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

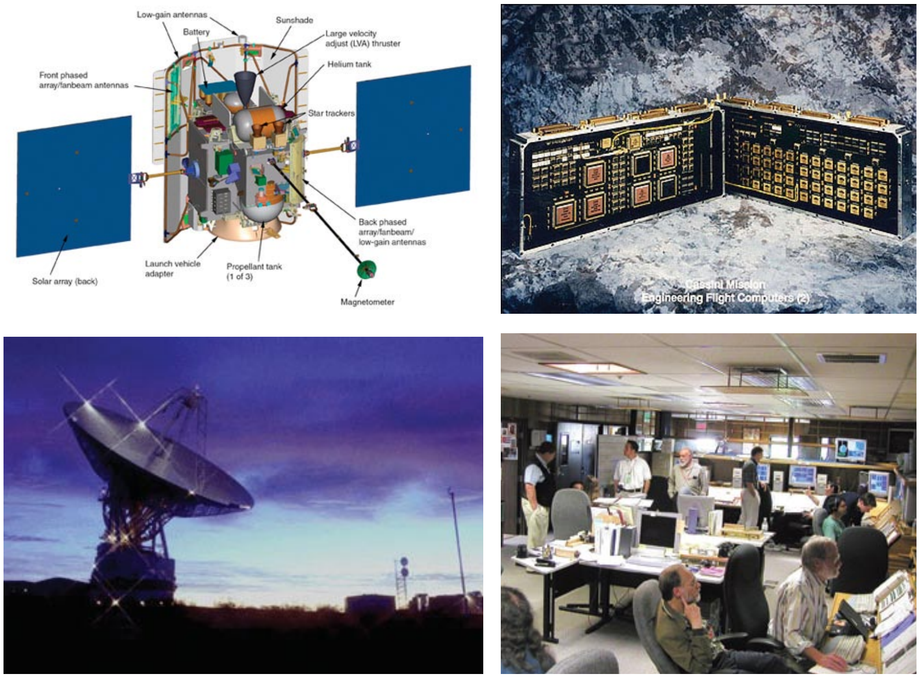

Figure 1. Robotic spacecraft cannot operate without reliable computers and communication protocols with ground control on Earth. Careful planning of these aspects is essential for all spacecraft mission designers, from planning the basic structure of the spacecraft (schematic of the MESSENGER spacecraft, 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)

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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:

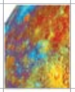
- Describe why careful design and implementation of computer programs is essential for spacecraft operations.
- Design a flowchart to describe the operation of a computer program.
- Explain how scientists select the optimum way for a spacecraft to compress and transmit data.

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

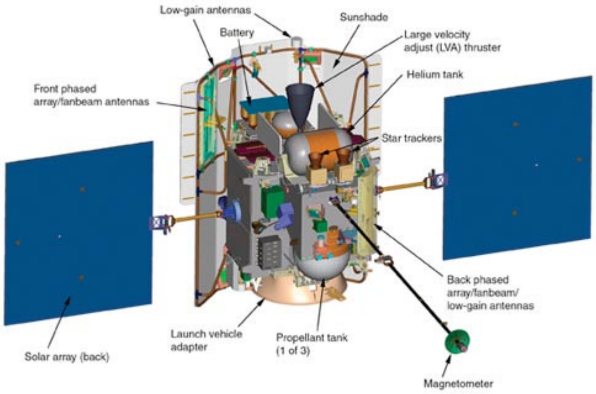


Figure 2. Schematic of the MESSENGER spacecraft. In designing a spacecraft mission such as the MESSENGER mission to Mercury, it is important to consider not only the instruments, power generation and engines, but also reliable computers and communication tools that are essential for robotic spacecraft. (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.

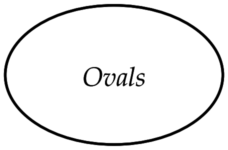
The basic unit of data in computer operations and communications is called a "bit." A bit is like a light switch: it can be either on or off. A single bit is represented as a one or a zero, and data is composed of long strings of ones and zeros. For example, the ASCII (American Standard Code for Information 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.

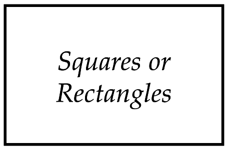
Flowcharts

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.

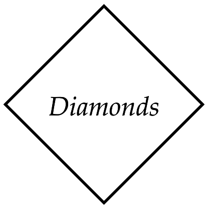
There are four basic symbols used in flowcharts:



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.

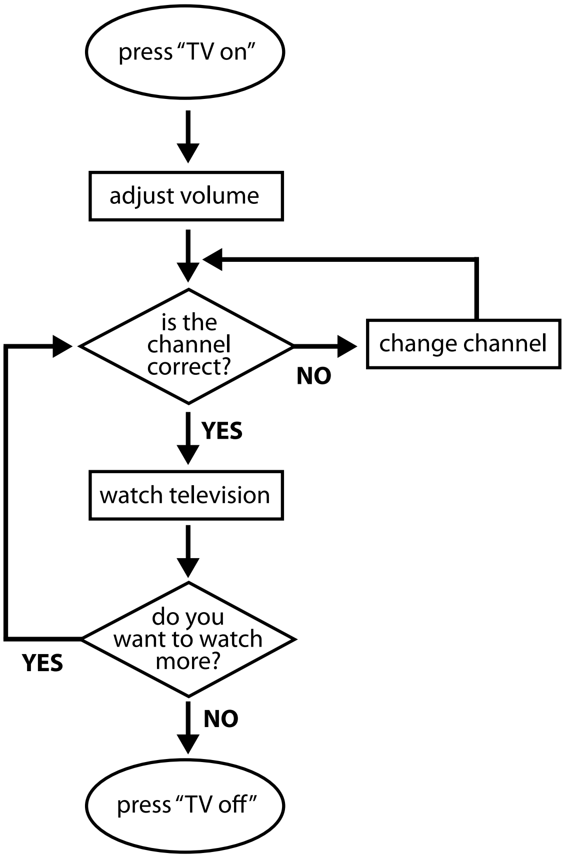


Figure 4. An example of a flowchart: how to watch television.

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.)

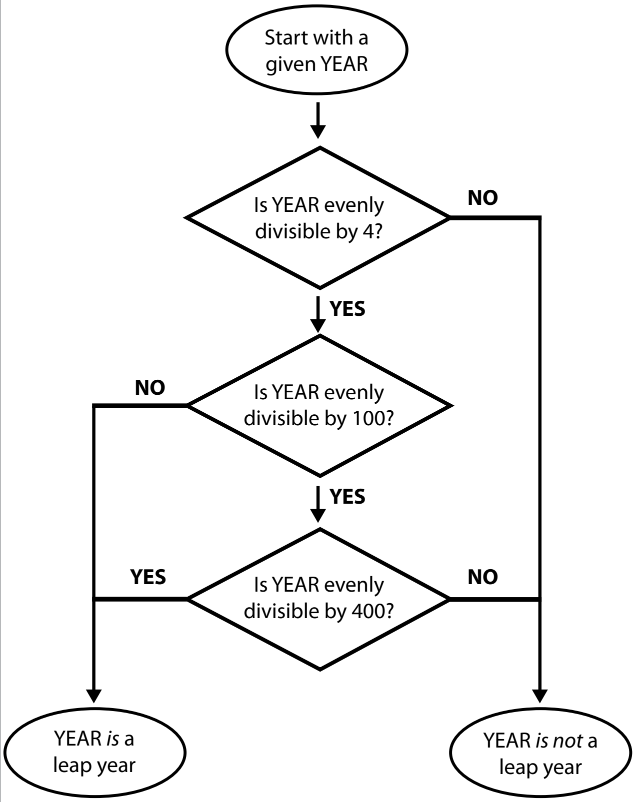


Figure 5. Flowchart to determine if a given year is a leap year.

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/

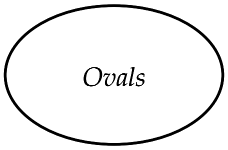
ACKNOWLEDGEMENT

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).

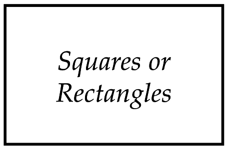
To Leap or Not to Leap?

Name: ______________________________ **Date:** ______________________

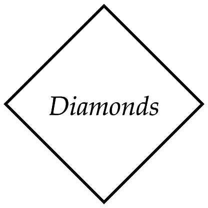
Flowcharts are a great tool in designing efficient computer programs. A flowchart is a visual representation of steps that are necessary to complete a task. It describes the individual steps to be taken, as well as the connections between them. A comprehensive flowchart can easily be converted to a computer 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.

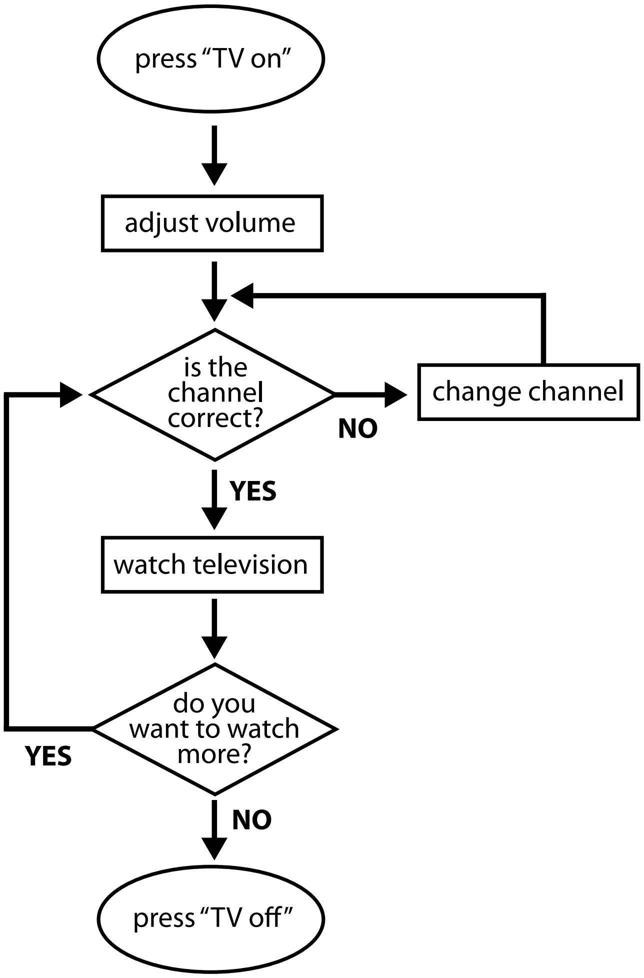


Figure S1. An example of a flowchart: how to watch television.

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

1-1-1-1-1-1-1-1-1-0-1-1-1-1-1-1-1-1-1-1-1-1-1-1-0-0-0-0-0-1-1-1-1-1-1-1-1-1-1-1-0-0-0-0-0-1-1-1-1-1-1-1-1-1-
1-0-0-1-1-0-0-1-1-1-1-1-1-1-0-0-0-0-0-0-0-0-0-1-1-1-1-1-1-0-0-0-0-0-0-0-0-0-0-0-1-1-1-1-1-0-0-0-0-0-0-0-0-1-
0-1-1-1-1-1-1-0-0-0-1-0-0-0-0-1-0-0-0-1-1-1-0-0-0-0-0-0-0-0-0-0-0-0-0-1-1-1-1-0-0-0-0-0-0-0-0-1-0-0-1-1-1-1-
0-0-0-0-0-0-0-0-0-0-0-0-1-1-1-1-0-0-0-0-0-1-0-0-0-0-0-1-1-1-1-1-1-1-0-0-0-0-0-0-0-1-1-1-1-1-1-1-1-1-1-1-1-0-
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

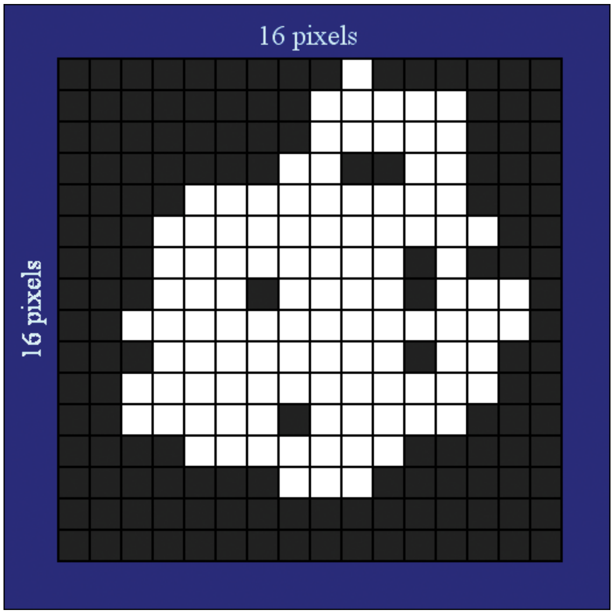


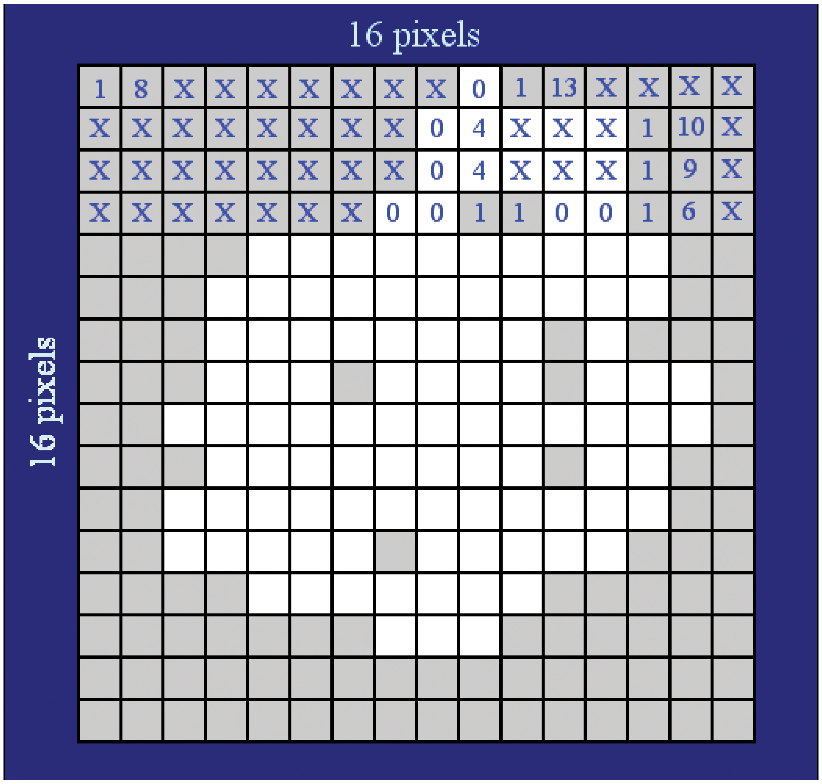
Figure S2. A picture that could be of an asteroid at the resolution of 16 × 16 pixels.

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.



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

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?

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.)

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?

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.

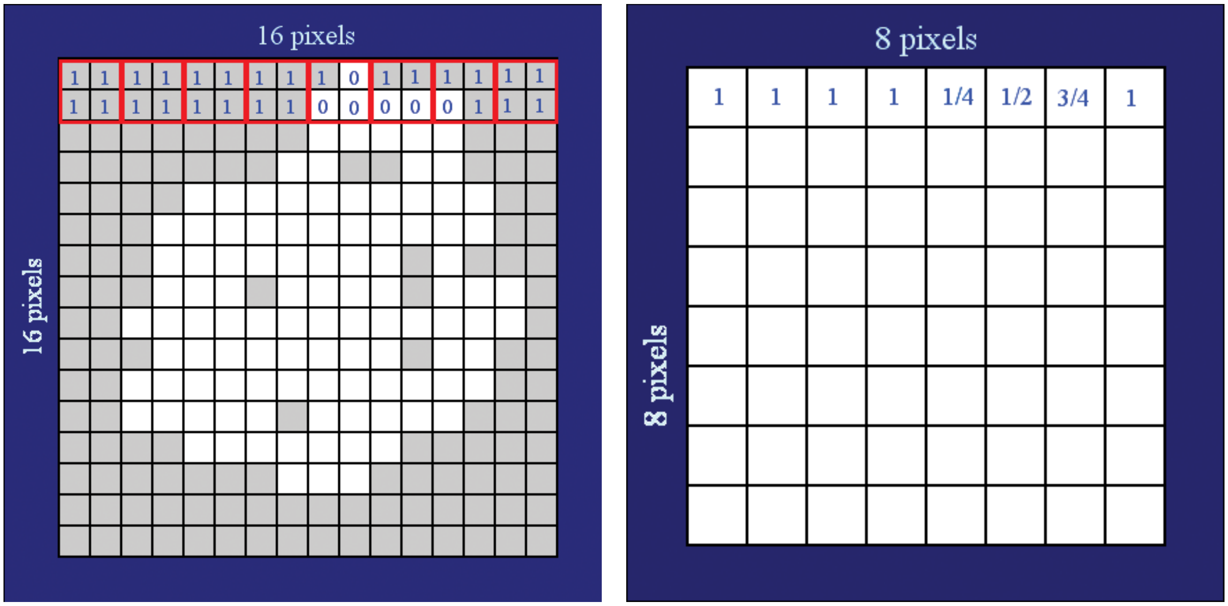


Figure S4. Using a lossy compression method to reduce the size of the original asteroid image through mathematical averaging. In this example, groups of four pixels in the original 16×16 image (left) are averaged to produce the values for pixels in the compressed 8×8 image (right.) The grouped pixels 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.

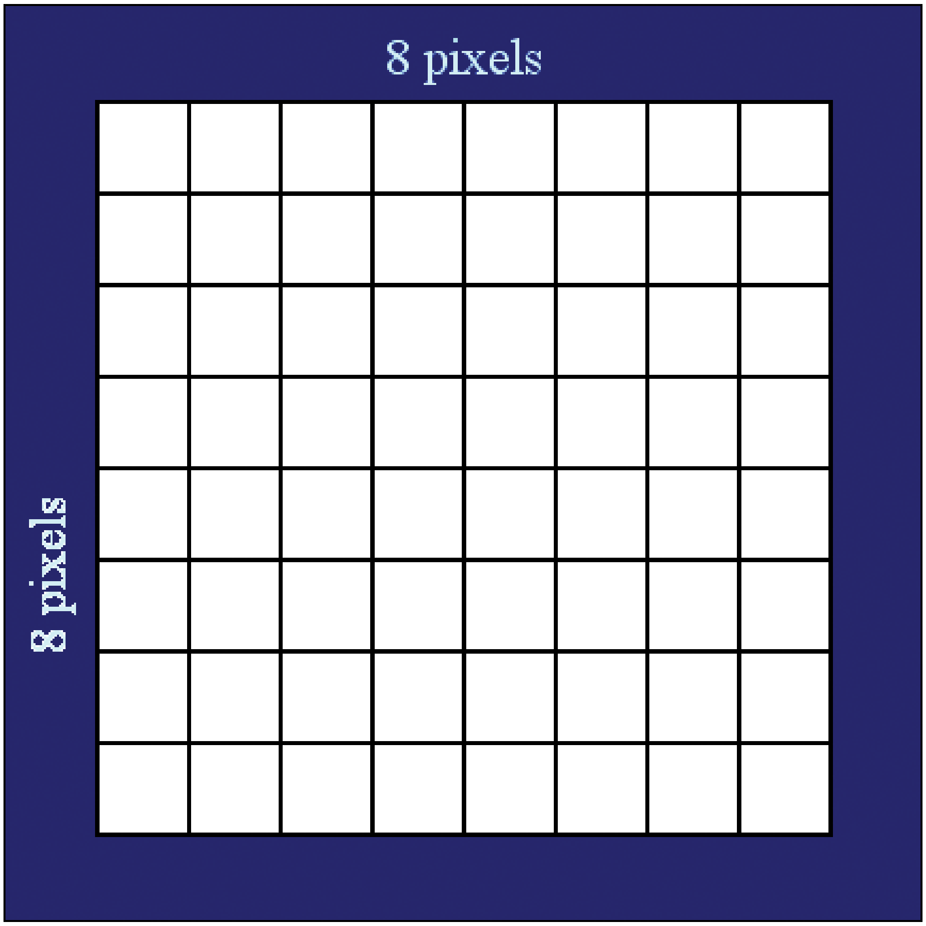


Figure S5. Compressed asteroid image. Shade the pixels based on the values you calculated in Figure S4.

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.

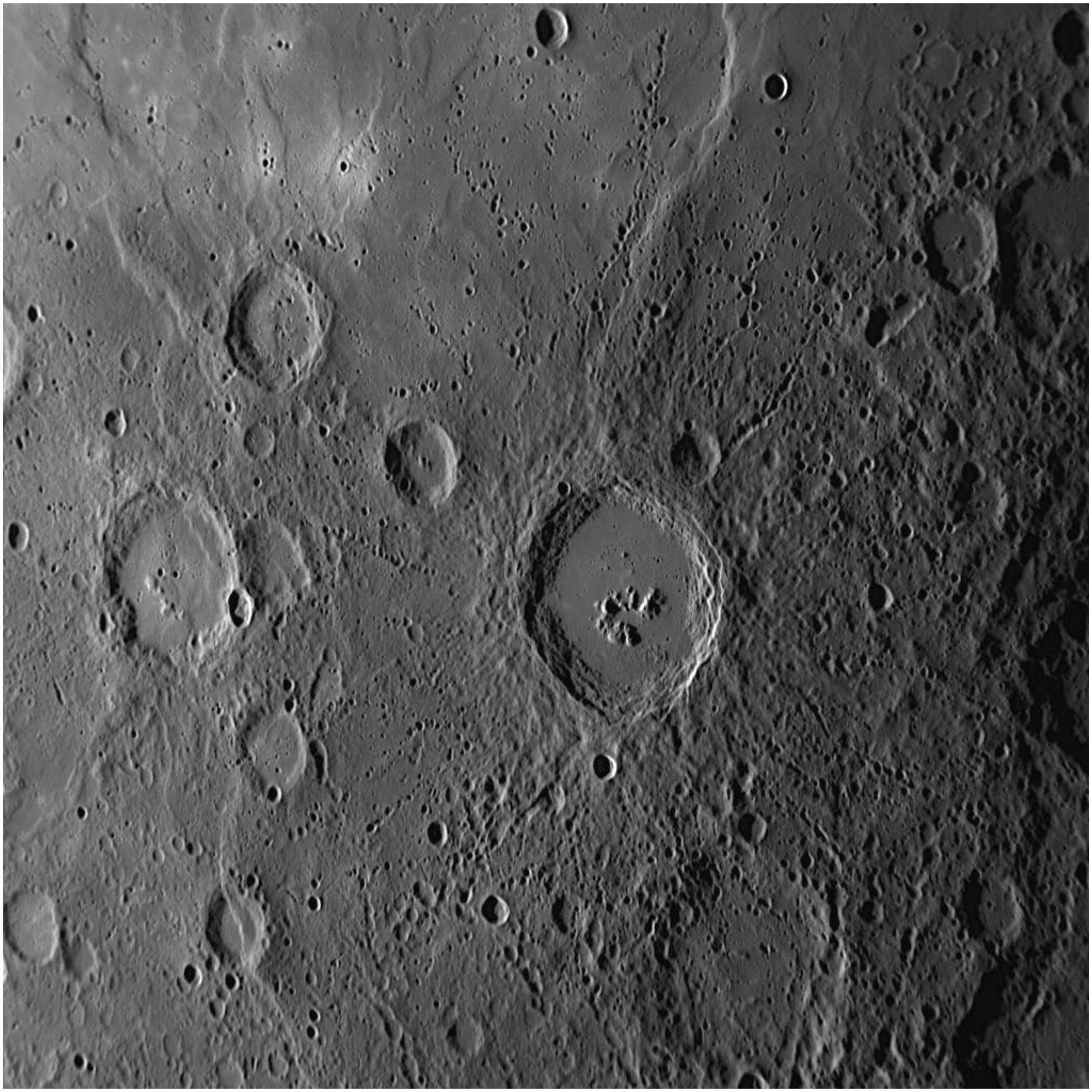


Figure S6. A picture of the surface of Mercury taken by the MESSENGER spacecraft in 2009. The image shows examples of the many geologic processes that have shaped Mercury's surface. There are impact craters of all sizes, down to the smallest craters barely visible in the image. Near the center of the 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)

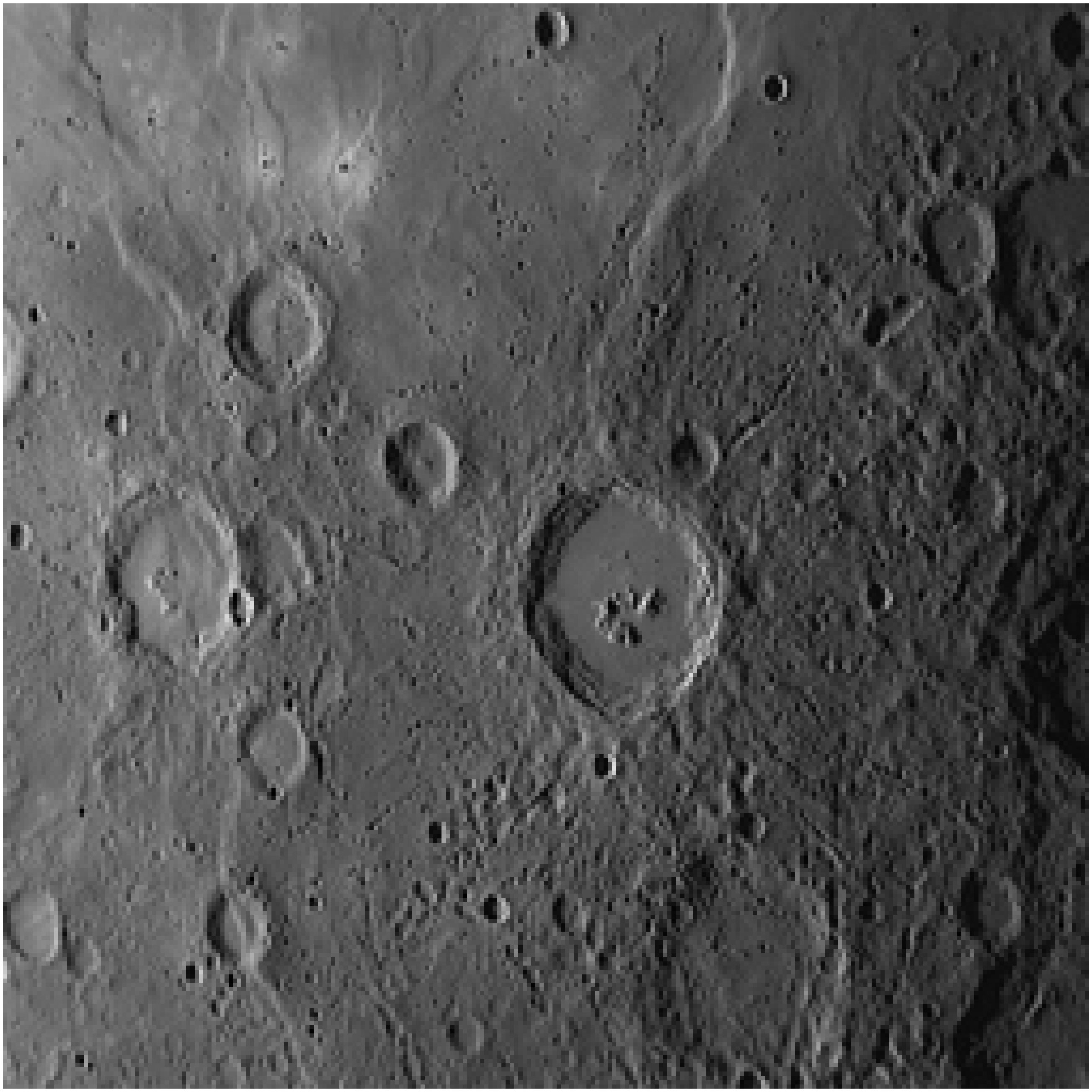


Figure S7. Same as Figure S6, but the image has been compressed so that the number of pixels in each direction is 1/4 of the original. The resulting resolution of the image is 255 × 256 pixels, and the size of the image file 48 KB.

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?

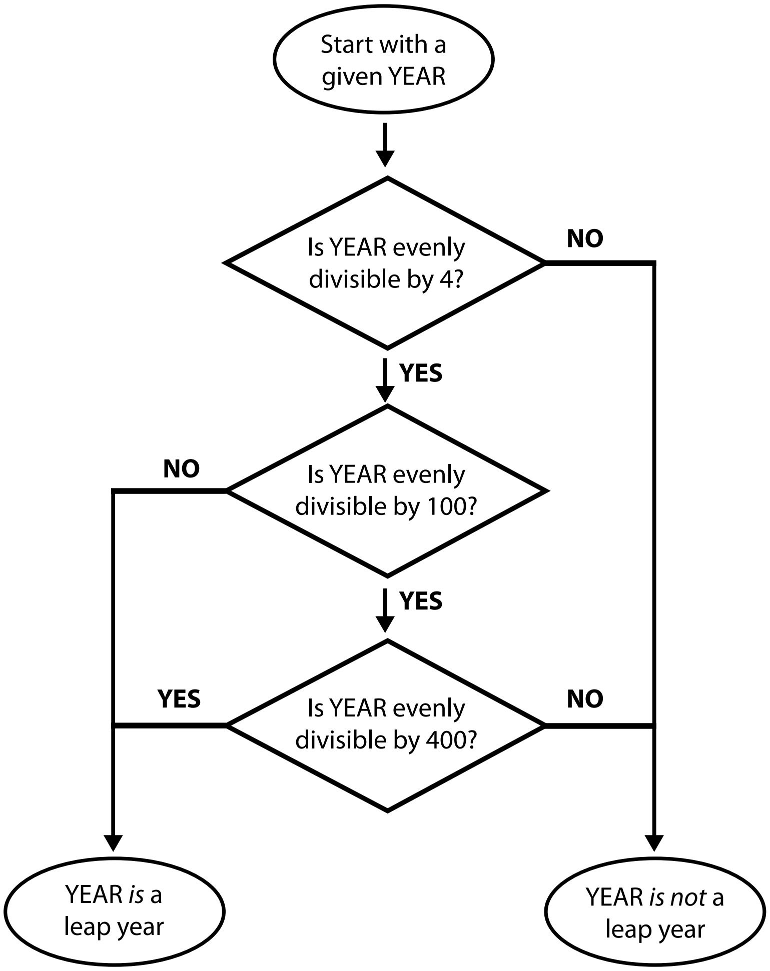
    d) What if there was a limit to the total amount of data you can receive from the spacecraft? Would you be willing to spend enough time to receive a couple of images similar to Figure S6, or would you rather have many images similar to Figure S7 or S8? Why or why not?

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

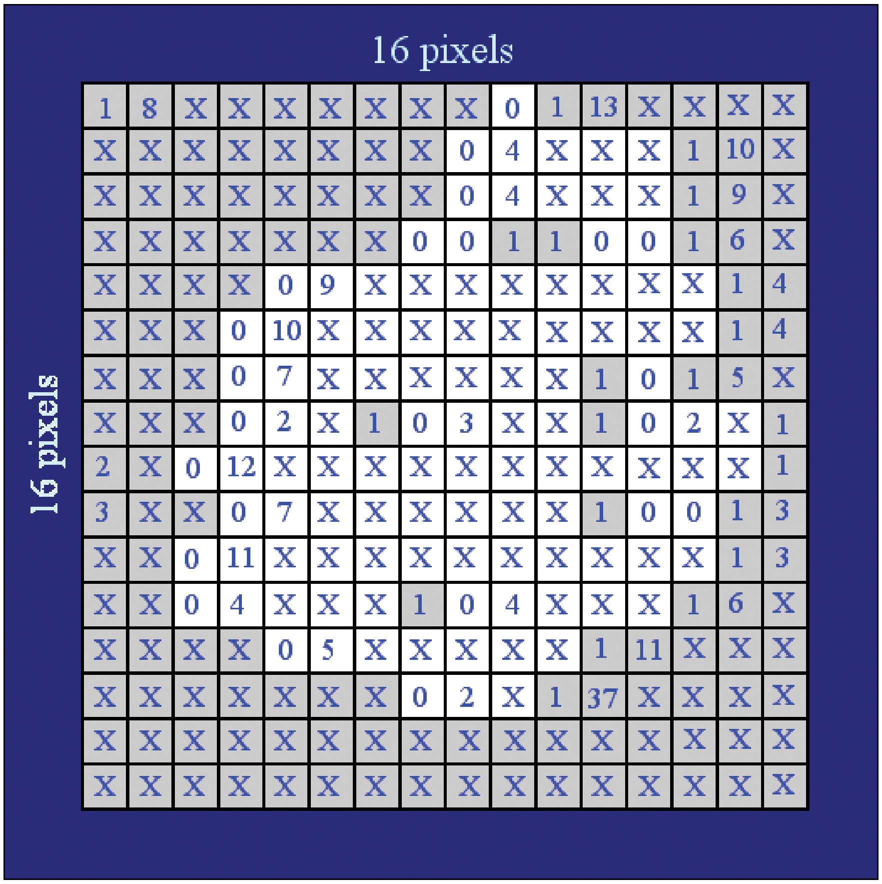
Flowchart to determine if a given year is a leap year or not.



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:



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

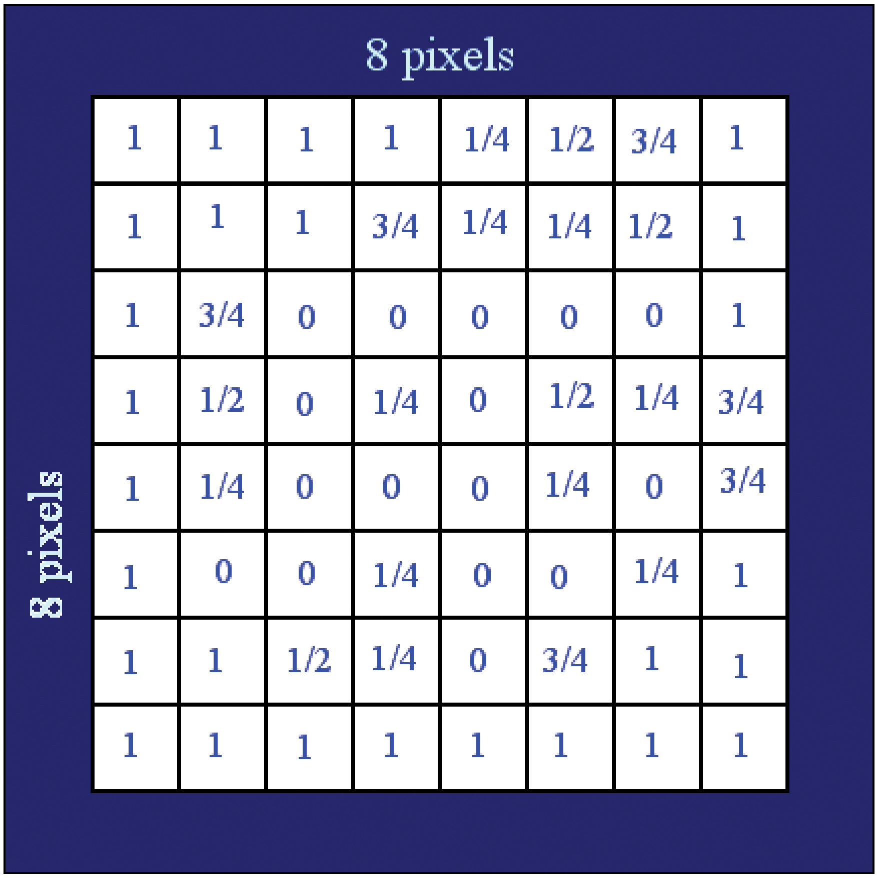
3. If the two pixels were given as "0" and "1," the second pixel could be thought of as being filled. In this case, since "0" and "1" are reserved for describing the color of the pixel, they cannot be used to denote the number of pixels with the same color.

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

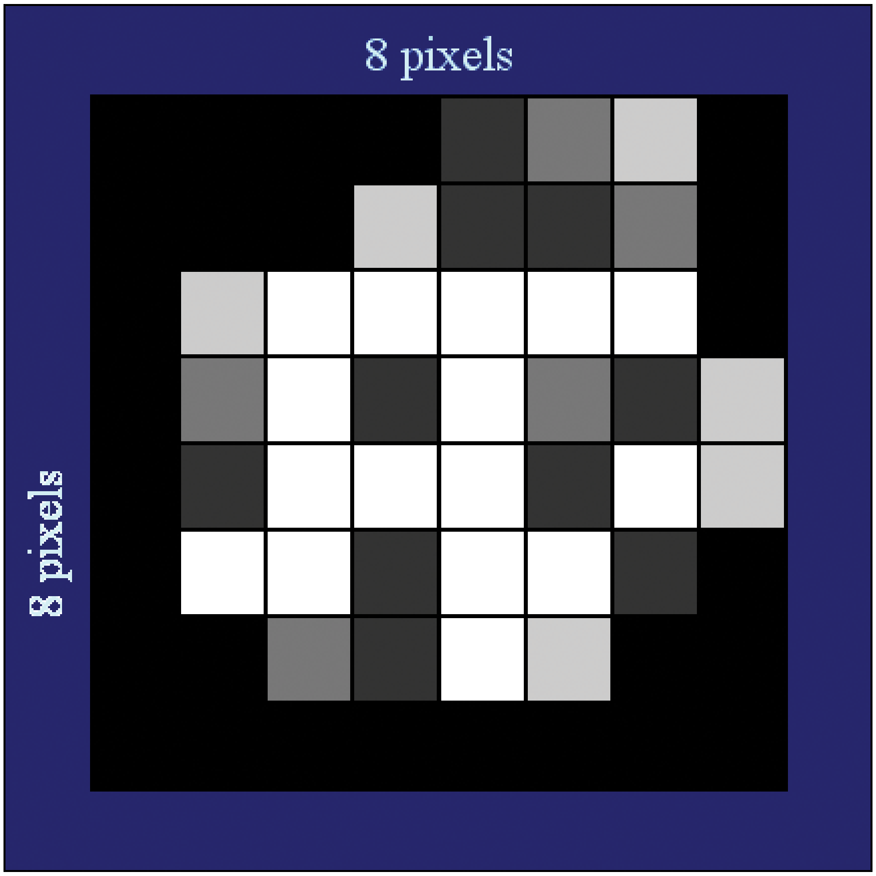
5. The compressed pixel string is much shorter than the original string. It also contains numbers other than "0" or "1." 181 pixels are saved. The number can be calculated by counting the number of "X"s in Figure S3, or by comparing the number of pixels in the original transmission string (16×16 = 256 pixels) and the reduced pixel transmission string in Step 4 (75 pixels.)

6. Completed Figure S4 (right):



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)

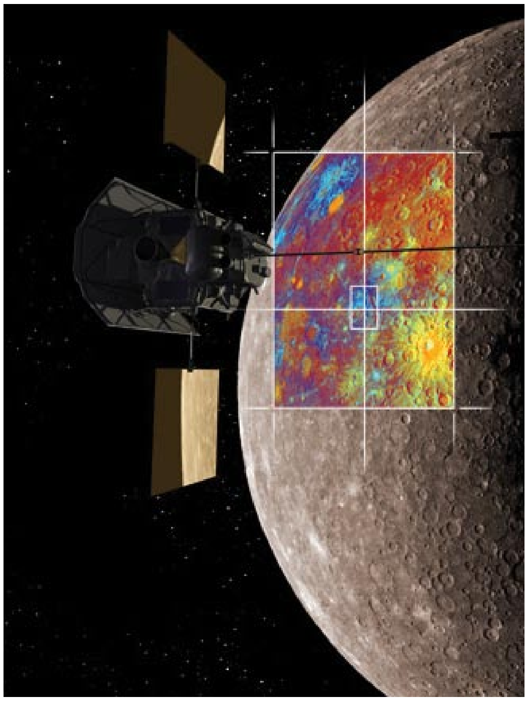
    b) 255 × 256 pixels × 8 bits per pixel / 400 bits per second = 1,306 s (21 min 46 s)

    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.

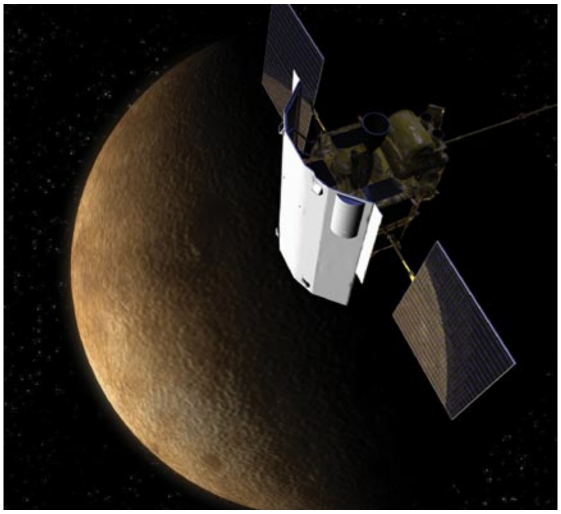
MESSENGER will be only the second spacecraft ever to study Mercury: In 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for one Earth year; its close-up observations will allow us to see the entire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

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.

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