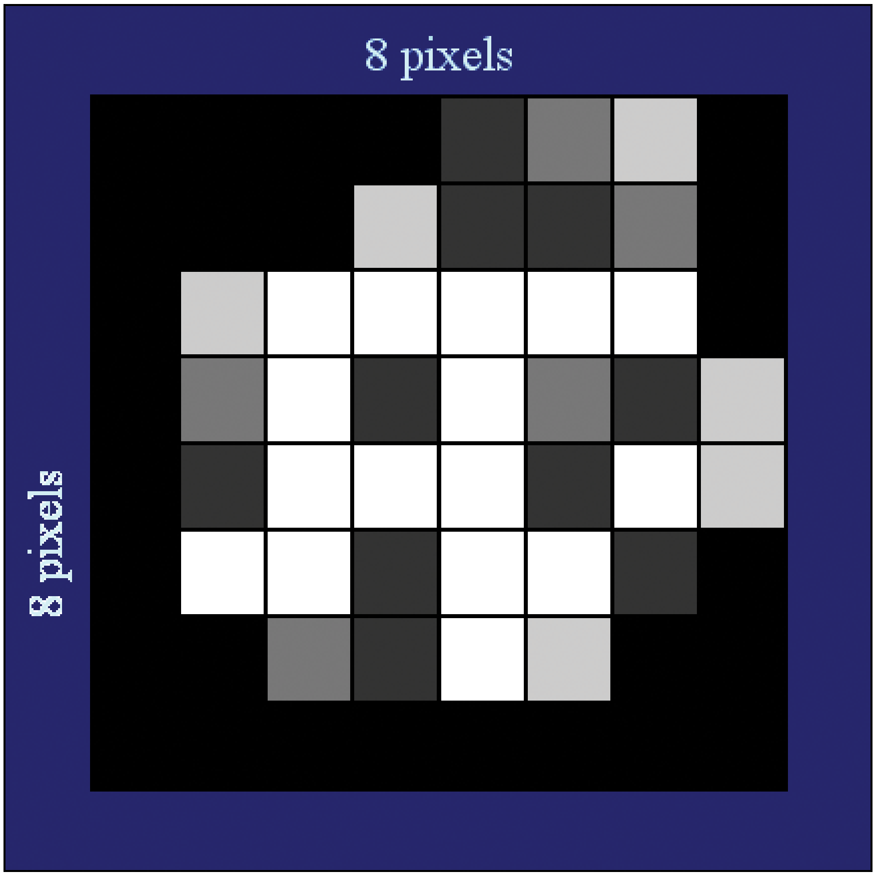
6. Completed Figure S4 (right):

8 pixels

8 pixels

1	1	1	1	1/4	1/2	3/4	1
1	1	1	3/4	1/4	1/4	1/2	1
1	3/4	0	0	0	0	0	1
1	1/2	0	1/4	0	1/2	1/4	3/4
1	1/4	0	0	0	1/4	0	3/4
1	0	0	1/4	0	0	1/4	1
1	1	1/2	1/4	0	3/4	1	1
1	1	1	1	1	1	1	1

7. a) Shaded Figure S5:



b) Answers to the questions will vary, but all answers should mention that even though the main features of the image are there—light-colored asteroid roughly at the center of the image—many details are coarse or lost.

8. There were 75 pixels in the image compressed with a lossless compression method, and 8×8 = 64 pixels in the image compressed with the lossy method. As usually is the case, the lossy method compresses the image more than the lossless method.

9. Answers will vary. Some of the points students may bring up include the fact that Figure S7 is not as clear as Figure S6 but still acceptable, while Figure S8 looks very choppy ("pixellated".) The smallest craters are not be visible in Figure S7, but the larger ones are; in Figure S8 only the largest craters are visible. In Figure S7, the shapes of the crater rims and features on the crater floors are difficult to see, while in Figure S8, the medium-size craters appear just as unresolved circular features, and it might be difficult to recognize them as

craters based on this image alone. The tectonic features are visible in Figure S7 (though they appear not quite as sharp as in Figure S6), but they are difficult to identify in Figure S8 The file sizes of Figures S7 and S8 are much smaller than Figure S6, but the quality of the data is also poorer (more so for Figure S8 than S7.)

10. a) 1018 × 1024 pixels × 8 bits per pixel / 400 bits per second = 20,849 s (5 hrs 47 min)

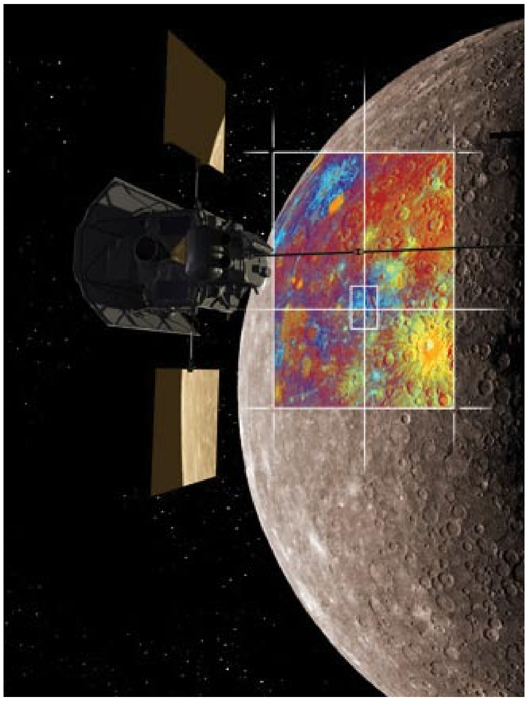
    b) 255 × 256 pixels × 8 bits per pixel / 400 bits per second = 1,306 s (21 min 46 s)

    c) 64 × 42 pixels × 8 bits per pixel / 400 bits per second = 54 s

    d) Answers will vary. Some students may prefer high-quality images which can yield a lot of information in close study, while others may prefer to receive several images which could then be compared with each other.

11. Answers will vary according to the file formats and image conversion software used.

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.

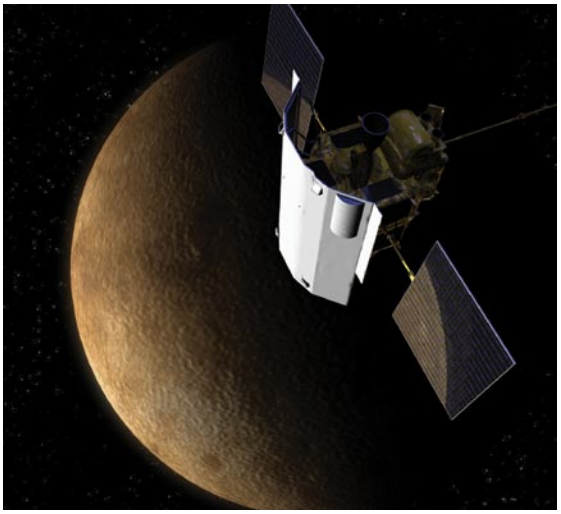
Sending a spacecraft to Mercury is complicated. The planet is so close to the Sun that MESSENGER will be exposed to up to 11 times more sunlight than it would in space near Earth. To prevent the intense heat and radiation from having catastrophic consequences, the mission has been planned carefully to 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!

For more information about the MESSENGER mission to Mercury, visit: http://messenger.jhuapl.edu/

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.

Transmitting collected data to the Earth. Advanced computer systems and communication protocols are some of the most important aspects of the MESSENGER mission. The spacecraft has to be able to operate largely autonomously at times when it cannot communicate with ground control on Earth. It is essential to make sure that the onboard computers can handle all probable circumstances the spacecraft may encounter during these times. MESSENGER's communications system includes several antennas to transmit science data to the Earth at different downlink rates, as well as receiving commands from ground control. The peak downlink rate while the spacecraft is in orbit around Mercury is about 400 bps. Before being sent to the Earth, the data is compressed using both lossless and lossy methods.