National Aeronautics and Space Administration

# Deep Space Communications

## Educator Guide

EARTH AND SPACE SCIENCE

## Next Gen STEM – Moon to Mars

For more about Next Gen STEM visit https://www.nasa.gov/stem/nextgenstem/moon_to_mars

| Education Product | |
|---|---|
| Educators and Students | Grades 6-8 |

# Contents

# Preface

*Deep Space Communications* was published by NASA's Office of STEM Engagement as part of a series of educator guides to help middle school students reach their potential to join the next-generation STEM workforce. The activities can be used in both formal and informal education settings as well as by families for individual use. Each activity is aligned to national standards for science, technology, engineering, and mathematics (STEM), and the NASA messaging is current as of September 2021.

# STEM Education Standards

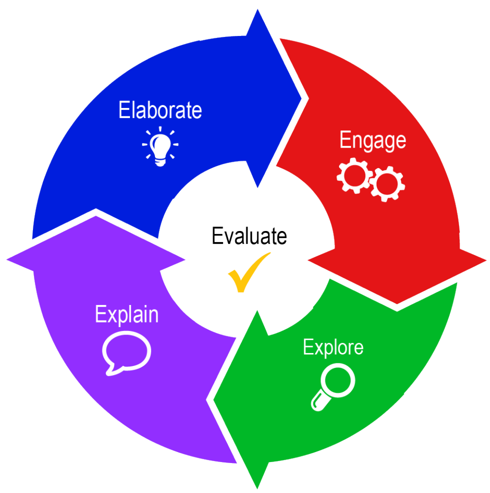
The STEM disciplines matrix shown below aligns each activity in this module to standards for teaching STEM according to four primary focus areas within each discipline. The four focus areas for science were adapted from the Next Generation Science Standards (NGSS) middle school disciplinary core ideas. The four focus areas for technology were adapted from the Computer Science Teachers Association (CSTA) Computer Science Standards. The four focus areas for engineering were adapted from the National Science Teaching Association (NSTA) and NGSS science and engineering practices. The four focus areas for mathematics were adapted from the Common Core State Standards (CCSS) for Math middle school content standards by domain.

| Activity | STEM Disciplines | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Science | | | | Technology | | | | Engineering | | | | Math | | | |
| | NGSS Disciplinary Core Ideas | | | | CSTA Standards for Students | | | | NSTA and NGSS Practices | | | | CCSS Content Standards by Domain | | | |
| | Physical Sciences | Life Sciences | Earth and Space Sciences | Engineering, Technology, and the Application of Sciences | Data Analysis | Networking and the Internet | Algorithms and Programming | Computing Systems | Ask Questions and Define Problems | Develop and Use Models | Plan and Carry Out Investigations | Construct Explanations and Design Solutions | Ratios and Proportional Relationships | The Number System | Expressions and Equations | Geometry |
| Communication | | | | | ✓ | | | | | ✓ | | | | | ✓ | |
| Latency | ✓ | | ✓ | | ✓ | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ |
| Performance | ✓ | | | ✓ | | ✓ | | | | ✓ | | | | | | |
| Networks | | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | | | | ✓ | |

# 5E Instructional Model

The 5E instructional model is a constructivist learning cycle that helps students build their own understanding from experiences and new ideas. This five-stage model was originally developed for the Biological Science and Curriculum Study (BSCS) Life and Living curriculum (https://bscs.org/bscs-5e-instructional-model/). Learn more about the 5E instructional model with NASA's eClips at https://nasaeclips.arc.nasa.gov/teachertoolbox/the5e.

1. **Engage**: Pique students' interest while pre-assessing prior knowledge. Students make connections between past and present learning experiences, which sets the groundwork for upcoming activities.
2. **Explore**: Get students involved in the activity by providing them with a chance to build their own understanding. Students usually work in teams during this stage, which allows them to build a set of common experiences through sharing and communicating.
3. **Explain**: Provide students with an opportunity to communicate their understanding of what they have learned so far. Students at this stage can communicate what they have learned by introducing vocabulary in context and correct or redirect misconceptions.
4. **Elaborate**: Allow students to use their new knowledge and explore its implications. Students expand the concepts they have learned, make connections, and apply their understanding in new ways.
5. **Evaluate**: Determine how much learning and understanding has taken place. Students can demonstrate their learning through journals, drawings, models, and other performance tasks.




# Computational Thinking Model

The seven core practices of the K–12 Computer Science Framework have been incorporated into most of the activities within this guide. More information about these core practices is available at https://k12cs.org/navigating-the-practices/.

1. **Fostering an inclusive computing culture**: Everyone needs computers, but not everyone uses computers in the same way. An inclusive computer culture requires advocating for features and approaches that make technology as accessible and accommodating as possible.
2. **Collaborating around computing**: Two heads are better than one, but only when the team shares mutual respect and understanding. This includes making sure that workloads are split fairly and feedback is constructive.
3. **Recognizing and defining computational problems**: Computers can help with many (but not all) situations, and the usefulness of computers depends on simplifying complex, real-world problems into small, repeatable pieces that a computer handles better than a human can.

4. **Developing and using abstractions**: While every sandwich is different, most sandwiches involve something between two slices of bread. Systems can often be more versatile and efficient when they are designed to reflect the “big picture” rather than one specific situation.
5. **Creating computational artifacts**: Ideas are great, but at some point progress requires a clear plan and, ultimately, the creation or modification of a program, video, robot, or other technology.
6. **Testing and refining computational artifacts**: Computers do not "think" the same way humans do, and end users do not always think the same way the designer did. This means that all technology must be thoroughly tested to minimize errors and maximize performance, reliability, usability, and accessibility.
7. **Communicating about computing**: The best technology in the world is useless if nobody knows that it exists or how to use it. It is important to create documentation (such as a user manual) and to justify the benefits of any new technology. It is also important to fairly and responsibly attribute or license any intellectual property that came from others.


K–12 Computer Science Framework's 7 Core Practices. (Adapted from K–12 Computer Science Framework, Creative Commons license CC BY-NC-SA 4.0.)

# Curriculum Connection

In this module, students will be learning about the following four concepts in the context of NASA's Deep Space Network (DSN): communication, latency, performance, and networking. These concepts are fundamental for modern telecommunications and are increasingly important the farther away from Earth we want to communicate. This guide will challenge students to build upon their prior understandings of communication (such as knowledge about waves, the speed of light, the solar system, and networking) in order to understand the creation, operation, and scale of NASA's DSN. Students will have an opportunity to communicate as if they were computers by encoding data into or decoding data from binary or hexadecimals; calculating latency time between the Earth and different objects in the solar system; simulating how a signal can be delivered, delayed, or degraded; and intertwining all of these concepts into the broader concept of networking. A variety of additional resources within each activity will not only enhance the experience but will also allow students to visualize how these concepts impact their everyday lives. Educators and facilitators are encouraged to explore the additional content provided in each activity as deep space communications are ever changing based on research. While NASA communications technologies can be found almost everywhere in the lives of students, the following two examples highlight recently developed NASA spinoff technologies related to research in deep space communications.

## SOFTLINK

An enormous amount of data is streamed from the International Space Station, located approximately 420 km (250 mi) above the Earth's surface. This space-to-Earth data transfer, which is communicated through the Near Space Network (NSN), is made possible by customizable software architecture produced by AMERGINT Technologies, Inc. AMERGINT is the developer of SOFTLINK, which consists of what the company calls Software Devices—software modules that can be virtually chained together in various configurations for any specific task. AMERGINT was able to use this customizable architecture to design Johnson Space Center's Communication Data Processor, which can stream massive amounts of data from the space station.

https://spinoff.nasa.gov/Spinoff2018/it_8.html

## Tule


NASA has more than two dozen satellites that observe how the planet is changing. These satellites, which communicate data through the NSN, also measure important climate indicators, such as clouds and precipitation, the depth of oceans and inland waters, and carbon dioxide levels in the atmosphere. Satellites can also help monitor the availability of groundwater as well as climate conditions that can lead to drought. This information can help farmers determine where and how often to water their crops. Tule Technologies uses data provided by NASA imagery from the Geostationary Operational Environmental Satellites (GOES) and Landsat satellites to measure the distribution of heat from the Sun across the surface of the Earth as well as the escape of heat back into space. This allows Tule to calculate how much water is being vaporized. This is done with the imagery from the GOES system, which allows Tule to get measurements every 5 minutes. Now farmers can know exactly how much water to use for their crops and prevent the wasting of such a valuable resource.

https://spinoff.nasa.gov/Spinoff2020/ee_2.html

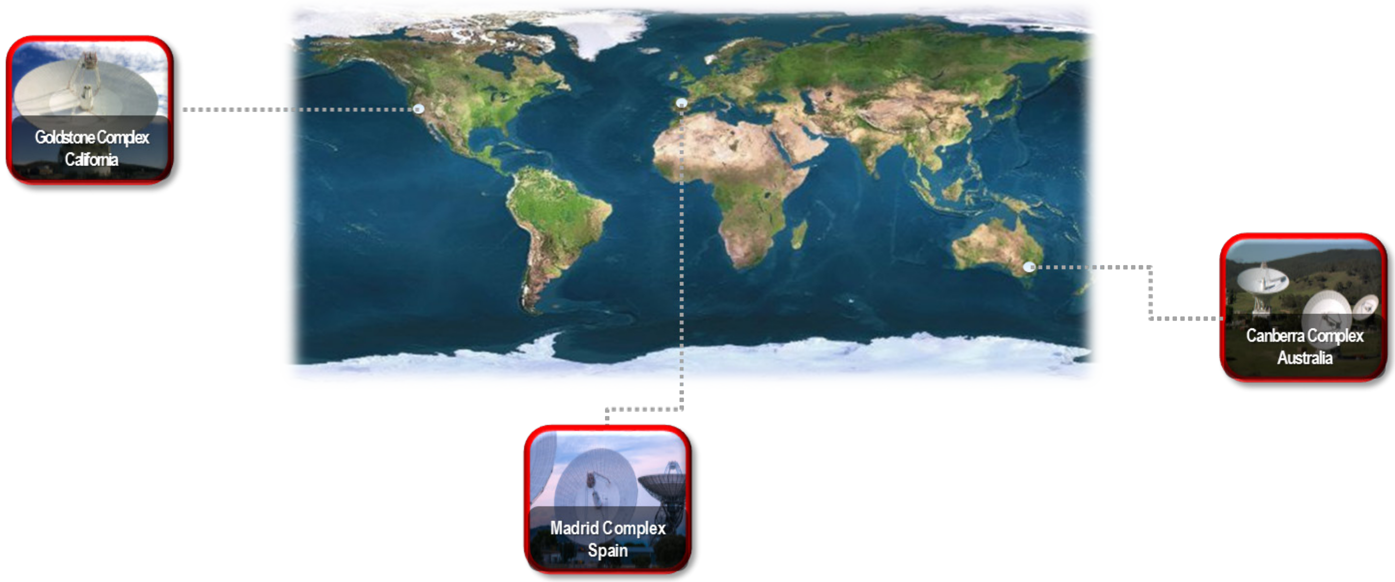
# Introduction and Background (Deep Space Network)


In 2013, NASA's Deep Space Network celebrated 50 years of providing communications and tracking services.

Space Communications and Navigation (SCaN) serves as the program office for all of NASA's space communications activities. SCaN manages and directs the ground-based facilities and services provided by the Deep Space Network (DSN) and the Near Space Network (NSN). The DSN and NSN support both NASA and non-NASA missions. Although most of this module focuses on the DSN, students will also learn about the role the NSN plays in deep space communications. The DSN's primary functions are telemetry, spacecraft command, tracking, radio science, and science research. The NSN is a single point of contact for missions in the near-space region (up to 35,000 km (21,728 mi) from Earth). It arranges communications services, space links, and data transmission for users. These two networks facilitate NASA's space communication activities.

The DSN is NASA's international array of giant radio antennas supporting interplanetary spacecraft missions. Deep space begins at approximately 42,000 km (26,098 mi) from Earth. While some of the satellites of the DSN are in deep space, many of them are in geostationary (GEO) orbit, with slightly closer altitudes of 35,000 to 42,000 km (21,748 to 26,097 mi). The DSN is a powerful system for commanding, tracking, and monitoring the health and safety of spacecraft. It also enables powerful science investigations that probe the nature of asteroids, planets, and moons. The DSN provides radar and radio astronomy observations that expand our understanding of the solar system and of the larger universe.

Established in January of 1958, the DSN is operated by NASA's Jet Propulsion Laboratory (JPL) in California, which also manages many of NASA's interplanetary robotic space missions. The DSN consists of three major facilities spaced equidistant from each other, approximately 120° apart in longitude, around the world: the Goldstone Deep Space Communications Complex near Barstow, California; the Madrid Deep Space Communications Complex in Spain; and the Canberra Deep Space Communications Complex in Australia. All three DSN sites are composed of multiple large antennas and are designed to enable constant radio communication between spacecraft and Earth. Each complex consists of at least four antenna stations equipped with large, parabolic dish antennas and ultrasensitive receiving systems capable of detecting faint radio signals sent from distant spacecraft. The large antennas must point toward the spacecraft with extreme accuracy. An antenna can "see" only a tiny portion of outer space at a time—not unlike looking at the sky through a soda straw.




Map showing the three Deep Space Network sites, which are located in Australia, California, and Spain. (NASA)

The antennas of the DSN are the indispensable link to explorers venturing beyond Earth. They provide the crucial connection for commanding our spacecraft and receiving their never-before-seen images and scientific information on Earth, propelling our understanding of the universe, our solar system, and ultimately our place within it.

## Communication

The DSN provides communication between planetary exploration spacecraft and scientists on Earth. The strategic placement of the DSN sites permits constant radio communication with spacecraft. As a distant spacecraft sinks below the horizon at one DSN site, another site can pick up the signal and carry on communication with no loss of signal. The DSN performs many functions, including spacecraft command and radiometric tracking of spacecraft. It monitors and controls real-time data and supports science such as radio astronomy. At its simplest, space communication relies on two things: a transmitter and a receiver. A transmitter encodes a message onto electromagnetic waves. The data moves through modulation, which changes the property of the wave to represent data. These waves then radiate through space to a receiver, which collects the electromagnetic waves and decodes the message. This is similar to a Wi-Fi (wireless fidelity) router and networked devices around the home. Each device receives a signal from the router, which transmits data from the internet. In space, however, the distortion of the message increases as a function of the square of the distance. This is because the energy of the signal is spread out more as the radius of the signal increases. For example, a candle placed in the center of a small room will light up all the surrounding walls; however, a candle placed in a larger room will not light the room as brightly because its light is spread over a larger area. For a strong signal to reach longer distances, it must be transmitted at higher powers. The following table shows the power needed to emit a signal that would have the same strength at the destination given the distance between the transmitter and receiver.

### Space Communications

| Application | Approximate distance, km (mi) | Relative power of transmitter needed, kW* |
|---|---|---|
| Smart phone cell tower | 1 (<1) | 1 |
| TV station to home | 10 (6) | 100 |
| International Space Station in low Earth orbit (at closest approach) | 400 (248) | 160,000 |
| Communications satellite at geosynchronous orbit | 40,000 (24,854) | 1,600,000,000 |
| Mars | 300,000,000 (186,411,357) | $9\times10^{16}$ |
| Pluto | 5,000,000,000 (3,106,855,961) | $2.5\times10^{19}$ |

*The powers listed are notional and not actual.

However, in deep space communications, due to size and weight constraints of the spacecraft, communication equipment transmits signals at a very low power, usually about the amount of energy spent pedaling a bicycle. The spacecraft antenna focuses the signal into a narrow beam. As they travel, these signals get weaker and weaker. By the time they reach their destination, the signals are sometimes so weak that trillions of messages could be sent before the receiver has absorbed enough power to light a lightbulb. Using multiple antennas together as one gigantic antenna is called an array. Arraying allows the capture of these weak signals and enables a better data rate. Therefore, the antennas of the DSN are great in size (70 and 34 m, or 230 and 112 ft). The larger antennas can be compared to the size of a football field. In addition to direct-to-Earth communications, NASA missions also depend on relay satellites to get their data to the ground.

Deep Space Station 56 (DSS–56), a 34-meter- (112-foot-) wide antenna in the Madrid Deep Space Communications Complex in Spain. (NASA)

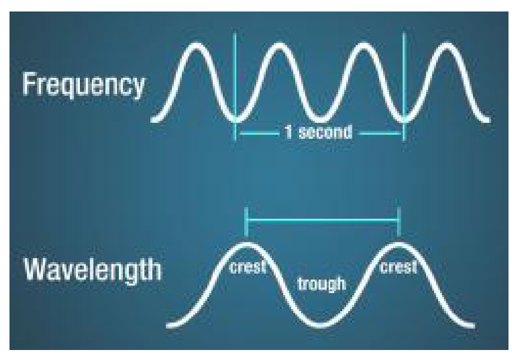
In Activity One, students will explain how NASA communicates with astronauts, satellites, rovers, and other spacecraft. Students will demonstrate how communications work in the DSN by encoding and decoding messages using binary code or hexadecimals.

## Latency

At some point, all communications (e.g., spoken words, text on a page, radio broadcasts, or laser transmissions) travel as waves through a medium. For spoken words, those waves would be sound waves, but long-distance communication is primarily based on electromagnetic waves such as visible light, infrared light, microwaves, or radio. For humans on Earth, the medium through which those waves travel is commonly air; but for most of the universe, the medium is the vacuum of space. In any medium, all waves of a given type travel at the same speed. NASA is mostly concerned with electromagnetic waves such as visible light and radio traveling through the vacuum of space. The speed of light in a vacuum is approximately 299,338 km (186,000 mi) per second, which is fast but not instantaneous. The amount of time it takes for a signal to travel to its destination is called *latency*. Light travels slightly slower through air or water, but nothing travels faster than light in a vacuum, and all electromagnetic waves in a vacuum travel at the speed of light. The speed of a wave can be broken into two parts: frequency and wavelength, as shown in the diagram below.

### Frequency

The number of crests that pass a given point within 1 second is described as the *frequency* of the wave. One wave—or cycle—per second is called a hertz (Hz), named for Heinrich Hertz, who established the existence of radio waves. A wave with two cycles that pass a point in 1 second has a frequency of 2 Hz.




Frequency is measured as the number of wave crests that pass a given point in 1 second. Wavelength is measured as the distance between two crests. (NASA)

### Wavelength

Electromagnetic waves have crests and troughs similar to those of ocean waves. The distance between crests is the *wavelength*. The shortest wavelengths are just fractions of the size of an atom, while the longest wavelengths scientists currently study can be larger than the diameter of our planet!

One way to think of it is this: the speed of a runner is based on the length of their stride (wavelength) and how often they take a step (frequency). If two runners with different lengths of strides are running at the same speed, the runner with a shorter stride must take steps more frequently than the runner with the longer stride in order to keep pace. Since all electromagnetic waves travel at the same speed through space, if they have different wavelengths, then their frequencies must also be different by a calculable amount. If we know any two of the three properties of a wave (speed, wavelength, or frequency), we can calculate the third according to the following formula: **speed = frequency × wavelength.**

### Deep Space Communications

While the speed of light is very fast, even light takes some time to travel over a distance. For example, the latency (travel time) from the surface of the Earth to low Earth orbit, which is approximately at an altitude of less than 1,000 km (621 mi), is about 0.001 seconds, and the latency from the surface of the Earth to the Moon is about 1 second. That may not seem like much, but when NASA is trying to communicate with something far from Earth, latency can become a major challenge. At its closest approach, Mars is approximately 56 million km (35 million mi) away, and the latency is 4 minutes. At its furthest, Mars is approximately 402 million km (250 million mi) away, and the latency would be approximately 24 minutes. This means that astronauts or rovers on Mars would have to wait 4 to 24 minutes for messages they send to reach mission control, and another 4 to 24 minutes to receive a response back from mission control.

In Activity Two, students will explain the relationships among frequency, wavelength, and speed. They will calculate the latency between Earth and other locations and construct a model to demonstrate the ongoing change in distance that occurs between Earth and Mars.

## Performance

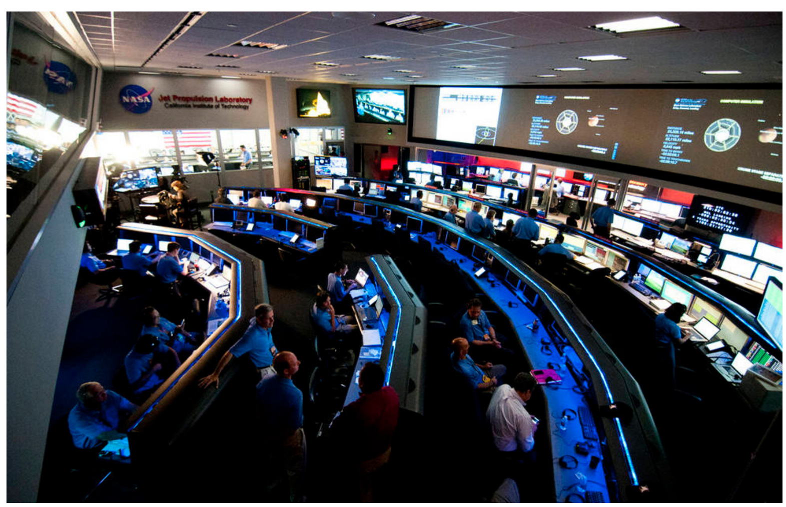
Sending messages and data gets more complicated the farther those signals have to travel. A signal might be blocked by something getting in the way, and radiation from the Sun or other celestial bodies can also interfere with the quality of transmissions. With enough of these types of complications, the message might degrade to static, be garbled into nonsense, or never arrive at all. To maximize the likelihood of sending a message successfully, NASA must take special precautions known as *communication protocols* or a *protocol suite* (a whole system of rules for transmitting information). For example, NASA encodes data on specific bands of electromagnetic frequencies to take advantage of their physical properties. One such property is that the higher the frequency of a wave, the more data that can be carried per second; this allows spacecraft to downlink data more quickly. NASA currently uses radio waves but is developing ways to communicate using infrared lasers. This new type of transmission, known as optical communications, will offer higher data rates than ever before.

Another communication technology NASA is developing is Delay/Disruption Tolerant Networking (DTN). DTN is a computer networking model and protocol suite that can handle frequent link disruptions or very long latency times (the time it takes to transfer information). The DTN protocol suite can work in tandem with the terrestrial internet protocol (IP) suite or independently. Computers have IP addresses in the same way a house has a street address. If there is any connection interruption, data is lost. The DTN assures delivery using a store-and-forward mechanism. Each piece of the message (data packet) received is forwarded immediately, if possible, or stored for future transmission if that is not possible.

In Activity Three, students will explore how a data packet may become degraded during deep space communications. They will develop a protocol that will diminish this degradation.

## Networks

The DSN is operated by NASA's Jet Propulsion Laboratory (JPL). The DSN is NASA's international array of giant radio antennas that provide the crucial connection for commanding spacecraft and receiving their never-before-seen images and scientific information. In 2020, the Near-Earth Network and Space Network combined to make the Near Space Network (NSN). Operated by NASA's Goddard Space Flight Center (GSFC), the NSN utilizes Government and commercial ground stations and antenna, including the relay capabilities of the Tracking and Data Relay Satellite (TDRS), to communicate with near-Earth missions. Some near-Earth missions look back at our Earth and observe the way the planet is changing. Other missions, like the



The present-day mission control room at the Jet Propulsion Laboratory—the Space Flight Operations Facility—serves as the nerve center for NASA's Deep Space Network. Because this control room supports many missions that expand humanity's cosmic horizons, it is sometimes informally referred to as "the center of the universe." (NASA/JPL-Caltech)

Hubble Space Telescope, look out at the universe and take pictures of stars and other phenomena millions of miles away. The International Space Station, which has had a human presence for over 20 years, conducts hundreds of science experiments by its astronauts that are necessary to understand how the world and the human body work.

In Activity Four, students will learn how computers solve networking problems using minimum spanning trees, which determine the shortest and most efficient route to each destination within a network. Students will then create their own minimum spanning trees as a culmination to the activity.

# Activity One: Communication

## Educator Notes

### Learning Objectives

Students will

- Analyze and interpret patterns when converting an 8-bit RGB (red, green, and blue) color code to hexadecimal notation.
- Encode and decode a variety of data into and from binary or hexadecimal notation.
- Replicate binary notation using objects or symbols to encode a message.

### Challenge Overview

In this activity, students will simulate how astronauts, satellites, rovers, and other spacecraft are able to send data digitally to Earth from deep space. Students will learn to convert between binary, decimal, and hexadecimal notation to decode images, create encoded messages, and create a cipher. Finally, students will design a unique project using one of the skills they have learned during this activity.

### Suggested Pacing

120 to 150 minutes

### National STEM Standards

| Computer Science (CSTA) |
|---|
| *Standards for Students*<br>• 2-DA-07: Represent data using multiple encoding schemes. |
| **Science and Engineering (NGSS)** |
| *Engineering Practices*<br>• Developing and Using Models: Develop or modify a model—based on evidence—to match what happens if a variable or component of a system is changed. |
| **Mathematics (CCSS)** |
| *Mathematical Practices*<br>• CCSS.MATH.CONTENT.6.EE.B.6: Use variables to represent numbers and write expressions when solving a real-world or mathematical problem; understand that a variable can represent an unknown number, or depending on the purpose at hand, any number in a specified set. |

### Challenge Preparation

- Read the introduction and background information to become familiar with the challenge. The Deep Space Network information will be of particular interest for this activity.
- Read the Educator Notes and Student Handout to become familiar with the activities.
- Read the sheet "Decimal, Hexadecimal, and Binary Number Systems Overview" (located at the end of the Educator Notes) to review how to express integers in bases other than 10 (decimal), specifically binary (base 2) and hexadecimal (base 16). This sheet also includes an overview on converting 8-bit RGB color codes to hexadecimal and binary notation.
  - At the discretion of the educator, students can use a calculator or internet-based converter to change numbers between the different bases (e.g., from decimal to binary, or from hexadecimal to decimal). In the **Elaborate** section, there are two optional advanced activities for students to learn to do the conversions by hand. Read the "Hexadecimal Conversions" and "Binary Conversions" activity sheets to learn more about converting 8-bit RGB color codes to hexadecimal and binary notation to determine if these advanced activities are appropriate for your students.
- Determine which of the 10 student activities listed in the **Elaborate** section will be available as choices for students. Decide how many activities each student must complete.

Download and review the student activity documents in the downloadable zipped file. https://www.nasa.gov/sites/default/files/atoms/files/deepspacecommunications.zip

- Make copies of the activities, if necessary, or ensure that computers and programs will be available.
- If putting students in groups, have the groups prearranged.
- Have a variety of miscellaneous craft materials available for the final project, or allow time for students to bring in materials found around the house.

## Materials

- ☐ Computer with internet access
- ☐ "Hello" name tags
- ☐ Pencils
- ☐ Student Handouts
- ☐ Printouts (Make copies for students as needed)
  - Decimal, Hexadecimal, and Binary Number Systems Overview
  - American Standard Code for Information Exchange (ASCII)
- ☐ Miscellaneous items for final project (e.g., safety pins and two different-color beads, two types of noodles, etc.—let students be creative)
- ☐ Calculators (optional)
- ☐ Coloring utensils (optional)
- ☐ Downloadable zipped file of documents for student activities https://www.nasa.gov/sites/default/files/atoms/files/deepspacecommunications.zip.

### Safety

- Students should be aware of their surroundings and carefully move throughout the room when viewing other teams' work.
- Before using sharp instruments, discuss safety issues surrounding proper use.

## Introduce the Challenge

- Introduce the activity by playing 15 seconds of fax machine "handshake" sounds. (Search the internet for "fax machine noise.")
- Ask students if they can identify the noise.
  - Answer: That is the sound of two fax machines communicating to confirm they are ready to share information. The sending fax machine then scans the document and turns the image into binary numbers that are transmitted over the telephone line using sound. The receiving fax machine converts the sound back into binary numbers and translates them into an image.

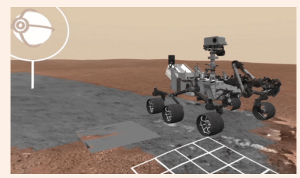
### Engage

- Post the word "communication" where students can view it. Hand out a blank sheet of paper and have students express the concept of communication in one or more of the following ways:
  - Draw a picture of what communication looks like to them.
  - Draw a concept map of communication.
  - Write a list of related words.
  - Come up with their own definition of communication.
- Share the student papers.
- Come to a consensus on the meaning of "communication." Explain that communication comes in many forms. There are times that the transmitter (the one sending the message) does not always speak the same language as the receiver (the one receiving the message).

## Share With Students

### Brain Booster

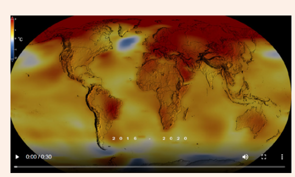
When NASA scientists want to follow the path of the Curiosity rover on Mars, they use special technology to virtually explore the Martian landscape. A free immersive experience called Access Mars lets anyone with an internet connection take a guided tour of the Red Planet! Access Mars offers a visceral impression of what it would be like to walk alongside Curiosity, wandering through the lonely red desert.



Learn more: https://www.nasa.gov/feature/jpl/take-a-walk-on-mars-in-your-own-living-room

### On Location

The Scientific Visualization Studio (SVS) works closely with NASA scientists in the creation of thousands of visualizations, animations, and images to promote a greater understanding of Earth and space science research activities. Visualizations and multimedia products are accessible to everyone and free to download!



Learn more: https://svs.gsfc.nasa.gov/

## Facilitate the Challenge

### Explore

- Instruct students to fill out the “Hello” name tag to communicate who they are—without using the letters of the alphabet to spell out their names. Options might include using emoji, sign language, pictures or numbers that look like a letter, and so forth.
- Collect the name tags and pass them back out at random. Have the receiving students try to decode or interpret the name that is supposed to be on the name tag.
- Ask students the following questions:
  - What strategies did you use to decode the name you were given?
  - How did you decide on the type of communication you used to write your name?
  - What happens if two people do not speak the same language but want to communicate? What could they do?
    - Answer: They must have an interpreter or some other way to translate the language to allow the other person to understand it.


### Explain

- Explain to students that communication is not limited to communication between people. Communication can take place between machines and between people and machines—even though people do not speak the same language as machines or computers.
- Have students examine some of the data that satellites in deep space have sent back to Earth. These brief video clips show amazing pictures sent to Earth from deep space satellites:
  - Deep Space Network: A Discussion on NASA's Vital Lifeline to Spacecraft. (Watch from time stamp 1:49 to 2:10.) https://youtu.be/NGgzq8eXZOQ?t=108
  - NASA | Magnificent Eruption in Full HD. (Watch from time stamp 0:15 to 0:55.) https://youtu.be/GrnGi-q6iWc?t=15
- In small groups, have students create a foldable or graphic organizer of the three types of encoded data—binary, RGB, and hexadecimal—from the following references:
  - How Does a Spacecraft Take a Picture? (Total time of video is 3:02.) https://solarsystem.nasa.gov/resources/10757/how-does-a-spacecraft-take-a-picture/
  - How Do We Talk to Machines? https://spaceplace.nasa.gov/binary-code2/en/
  - Why Is Sixteen so Sweet? https://spaceplace.nasa.gov/binary-code3/en/
- Once the graphic organizers are completed and students have shared, it is time to have fun with the numbers. Locate a converter on the internet by searching “convert decimal to binary.” There may be a converter that converts a decimal number to binary and hexadecimal formats simultaneously. It is recommended that the instructor chooses a converter and shares the link with students, so everyone is using the same converter.
- Have students use the following table to practice using the converter. If given a binary or hexadecimal number, convert it back to decimal. For the blank rows in the Decimal column, students will add their own numbers to convert.

| Decimal | Binary | Hexadecimal |
|---|---|---|
| 99 | 01100011 | 63 |
| 14 | | |
| 107 | | |
| 156 | | |
| 250 | | |
| | | F |
| | 00010011 | |
| | | |
| | | |
| | | |
| | | |

- After students have completed the task, ask if they can recall how a satellite captures an image and uses the RGB value to transmit a picture back to Earth.
  - Answer: As light passes through the satellite's camera filter to a computer chip, the color and brightness are recorded using RGB (red, green, and blue) color codes for every pixel of data. Those color codes are converted to binary numbers and transmitted to a computer on Earth. The computer converts the binary numbers back into RGB color codes and reassembles the picture pixel by pixel.

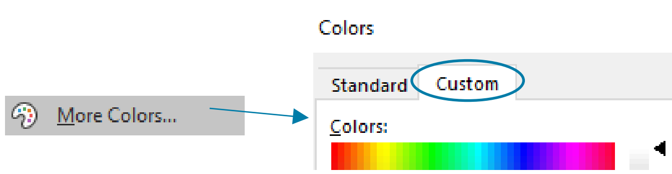
***Practice With RGB Color Codes***

Students should have individual devices (computers or tablets), or the instructor can do this as a demonstration.

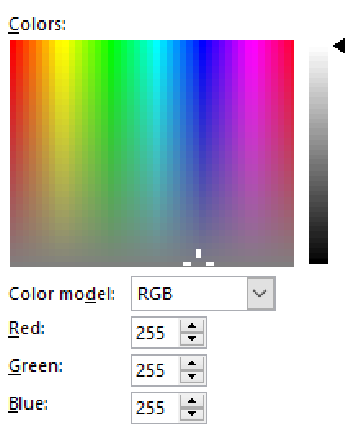
- On a blank document, insert a 2 × 2 table.
- Click inside a cell to fill or shade. 

| | |
|---|---|
| | |
| | |

- Navigate to where the color schemes and RGB numbers are shown (fill or shading>more colors>custom).




- In the custom colors window, click on different colors to observe how the RGB values change according to the colors.




Have students write down RGB color codes for various colors and brightness. Have them write the RGB color codes on the right as the color gets darker. If they are doing this on a device (computer or tablet), they can also fill in the colors in the cells on the left. If students do not have the chart available on a device or in the Student Handout, have them write it on a sheet of paper.

| Color | RGB |
|---|---|
| Light red ↓ | |
| | |
| Red | |
| | |
| Dark red | |

| Color | RGB |
|---|---|
| Light blue ↓ | |
| | |
| Blue | |
| | |
| Dark blue | |

| Color | RGB |
|---|---|
| Light green ↓ | |
| | |
| Green | |
| | |
| Dark green | |

- Let students explain what is happening to the RGB color code as each color gets darker.

***Convert the RGB Color Code to Hexadecimal and Binary Notation***

Students will practice converting RGB color codes to hexadecimal and binary notation. Students can use a calculator or internet-based converter or learn to convert by hand. (In the **Elaborate** section, there are two optional advanced activities for students to learn to do the conversions by hand. Refer to the "Hexadecimal Conversions" and "Binary Conversions" activity sheets to determine if these advanced activities are appropriate for your students.)

- Students will find the RGB triplet for the given colors, then convert the decimal RGB color code to hexadecimal and binary notation. For the blanks in the Color column, students will choose their own color and fill in the chart accordingly.

| **Color** | **8-Bit RGB Triplet** | | |
|---|---|---|---|
| | **Decimal Color Code** | **Hexadecimal Color Code** | **Binary Color Code** |
| White | 255, 255, 255 | #FFFFFF | 111111111111111111111111<br>FF |
| Bright yellow | 247, 252, 32 | #F7FC20 | 111101111111110000100000<br>F7 FC 20 |
| Black | | | |
| Light blue | | | |
| Dark blue | | | |
| | | | |
| | | | |
| | | | |

## Elaborate

- Divide students into teams.
- Present the pool of activities students may choose from and explain how many activities they will need to complete.
- If activities will be set up in stations, be sure students are aware of the location of each assignment.

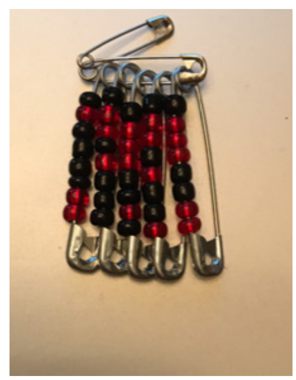
***Activities***

Follow the link to access the downloadable zipped file of student activity documents for the first five activities. https://www.nasa.gov/sites/default/files/atoms/files/deepspacecommunications.zip.

1. Mystery Pictures (Convert RGB to hexadecimal). *Can be completed on computer or printed handout.*
2. Fill in the Picture (Convert RGB to hexadecimal). *Computer only.*
3. Paint by Number (Convert binary to decimal). *Printed handout.*
4. Binary Conversions (Advanced activity—Solve without a converter tool using mathematics, either manually or using a calculator). *Printed handout.*
5. Hexadecimal Conversions (Advanced activity—Solve without a converter tool using mathematics, either manually or using a calculator). *Printed handout.*
6. Learn more about NASA's Deep Space Network (DSN).
   - Research and write about the different parts of the DSN and how it works.
7. Create a poem. The poem should explain how NASA receives data from deep space.
8. Write an uplifting message. Write a message to someone in your group using hexadecimal or binary notation.
   - Search online for a positive quotation if needed. Do not use a predictable one. Trade quotes and decode the messages.
   - Use the American Standard Code for Information Exchange (ASCII) table to convert letters to binary or hexadecimal notation.
9. Create your own cipher. A cipher is a protocol meant specifically to hide or encrypt messages from others. Create the cipher as a group, then encode your own individual messages. Swap encoded messages with team members and then decode.
   - Using your cipher, write a nice note to your favorite educator. Send that educator a copy of your cipher and your encoded message.
10. Draw a diagram illustrating the data being transferred from one computer to another.

### ✓ Evaluate

Each student will create a physical project of their choice using any encoding process learned about in this activity. To convert letters to binary or hexadecimal, have students use the American Standard Code for Information Interchange (ASCII) table found at the end of the Educator Notes. Encourage creativity within the project. Here are just a few possible project ideas:



The name "Chris" in beads using a binary encoding of the ASCII values for each letter in the name.

- Encode your name, initials, or a message in binary notation.
  - Put it on a necklace or bracelet using two different beads to represent the 0s and 1s.
  - Try using two different-color ultraviolet (UV) beads to create an encoded message that only appears in the sunlight or under UV light.
  - Put the different-color beads on safety pins to string them together, as shown in the picture.
- Using different types of noodles, create a message on paper. Be sure to have a key.
- Create your own cipher with color. (Tip: There are 16 digits in hexadecimal and 16 colors in a box of crayons.)

### Extensions

Two advanced activities are suggested in the **Elaborate** section. Students will practice changing numbers between the different bases (e.g., from decimal to binary or from hexadecimal to decimal) without an internet-based converter. Read the "Binary Conversions" and "Hexadecimal Conversions" activity sheets to determine if these advanced activities are appropriate for your students.

### References

Binary Nametag. https://chandra.si.edu/binary/nametag.html#nametag

Binary Pins. https://chandra.si.edu/binary/pin.html#pin

# Decimal, Hexadecimal, and Binary Number Systems Overview

**Decimal or Base 10 Number System**

The decimal or base 10 number system has 10 digits (numerals 0 to 9) and the position of each digit indicates its place value. These place values are based on powers of 10 (i.e., ones, tens, hundreds, thousands, etc.).

$10^0 = 1$ (one)

$10^1 = 10$ (ten)

$10^2 = 100$ (hundred)

$10^3 = 1{,}000$ (thousand)

In base 10, the number 247 has three digits. Reading from right to left, 7 is in the ones ($10^0$) place, 4 is in the tens ($10^1$) place, and 2 is in the hundreds ($10^2$) place, so 247 is equivalent to: $(2 \times 100) + (4 \times 10) + (7 \times 1) = 200 + 40 + 7 = 247$.

**Hexadecimal or Base 16 Number System**

The hexadecimal or base 16 number system uses 16 digits (numerals 0 to 9 and letters A to F, where A = 10, B = 11, C = 12, D = 13, E = 14, and F = 15). The position of each digit indicates its place value, but these place values are based on powers of 16.

$16^0 = 1$ (one)

$16^1 = 16$ (sixteen)

$16^2 = 256$ (two hundred fifty-six)

$16^3 = 4{,}096$ (four thousand ninety-six)

In base 16, the number F7 has two digits. Reading from right to left, 7 is in the ones ($16^0$) place and F, which is equal to decimal number 15, is in the sixteens ($16^1$) place, so F7 is equivalent to: $(15 \times 16) + (7 \times 1) = 240 + 7 = 247$.

**Binary or Base 2 Number System**

The binary or base 2 number system has only two digits (numerals 0 and 1), and the position or place value of each digit is based on powers of 2.

$2^0 = 1$ (one)

$2^1 = 2$ (two)

$2^2 = 4$ (four)

$2^3 = 8$ (eight)

$2^4 = 16$ (sixteen)

$2^5 = 32$ (thirty-two)

$2^6 = 64$ (sixty-four)

$2^7 = 128$ (one hundred twenty-eight)

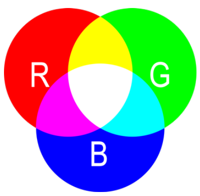
With only two digits, binary numbers require a long string of digits to express large numbers. In base 2, the number 11110111 has eight digits. Reading from right to left, the first three digits (111) are in the ones ($2^0$), twos ($2^1$), and fours ($2^2$) places, respectively. The zero is in the eights ($2^3$) place, and the last four digits (1111) are in the sixteens ($2^4$), thirty-twos ($2^5$), sixty-fours ($2^6$), and one hundred twenty-eights ($2^7$) places. The number 11110111 is equivalent to: $(1 \times 128) + (1 \times 64) + (1 \times 32) + (1 \times 16) + (0 \times 8) + (1 \times 4) + (1 \times 2) + (1 \times 1) = 128 + 64 + 32 + 16 + 0 + 4 + 2 + 1 = 247$.

Another option is to segment long strings of binary numbers into sets of four and convert each group (0000 to 1111) into the decimal equivalent (0 to 15), where each set of four equates to one hexadecimal place value. Since binary is based on powers of 2 and hexadecimal is based on powers of 16 or $2^4$, four binary digits or four bits (also called a nybble) are equivalent to a single hexadecimal digit (0 to F). Using the same example 11110111, the first nybble starting from the right (0111) is in the ones place ($16^0$), and the second nybble (1111) is in the sixteens place ($16^1$). After calculating the value of each nybble below, 11110111 is equivalent to hexadecimal number F7 = (15 × 16) + (7 × 1) = 240 + 7 = 247.

1111 = (1 × 8) + (1 × 4) + (1 × 2) + (1 × 1) = 8 + 4 + 2 + 1 = 15 (F in hexadecimal)

0111 = (0 × 8) + (1 × 4) + (1 × 2) + (1 × 1) = 0 + 4 + 2 + 1 = 7

## Converting 8-Bit RGB Color Codes to Hexadecimal and Binary Notation




Decimal, hexadecimal, and binary numbers can be used to express 8-bit RGB color codes.

Each value in an 8-bit RGB triplet represents an integer number from 0 to 255 and defines a recipe for the amount of each primary color (red, green, and blue) that would be combined to make different shades of color in the visible spectrum. Hexadecimal color codes start with a pound or hashtag (#). Red is displayed in the first two places on the left (after the # symbol), then green, and finally blue (#RRGGBB). If any of the colors are converted into a 1-digit number, use a zero as a placeholder in front of the number. Binary color codes start with the 8-bit binary number for red, followed by the 8-bit binary number for green, followed by the 8-bit binary number for blue. Again, use place-holding zeros in front of any number that is smaller than 8 bits.

| Color | RGB 8-Bit Triplet | | |
|---|---|---|---|
| | Decimal Color Code | Hexadecimal Color Code | Binary Color Code |
| White | (255, 255, 255) | #FFFFFF | 111111111111111111111111<br>FF |
| Bright yellow | (247, 252, 32) | #F7FC20 | 111101111111110000100000<br>F7 FC 20 |

Hexadecimal numbers require fewer digits than decimal or binary numbers to convey large values and are often used for expressing color codes in computer programming. While computers work in binary, hexadecimal is commonly used by programmers because it is easier to read and easily converts to decimal and binary number systems. All decimal integers from 0 to 255 can be expressed with a combination of just two hexadecimal digits (00 to FF), whereas the binary number equivalent would require up to eight digits, or eight bits (00000000 to 11111111). The RGB color code for white (255, 255, 255) would require only six hexadecimal digits (#FFFFFF) but twenty-four binary digits (111111111111111111111111).

Students can use a calculator or internet-based converter or learn to convert by hand. Converting with a calculator or by hand requires division. Divide the decimal number by the appropriate base number (16 for hexadecimal and 2 for binary) repeatedly until the quotient is zero. The remainder for each step of the division process provides the digit for each successive place value of the number system (hexadecimal or binary). Review the “Hexadecimal Conversions” and “Binary Conversions” activity sheets for examples of converting RGB triplets from decimal to hexadecimal and binary notation without an online conversion tool.

# American Standard Code for Information Interchange (ASCII)

Use this chart to encode letters and symbols in hexadecimal or binary notation.

| ASCII character | Hex value | Binary value |
|---|---|---|
| A | 41 | 01000001 |
| B | 42 | 01000010 |
| C | 43 | 01000011 |
| D | 44 | 01000100 |
| E | 45 | 01000101 |
| F | 46 | 01000110 |
| G | 47 | 01000111 |
| H | 48 | 01001000 |
| I | 49 | 01001001 |
| J | 4A | 01001010 |
| K | 4B | 01001011 |
| L | 4C | 01001100 |
| M | 4D | 01001101 |
| N | 4E | 01001110 |
| O | 4F | 01001111 |
| P | 50 | 01010000 |
| Q | 51 | 01010001 |
| R | 52 | 01010010 |
| S | 53 | 01010011 |
| T | 54 | 01010100 |

| ASCII character | Hex value | Binary value |
|---|---|---|
| U | 55 | 01010101 |
| V | 56 | 01010110 |
| W | 57 | 01010111 |
| X | 58 | 01011000 |
| Y | 59 | 01011001 |
| Z | 5A | 01011010 |
| [ | 5B | 01011011 |
| \ | 5C | 01011100 |
| ] | 5D | 01011101 |
| ^ | 5E | 01011110 |
| _ | 5F | 01011111 |
| ` | 60 | 01100000 |
| a | 61 | 01100001 |
| b | 62 | 01100010 |
| c | 63 | 01100011 |
| d | 64 | 01100100 |
| e | 65 | 01100101 |
| f | 66 | 01100110 |
| g | 67 | 01100111 |
| h | 68 | 01101000 |

| ASCII character | Hex value | Binary value |
|---|---|---|
| i | 69 | 01101001 |
| j | 6A | 01101010 |
| k | 6B | 01101011 |
| l | 6C | 01101100 |
| m | 6D | 01101101 |
| n | 6E | 01101110 |
| o | 6F | 01101111 |
| p | 70 | 01110000 |
| q | 71 | 01110001 |
| r | 72 | 01110010 |
| s | 73 | 01110011 |
| t | 74 | 01110100 |
| u | 75 | 01110101 |
| v | 76 | 01110110 |
| w | 77 | 01110111 |
| x | 78 | 01111000 |
| y | 79 | 01111001 |
| z | 7A | 01111010 |

# Activity One: Communication

## Student Handout

### Your Challenge

In this activity, you will be able to simulate how astronauts, satellites, rovers, and other spacecraft are able to send data digitally to Earth from deep space. You will learn to convert between binary, decimal, and hexadecimal notation to decode images, create encoded messages, and create a cipher. Finally, you will design a unique project using one of the skills learned during this activity.

### Engage

On a sheet of paper, express what the concept of “communication” means to you in one or more of the following ways:

- Draw a picture of what communication looks like to you.
- Draw a concept map of communication.
- Write a list of related words.
- Come up with your own definition of communication.

### Explore

- On a “Hello” name tag, create a way to communicate your name without using letters of the alphabet. You may want to practice on scrap paper first.
- Next, you will receive a “Hello” name tag completed by someone else. Try to decode the name you have been given.
  - What strategies did you use to decode the name you were given?
  - How did you decide on the type of communication you used to write your own name?
  - What happens if two people do not speak the same language, but they want to communicate? What could they do?

### Explain

In a small group, use the resources below to

- Create a foldable or a graphic organizer of the three types of encoded data: binary, RGB (red, green, and blue), and hexadecimal.
- Explain how data is sent from deep space to Earth.

### Resources

How Does a Spacecraft Take a Picture? (Total time of video is 3:02.)
https://www.youtube.com/watch?v=5ueMGZTezfY

How Do We Talk to Machines?
https://spaceplace.nasa.gov/binary-code2/en/

Why Is Sixteen so Sweet?
https://spaceplace.nasa.gov/binary-code3/en/

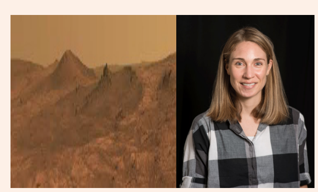
### Fun Fact

NASA Visualization Explorer is your portal to the coolest stories about NASA’s exploration of Earth, the Sun, the Moon, planets, and the universe. A new story is released every other Monday. Download the app and get stories delivered to your iOS and Android devices.


Learn more:
https://nasaviz.gsfc.nasa.gov/

### Career Corner

Elizabeth Rampe is a planetary geologist on the Astromaterials Research and Exploration Science (ARES) team at NASA’s Johnson Space Center. Rampe and other ARES scientists work to understand and decipher the properties of Martian surface materials that can inform us about past and present conditions on Mars. The secrets hiding within Martian geology and minerology may one day help astronauts navigate the perils of the Red Planet.



Learn more about ARES:
http://www.nasa.gov/centers/johnson/astromaterials

***Practice converting decimals***

Your teacher will instruct you on how to convert between decimal, binary, and hexadecimal.

- If given a binary or hexadecimal number, convert it back to decimal. For the blank rows in the Decimal column, choose your own numbers to convert.

| Decimal | Binary | Hexadecimal |
|---|---|---|
| 99 | 01100011 | 63 |
| 14 | | |
| 107 | | |
| 156 | | |
| 250 | | |
| | | F |
| | 00010011 | |
| | | |
| | | |
| | | |
| | | |

***RGB Color Codes***

What does an RGB triplet indicate?

- Use a computer to find the RGB triplets for each of the colors (red, green, and blue) in the tables below. Then write the RGB triplets (#, #, #) in the right column as the color gets lighter and darker.

| Color | RGB |
|---|---|
| Light red ↓ | |
| | |
| Red | |
| | |
| Dark red | |

| Color | RGB |
|---|---|
| Light blue ↓ | |
| | |
| Blue | |
| | |
| Dark blue | |

| Color | RGB |
|---|---|
| Light green ↓ | |
| | |
| Green | |
| | |
| Dark green | |

What do you notice about the RGB values in the

- Red table?
- Blue table?
- Green table?

Now, use the following chart to practice converting RGB color codes to hexadecimal and binary notation. Refer to the sheet "Converting 8-Bit RGB Color Codes to Hexadecimal and Binary Notation."

- Review the examples, then practice with the given colors. You will find the RGB triplet for the given colors, then convert the decimal RGB color code to hexadecimal and binary notation.
- For the blank rows in the Color column, choose your own colors and fill in the chart accordingly.

| Color | 8-Bit RGB Triplet | | |
|---|---|---|---|
| | Decimal Color Code | Hexadecimal Color Code | Binary Color Code |
| White | 255, 255, 255 | #FFFFFF | 111111111111111111111111<br>FF |
| Bright yellow | 247, 252, 32 | #F7FC20 | 111101111111110000100000<br>F7 FC 20 |
| Black | | | |
| Light blue | | | |
| Dark blue | | | |
| | | | |
| | | | |
| | | | |

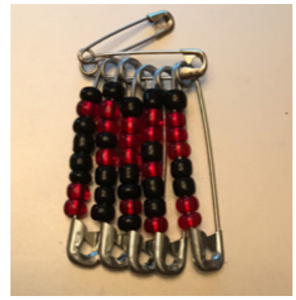
### Elaborate

Activities are listed below. Your teacher will tell you which of the activities you are able to choose from and how many you need to complete.

1. Mystery Pictures (Convert RGB to hexadecimal).
2. Fill in the Picture (Convert RGB to hexadecimal).
3. Paint by Number (Convert binary to decimal).
4. Binary Conversions (Solve without a converter tool using mathematics, either manually or using a calculator).
5. Hexadecimal Conversions (Solve without a converter tool using mathematics, either manually or using a calculator).
6. Learn more about NASA's Deep Space Network (DSN).
   - Research and write about the different parts of the DSN and how it works.
7. Create a poem. The poem should explain how NASA receives data from deep space.
8. Write an uplifting message. Write a message to someone in your group using hexadecimal or binary notation.
   - Search online for a positive quotation if needed. Do not use a predictable one. Trade quotes and decode the messages.
   - Use the "American Standard Code for Information Interchange (ASCII)" table to convert letters to binary or hexadecimal notation.
9. Create your own cipher. A cipher is a protocol meant specifically to hide or encrypt messages from others. Create the cipher as a group, then encode your own individual messages. Swap encoded messages with team members and then decode.
   - Using your cipher, write a nice note to your favorite educator. Send that educator a copy of your cipher and your encoded message.
10. Draw a diagram illustrating data being transferred from one computer to another.

## Evaluate

Create a physical project of your choice using any encoding process you learned about in this activity. To convert letters to binary or hexadecimal, use the "American Standard Code for Information Interchange (ASCII)" table. Be creative! Here are just a few possible project ideas:



The name "Chris" in beads using a binary encoding of the ASCII values for each letter in the name.

- Encode your name, initials, or a message in binary notation.
  - Put it on a necklace or bracelet using two different beads to represent the 0s and 1s.
  - Try using two different-color ultraviolet (UV) beads to create an encoded message that only appears in the sunlight or under UV light.
  - Put the different-color beads on safety pins to string them together, as shown in the picture.
- Using different types of noodles, create a message on paper. Be sure to have a key.
- Create your own cipher with color. (Tip: there are 16 digits in hexadecimal and 16 colors in a box of crayons.)

# Activity Two: Latency

## Educator Notes

### Learning Objectives

Students will

- Explain the relationship among frequency, wavelength, and speed with respect to electromagnetic waves.
- Calculate the latency time for signals transmitted between Earth and other locations in the solar system.
- Construct and use a model to demonstrate the ongoing change in distance, and thus signal latency, between Earth and Mars due to their differing orbital periods.

### Challenge Overview

In this activity, students will derive the speed of light by observing a microwave oven and using the formula **Speed = Frequency × Wavelength**. Using the known operating frequency of microwave ovens and measuring the wavelength of the microwaves by observing the interactions between the microwaves and food within a microwave oven, students will be able to calculate the speed of light. They will then use the speed of light to calculate the latency, or signal delay time, between the Earth and other objects in the solar system. Finally, students will create a device that allows them to model the distance between Earth and Mars at different points in their orbits and determine the latency for a signal to reach Mars at different times during a Mars mission.

### Suggested Pacing

60 to 90 minutes

### National STEM Standards

| **Computer Science (CSTA)** | |
|---|---|
| *Standards for Students*<br>• 2-DA-09: Refine computational models based on the data they have generated. | |
| **Science and Engineering (NGSS)** | |
| • MS-PS4-2: Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.<br>• MS-ESS1.B Earth and the Solar System: The solar system consists of the Sun and a collection of objects, including planets, their moons, and asteroids that are held in orbit around the Sun by its gravitational pull on them.<br>*Disciplinary Core Ideas*<br>• PS4.A Wave Properties: A simple wave has a repeating pattern with a specific wavelength, frequency, and amplitude. | *Disciplinary Core Ideas (continued)*<br>• PS4.B Electromagnetic Radiation: When light shines on an object, it is reflected, absorbed, or transmitted through the object, depending on the object's material and the frequency (color) of the light.<br>*Crosscutting Concepts*<br>• Structure and Function: Structures can be designed to serve particular functions by taking into account properties of different materials and how materials can be shaped and used.<br>*Science and Engineering Practices*<br>• Developing and Using Models: Develop and use a model to describe phenomena. |
| **Mathematics (CCSS)** | |
| *Mathematical Practices*<br>• CCSS.MATH.CONTENT.8.EE.A.4: Perform operations with numbers expressed in scientific notation, including problems where both decimal and scientific notation are used. Use scientific notation and choose units of appropriate size for measurements of very large or very small quantities. Interpret scientific notation that has been generated by technology. | *Mathematical Practices (continued)*<br>• CCSS.MATH.CONTENT.7.G.A: Draw, construct, and describe geometrical figures and describe the relationship between them.<br>• CSS.MATH.CONTENT.7.EE.B.3: Solve real-life and mathematical problems using numerical and algebraic expressions and equations. |

### Challenge Preparation

The educator should

- Read the introduction and background information, particularly the information about latency.
- Read the Educator Notes and the Student Handout to become familiar with the activity.
- Make copies of the Student Handout and templates and gather necessary materials.
- Locate the label on the microwave oven and note the frequency. Most commercial microwaves utilize a frequency of 2,450 MHz (2.4 GHz).

### Materials

- ☐ Microwave oven with removable turntable
- ☐ Microwave-safe casserole dish
- ☐ Miniature marshmallows (enough to cover the bottom of the casserole dish one layer thick). Note: Chocolate chips, shredded cheese, or other small, easily meltable food may be substituted for the marshmallows.
- ☐ Metric ruler
- ☐ Copies of Student Handout and Compass Template, Mars Orbit Template, and Earth Orbit Template
- ☐ Scissors
- ☐ Brass fasteners
- ☐ Calculator (optional)

### Safety

- Use safety when operating the microwave oven. Only heat food in 5- to 10-second intervals. Contents may be hot when removed for inspection.
- Be careful of any food allergies of students who participate in the activity.
- Practice safety when using scissors and brass fasteners to avoid cut and puncture hazards.

### Introduce the Challenge

Ask students a few of the following questions:

- How long does it take for your voice to travel from your phone to the phone of another person?
- How long does it take for information from the internet to travel from a wireless router in your home or school to your computer?
- How long does it take for a TV signal to travel from a satellite to your home TV?
- Why is there a delay between lightning and thunder?
- How fast do all these signals travel?

Students will likely give answers such as “instantly,” “right away,” or “less than a second.” Inform students that all these signals are sent as waves of the electromagnetic spectrum (usually microwaves or radio waves), and, like all waves of the electromagnetic spectrum, they travel at the speed of light. Even though the speed of light seems very fast, it is not instantaneous, and there is a measurable delay between when a signal is sent and when it is received. This delay is known as *latency*. On Earth, latency is a fraction of a second, but sending messages deep into our solar system can result in latency times measured in hours.

Tell students they will be

- Measuring the speed of light using common household items
- Using that measurement to calculate the latency times for signals traveling from Earth to other parts of the solar system

## Share With Students

### Brain Booster

Upgrades to the Deep Space Network allowed NASA to reconnect with Voyager 2, a space probe launched in 1977. The probe is currently about 18 billion kilometers from Earth, and it takes over 16 hours for signals traveling at the speed of light to make the trip each way.

Learn more: https://voyager.jpl.nasa.gov/

### On Location

The Hawaii Space Exploration Analog and Simulation (HI-SEAS) habitat, operated by the University of Hawaii and funded by NASA, simulates the experience of being isolated in a Mars-like environment. To enhance this experience, crews cannot communicate with the outside world in real time. All communications are delayed by 20 minutes to simulate the high-latency times one would experience on Mars.

Learn more: https://earthobservatory.nasa.gov/images/92630/living-the-mars-life-on-mauna-loa

## Engage

Ask students the following questions and have them write their answers in their Student Handouts. Ask for a few volunteers to share their answers aloud and record them on the board to reference later.

- How fast is the speed of light (in km/s)?
- How long would it take (in seconds or minutes) for a beam of light to travel from the Earth to
  - The Sun?
  - A spacecraft in near Earth orbit?
  - A communications satellite in geosynchronous orbit?
  - The Moon?

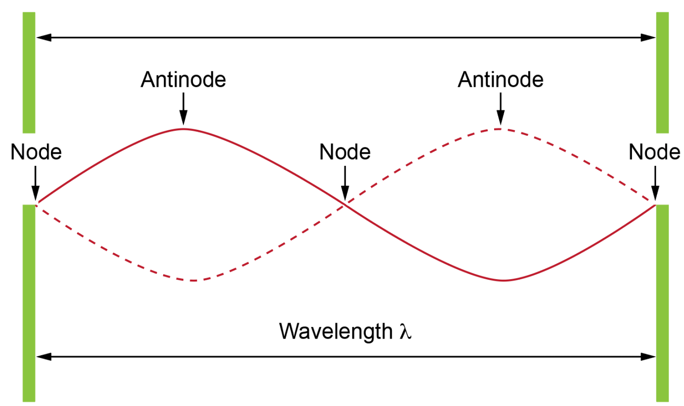
## Facilitate the Challenge

### Explore

Have students find the wavelengths emitted by the microwave oven by following the listed procedures:

1. Completely cover the bottom of the casserole dish with a single layer of marshmallows. The marshmallows should be packed together side by side but not piled on top of each other.
2. Remove the turntable from the microwave. The experiment will fail if the casserole dish does not remain stationary while in the microwave.
3. Place the marshmallows and dish in the microwave and power it on a low setting.
4. Observe the marshmallows, either through the front window or by opening the door at 10-second intervals. Continue to heat the marshmallows until several melted spots can be seen. Do not melt all the marshmallows, and do not move the casserole dish while inspecting.
5. Once several melted spots are visible, remove the dish from the microwave and return it to the work area.

Explain to students that microwaves heat food by sending a steady stream of microwaves into the food at a very specific frequency. This particular frequency of microwaves is absorbed by the water molecules in the food, causing them to gain kinetic energy and therefore heat up. But the energy within electromagnetic waves, such as microwaves, is not consistent throughout the wave. It is concentrated at the antinodes of the waves, or the areas where the crests and troughs of the waves oscillate (move back and forth).




As a result, the food within a microwave is heated unevenly where the antinodes collide with the food. This is why most microwaves have a turntable to help even out the heating of the food. Explain to students that eliminating the turntable concentrated the energy of the microwaves into small areas where the antinodes intersected the marshmallows and created hotspots. Now that they can see where each antinode passed through the marshmallows, they can measure the wavelength of the microwaves.

Have students perform the following procedures:

1. Using a metric ruler, carefully measure (to the nearest tenth of a centimeter) the distance between the centers of the melted spots in two of the marshmallows. The melted spots should be uniformly spaced from one another, so students may use any two adjacent melted spots to take this measurement.
2. Record this measurement (in centimeters to the first decimal place) in the Student Handout.
3. Because there are two antinodes in each wavelength, where both the crest and trough oscillate, the measurement will be for 1/2 the wavelength. Double the antinode measurement to find one full wavelength of the microwaves from the oven and record it (in centimeters) in the Student Handout.

Explain to students the formula for speed of waves**: Speed = Frequency × Wavelength**. Frequency is the measurement of how often a single wavelength is given off and is measured in cycles per second, or Hertz (Hz). Show students where the frequency is listed on the microwave oven's label (it is likely listed as 2,450 MHz or 2.45 GHz) and have them convert this to Hz and record it in their Student Handouts. Multiplying the frequency and the wavelength (measured in centimeters) will yield a very large number in cm/s. Have students convert their calculations to km/s as whole numbers and, if they are able, in scientific notation. These final calculations are the students' measured speed of light. Answers are given in bold in the table below.

Note: Many of the calculations are based on students' measurements and will therefore not be precise answers. The following answer key should be used as a guide to ensure that students are on the right track, not as a grading assessment.

| | |
|---|---|
| **Frequency of microwave, Hz** | 2,450,000,000 Hz or 2,450 MHz or 2.45 GHz |
| **Measured antinode, cm** | Approx. 6.1 cm |
| **Calculated wavelength, cm** | Approx. 12.2 cm |
| **Calculated speed of light, cm/s** | Approx. 29,900,000,000 cm/s |
| **Calculated speed of light, km/s (whole number)** | Approx. 299,000 km/s |
| **Calculated speed of light, km/s (scientific notation)** | Approx. $2.99\times10^5$ km/s |

After students have completed their calculations, have them look up the actual speed of light in km/s (299,800 km/s). Have students use this value as the theoretical value and their measured value as the experimental value to calculate their percent error and to find out how close they were to measuring the actual speed of light. With careful measurements, they should get within 10 percent.

$$\%\ \text{Error} \left| \frac{\text{Theoretical value} - \text{Experimental value}}{\text{Theoretical value}} \right| \times 100$$

For the remainder of this activity, have students use the actual speed of light (299,800 km/s) for all their calculations.

## Explain

Have students show that they can now accurately calculate the latency of signals by completing the following table in their Student Handouts.

| Object | Distance, km | Latency, s | Latency, s (scientific notation) |
|---|---|---|---|
| Spacecraft in near Earth orbit | 408 ($4.08\times10^2$) | **0.00136** | **$1.36\times10^{-3}$** |
| Geosynchronous satellite | 35,800 ($3.58\times10^4$) | **0.119** | **$1.19\times10^{-1}$** |
| Moon | 383,000 ($3.83\times10^5$) | **1.28** | **1.28** |
| Sun | 150,000,000 ($1.50\times10^8$) | (In min, s)<br>**8 min 20 s** | **$5.00\times10^2$** |

Have students answer the following questions in their Student Handout:

- All waves in the electromagnetic spectrum travel at the same speed. Would waves that have longer wavelengths than microwaves, like radio waves, have higher or lower frequencies?
- Visible light has much higher frequencies than microwaves. Are its wavelengths longer or shorter than those of microwaves?
- If you are a spectator at a live sporting event and you are also watching the same event live on your phone while in the stands, would you expect the action that you see on your phone to happen at the same time as the action you see on the field? Is watching live sporting events from home really "live"?
- What problems could arise by trying to operate a remotely controlled rover on the lunar surface from Earth?
- What other problems could occur from a delay in communication with astronauts on a deep space mission caused by signal latency?
- The speed of light is different in different mediums (water, air, and the vacuum of space). What can you explain about light that you have observed moving from one medium to another?

### Elaborate

Share with students that finding the signal latency to the International Space Station, satellites, and the Moon is fairly straightforward: because they all orbit the Earth in nearly circular orbits, their distances to Earth are constant. The same can be said for the Sun, because Earth's orbit around the Sun is also nearly circular. How can we find the signal latency between two bodies in space whose distance apart is constantly changing? Mars, for example, has an orbital period of 687 days, while Earth's is 365 days. This means that the Earth is orbiting the Sun at a faster rate than Mars, and as the Earth passes Mars, the two planets are getting farther apart until they are 180° apart from each other. At this point, Earth begins to catch up with Mars in its orbit and the two planets continue to get closer together until Earth begins to pass Mars again. Tell students they will build a scale model of the Sun–Earth–Mars system that will allow them to measure the distance between Earth and Mars at different times based on their positions in their orbits.

Have students

- Cut out the three templates located at the end of the Student Handout ("Compass," "Mars Orbit," and "Earth Orbit").
- Punch a small hole in the center dot of each of the three discs.
- Secure the three discs together using the brass fastener, with the 360° protractor on the bottom, the Mars orbit disc in the middle, and the Earth orbit disc on top.

To use their models, students must determine the scale of their models as well as the orbital period of Earth and Mars in degrees per day. Have students take the following measurements, make the necessary calculations, and record their results in the chart in their Student Handout.

Note: The measurements (listed in parentheses below and on the chart that follows) will only be accurate if the templates are printed to the correct scale. A 20-cm line is on the first page of the template to help determine if they have been printed to scale.

- Using a metric ruler, students will measure the distance between the center of Mars and the center of the Sun (brass fastener). (This distance should be 9.0 cm.)
- The average distance between Mars and the Sun is 228 million km. Students will divide this distance by the distance they measured to get the scale of their model in millions of kilometers per centimeter.
- Have students double check this scale by measuring the distance from the center of Earth to the center of the Sun (brass fastener). (This distance should be 5.9 cm).
- The average distance between the Earth and the Sun is 150 million km. Students will divide this distance by the distance they measured to get a number, in millions of kilometers per centimeter, that is very close to the scale they calculated using Mars and the Sun.

| Planet | Measured distance to Sun, cm | Average distance to Sun, km | Scale, million km/cm | Are the two scales close? (Yes/No) |
|---|---|---|---|---|
| Mars | **Approx. 9.0 cm** | 228 million km | **25.3 million km/cm** | **Yes** |
| Earth | **Approx. 5.9 cm** | 150 million km | **25.4 million km/cm** | |

Help students calculate how far, in degrees, each planet travels each day in its 360° orbit, according to its orbital period.

- Have students record the orbital periods in the table in their Student Handout. This rate, measured in degrees per day, will be used to calculate how far each planet travels in its orbit over different periods of time.
- The orbital period of Mars is 687 days. How far, in degrees, does Mars travel along in its 360° orbit each day? (Should be 0.52° per day)
- The orbital period of Earth is 365 days. How far, in degrees, does the Earth travel along in its 360° orbit each day? (Should be 0.99° per day)

| Planet | Orbital period, days | Distance traveled per day, degrees |
|---|---|---|
| Mars | 687 | **0.52°** |
| Earth | 365 | **0.99°** |

Have students use the following steps to calculate signal latency between Earth and Mars at different times in the planets' orbits.

1. On the model, rotate Earth and Mars so that both planets are at 0°. This point is known as opposition, because Mars and the Sun are on opposite ends of the Earth. This is the point where Earth and Mars are closest in their orbits.
2. Measure the distance between the center of Earth and the center of Mars, and record it in the table.
3. Use the scale of the model that was calculated earlier to find the actual distance, in millions of kilometers. List the actual distance in the table in both whole numbers and in scientific notation.
4. Use the speed of light to find the latency time for a signal to get from the Earth to Mars.
5. Now, on the model, keep Earth at 0° and rotate Mars to 180°. This point is known as solar conjunction, because the Sun and Mars form a straight line with Earth and would appear "conjoined" if viewed from Earth. This is the point where Earth and Mars are farthest apart in their orbits.
6. Follow steps 2 through 4 to find the latency of time for a signal to get from Earth to Mars during solar conjunction.

What if the Earth and Mars were somewhere between opposition and conjunction? Most Mars missions last several years. These missions include orbiting satellites, landers, and rovers, and will one day include crewed missions. The distance between Earth and Mars is constantly changing as time goes by and as the planets move through their orbits. Reliable communication between Earth and Mars is vital for mission success, so it is necessary for mission control to know when a message will be received as well as when to expect a message back. Can latency time be calculated at different times in their orbits? The first orbit timeframe, 100 days after opposition, is worked below. This example would be beneficial to work with your students if they are having difficulty.

- What will the latency time be 100 days after a mission begins while Mars is at opposition? To find this, start with both planets at 0° again. Use the rates that were calculated earlier to determine how far each planet will travel in its orbit, in degrees, after 100 days. At a rate of 0.52° per day, Mars will have traveled 52° after 100 days. At a rate of 0.99° per day, Earth will have traveled 99° in its orbit after 100 days. Place the planets in these positions on your model.
- Measure the distance between Mars and Earth on the model; this should be about 6.5 cm.
- Next, use the scale of the model calculated earlier (25.3 million km in the real world per 1 cm on the model) to find the distance between the planets; this should be about 164 million (1.64 × 108) km.
- Finally, calculate the latency as before, by dividing this distance by the speed of light:
  - 164,000,000 km/299,800 km/s = 547 s, or 9 min, 7 s.
- Use this same method to calculate the signal latency for the rest of the time periods listed in the table.

| Time period | Earth position | Mars position | Measured distance, cm | Calculated distance, million km | Calculated distance, km (whole number) | Calculated distance, km (scientific notation) | Latency time, min, s |
|---|---|---|---|---|---|---|---|
| At opposition | 0° | 0° | **Approx. 3.1** | **78.4** | **78,400,000** | **$7.84×10^7$** | **4 min 22 s** |
| At solar conjunction | 0° | 180° | **Approx. 14.8** | **374** | **374,000,000** | **$3.74×10^8$** | **20 min 47 s** |
| 100 days after opposition | **99°** | **52°** | **Approx. 6.5** | **164** | **164,000,000** | **$1.64×10^8$** | **9 min 7 s** |
| 156 days after opposition | **154°** | **81°** | **Approx. 9.3** | **235** | **235,000,000** | **$2.35×10^8$** | **13 min 4 s** |
| 320 days after opposition | **317°** | **166°** | **Approx. 14.4** | **364** | **364,000,000** | **$3.64×10^8$** | **20 min 14 s** |
| 420 days after opposition | **56°** | **218°** | **Approx. 14.7** | **372** | **372,000,000** | **$3.72×10^8$** | **20 min 41 s** |

- If an opposition occurred on October 6, 2020, what would the latency time be for a signal to reach Mars from Earth today? Have students choose another significant date, such as their next birthday, and calculate the latency time for that date as well.

## ✓ Evaluate

Wrap up the activity by leading a discussion with the following questions:

- How close were you to measuring the speed of light (their percent error)? Anyone within 5 percent, 3 percent, 1 percent?
- Record the percent error of the other groups. What are the mean, median, mode, and range for the percent errors?
- What could some of the possible sources of error be in measuring speed of light?
  - Possible answers: The melted spots were too irregular to find the centers. It was difficult to measure and be precise with a ruler.
- Look at the latency time when Mars was at solar conjunction. If it took 1 minute for someone on Mars to respond to your message, how long would you have to wait for a response after you first sent the message?
- What are some ways long latency times could make communication between deep space astronauts or spacecraft difficult or problematic for mission?
  - Possible answers: Unable to communicate in real time. Unable to control craft remotely in real time. Impossible to know the current status of mission. Slower response to emergencies.
- What are some things that mission controllers can do to mitigate the issues associated with latency?
  - Possible answers: Give more autonomy to astronauts or rovers to make decisions "on the ground." Create detailed schedules so they can anticipate when information will arrive.

## Extensions

- Have students find an online resource that gives the current position of Earth and Mars in the solar system. Ask them if Earth is currently moving closer to Mars or farther away. Have students calculate the latency for a signal to get to Mars today, 2 months from now, and 6 months from now.
- Have students calculate the time between Mars opposition to the next opposition.

  Hint: How much farther (in degrees) does the Earth travel in its orbit than Mars each day? How many days would it take for Earth to catch up with Mars after an opposition?
- Have students look up the average distance from the Sun for the planets Mercury, Jupiter, and Saturn. Using the same scale they used for their model, have students calculate how large each of the orbit circles would need to be for each planet in order for students to be able to use them with their models.

## Accommodations

- Scientific notation is a concept that is generally introduced as an 8th grade standard. This activity can be used to introduce scientific notation to students; however, it is not necessary for the completion of this activity. If it is above the students' ability level, the scientific notation columns in the data tables may be omitted or reserved for advanced students.
- If students are having a difficult time with the concept of the ratio calculations, try using descriptive language, such as, "One centimeter on your model is equal to 25.3 million kilometers in the real world."
- The "100 days after opposition" problem was worked out step by step in the Educator Notes. Refer to this section as well as to the answers in the key to help students who may need additional help.
- Some students may have difficulty constructing or manipulating the Sun, Earth, and Mars model. For these students, a larger, more easily manipulated model may be made ahead of time out of materials like poster board or foam board. However, a new ratio will need to be created based on the size of the model. All other concepts and calculated answers will remain the same.

# Activity Two: Latency

## Student Handout

### Your Challenge

In this activity, you will derive the speed of light by observing a microwave oven and using the formula **Speed = Frequency × Wavelength**. Using the known operating frequency of microwave ovens and measuring the wavelength of the microwaves by observing the interactions between the microwaves and food within a microwave oven, you will be able to calculate the speed of light. You will then use the speed of light to calculate the latency, or signal delay time, between the Earth and other objects in the solar system. Finally, you will create a device that will allow you to model the distance between the Earth and Mars at different points in their orbits and determine the latency for a signal to reach Mars at different times during a Mars mission.

### Engage

Record your answers to the following questions as they are read aloud.

- How fast is the speed of light (in km/s)? ______________
- How long would it take (in seconds or minutes) for a beam of light to travel from the Earth to
  - The Sun? ___________
  - A spacecraft in near Earth orbit? ___________
  - A communications satellite in geosynchronous orbit? __________
  - The Moon? ___________

### Explore

Carefully follow instructions and safety guidelines to find the frequency of the microwave, measure the wavelength of the microwaves, and calculate the speed of light.

| | |
|---|---|
| **Frequency of microwave, Hz** | |
| **Measured antinode, cm** | |
| **Calculated wavelength, cm** | |
| **Calculated speed of light, cm/s** | |
| **Calculated speed of light, km/s (whole number)** | |
| **Calculated speed of light, km/s (scientific notation)** | |

- What is the actual speed of light? _________
- What is your percent error? __________

### Explain

Now that you know the actual speed of light, use it to calculate the time delay (latency) for a signal to reach the following:

## Fun Fact

Is your internet service as fast as the Moon's? In the Lunar Laser Communication Demonstration, NASA was able to transmit data from lunar orbit to Earth at a rate of 622 Mbps using a laser transmitter aboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) satellite. Now, that is some serious streaming!

Learn more: https://www.nasa.gov/content/goddard/historic-demonstration-proves-laser-communication-possible

## Career Corner

Interested in a career in space communications? NASA's Space Communications and Navigation (SCaN) has an internship program dedicated to providing hands-on training, and the program is open to high school students. The SCaN Internship Project (SIP) allows students to gain experience working on real missions with cutting-edge space communications systems.

Learn more: https://www.nasa.gov/directorates/heo/scan/communications/outreach/internships

| Object | Distance, km | Latency, s (decimals) | Latency, s (scientific notation) |
|---|---|---|---|
| Spacecraft in near Earth orbit | 408 ($4.08 \times 10^2$) | | |
| Geosynchronous satellite | 35,800 ($3.58 \times 10^4$) | | |
| The Moon | 383,000 ($3.83 \times 10^5$) | | |
| The Sun | 150,000,000 ($1.50 \times 10^8$) | (In min, s) | |

Use your understanding of the relationship among frequency, wavelength, and speed regarding waves in the electromagnetic spectrum, as well as the implications of signal latency, to answer the following questions:

- All waves in the electromagnetic spectrum travel at the same speed. Would waves that have longer wavelengths than microwaves, like radio waves, have higher or lower frequencies?
- Visible light has much higher frequencies than microwaves. Are its wavelengths longer or shorter than microwaves?
- If you are a spectator at a live sporting event and you are also watching the same event live on your phone while in the stands, would you expect the action that you see on your phone happen at the same time as the action you see on the field? Is watching live sporting events from home really "live"?
- What problems could arise by trying to operate a remotely controlled rover on the lunar surface from Earth?
- What other problems could occur from a delay in communication with astronauts on a deep space mission caused by signal latency?
- The speed of light is different in different mediums (water, air, and the vacuum of space). What can you explain about light that you have observed moving from one medium to another?

### Elaborate

Follow your instructor's instructions to build a scale model of the orbits of the Earth and Mars around the Sun. Determine the scale of the model and fill in the table below.

| Planet | Measured distance to Sun, km | Average distance to Sun | Scale, million km/cm | Are the two scales close? Yes/No |
|---|---|---|---|---|
| Mars | | 228 million km | | |
| Earth | | 150 million km | | |

With the help of your instructor, determine how far, in degrees, each planet travels along its 360° orbit each day and fill in the table below. This rate, measured in degrees per day, will be used to calculate how far each planet travels in its orbit over different periods of time.

| Planet | Orbital period, days | Distance traveled per day, degrees |
|---|---|---|
| Mars | 687 | |
| Earth | 365 | |

Use the following steps to calculate signal latency between Earth and Mars at different times in the planets' orbits.

1. On your model, rotate Earth and Mars so that both planets are at 0°. This point is known as opposition, because Mars and the Sun are on opposite ends of the Earth. This is the point where Earth and Mars are closest in their orbits.
2. Measure the distance between the center of Earth and the center of Mars, and record it in the table.
3. Use the scale of the model that you calculated earlier to find the actual distance, in millions of kilometers, and list it in the table in both whole numbers and in scientific notation.

4. Use the speed of light to find the latency time for a signal to get from the Earth to Mars.
5. Now, on your model, keep Earth at 0° and rotate Mars to 180°.This point is known as solar conjunction, because the Sun and Mars form a straight line with Earth and would appear "conjoined" if viewed from Earth. This is the point where Earth and Mars a farthest apart in their orbits.
6. Follow steps 2 through 4 to find the latency of time for a signal to get from Earth to Mars during solar conjunction.

What if the Earth and Mars here somewhere between opposition and conjunction? Most Mars missions last several years. These include orbiting satellites, landers, rovers, and one day will include manned missions. The distance between Earth and Mars is constantly changing as time goes by and the planets move through their orbits. Reliable communication between Earth and Mars is vital for mission success, so it is necessary for mission control to know when a message will be received as well as when to expect a message back. Can we calculate the latency time at different times in their orbits?

- What will the latency time be 100 days after a mission begins while Mars is at opposition? To find this, start with both planets at 0° again. Use the rates that you calculated earlier to determine how far each planet will travel in its orbit, in degrees, after 100 days. Place the planets in these positions on your model. You can now measure the distance between them and calculate the latency as you did before.
- Use this same method to calculate the signal latency for the rest of the time periods listed in the table.

| Time period | Earth position | Mars position | Measured distance, cm | Calculated distance, millions km | Calculated distance, km (whole number) | Calculated distance, km (scientific notation) | Latency time, min, s |
|---|---|---|---|---|---|---|---|
| At opposition | 0° | 0° | | | | | |
| At solar conjunction | 0° | 180° | | | | | |
| 100 days after opposition | | | | | | | |
| 156 days after opposition | | | | | | | |
| 320 days after opposition | | | | | | | |
| 420 days after opposition | | | | | | | |

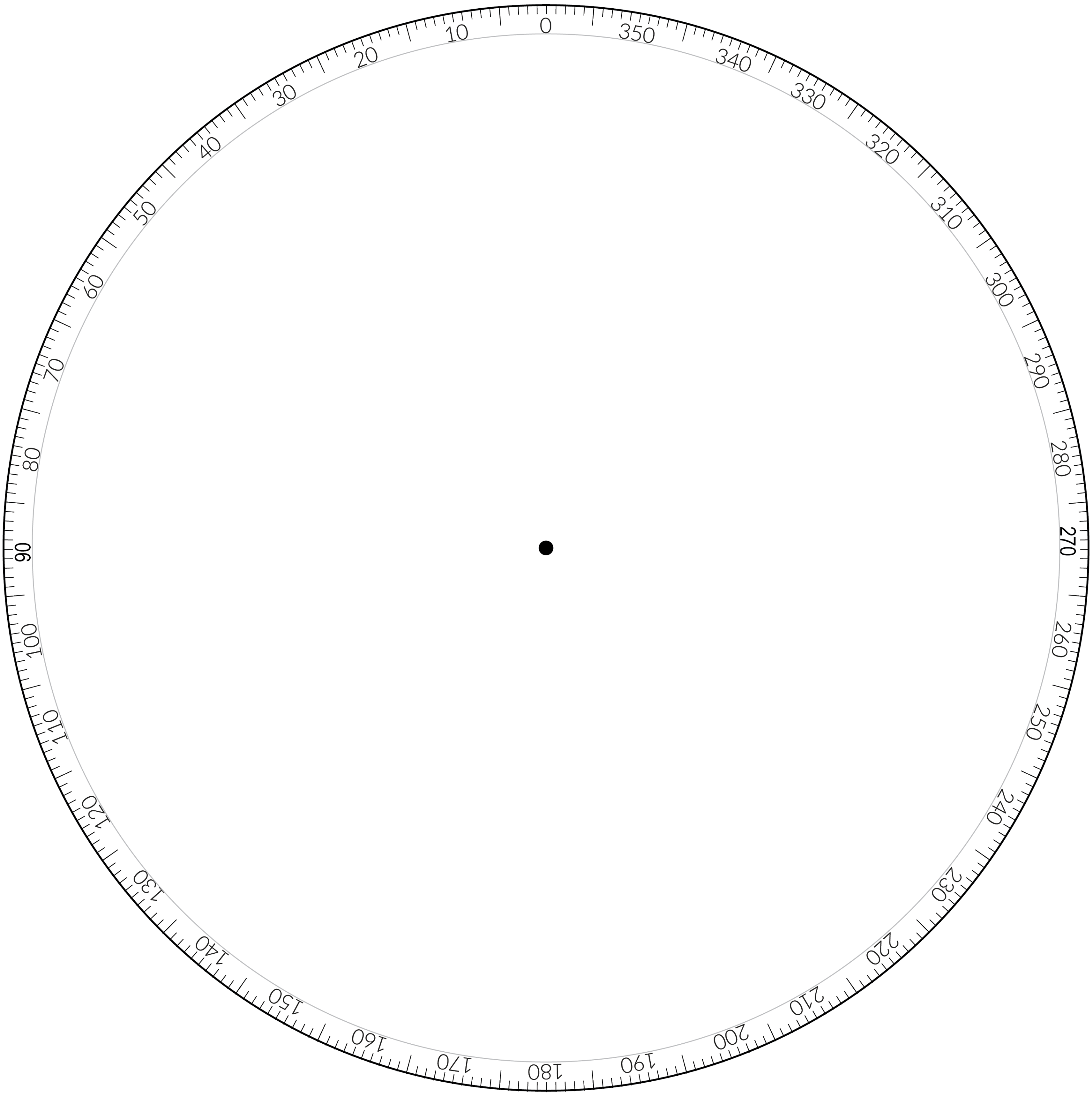
- If an opposition occurred on October 6, 2020, what would the latency time be for a signal to reach Mars from Earth today?
- Choose another significant date, such as your next birthday, and calculate the latency time for that date as well.

### Evaluate

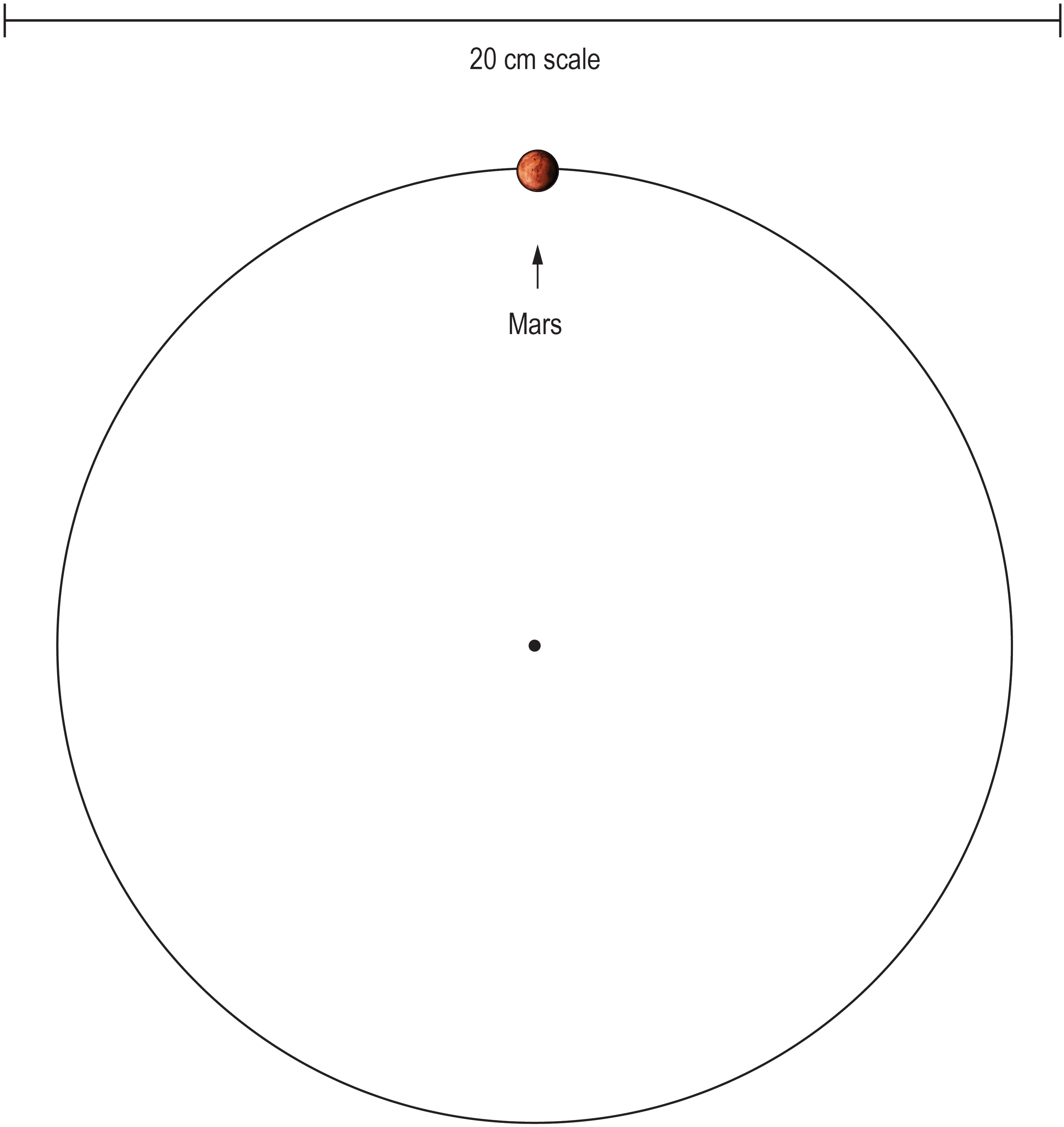
Be prepared to show your understanding of the activity by engaging in the following questions with the rest of your group:

- How close were you to measuring the speed of light (your percent error)? Was anyone within 5 percent, 3 percent, 1 percent?
- Record the percent error of the other groups. What are the mean, median, mode, and range for the percent errors?
- What could some of the possible sources of error be in measuring speed of light?
- Look at the latency time when Mars was at solar conjunction. If it took 1 minute for someone on Mars to respond to your message, how long would you have to wait for a response after you first sent the message?
- What are some ways long latency times could make communication between deep space astronauts or spacecraft difficult or problematic for missions?
- What are some things that mission controllers can do to mitigate the issues associated with latency?

# Compass Template

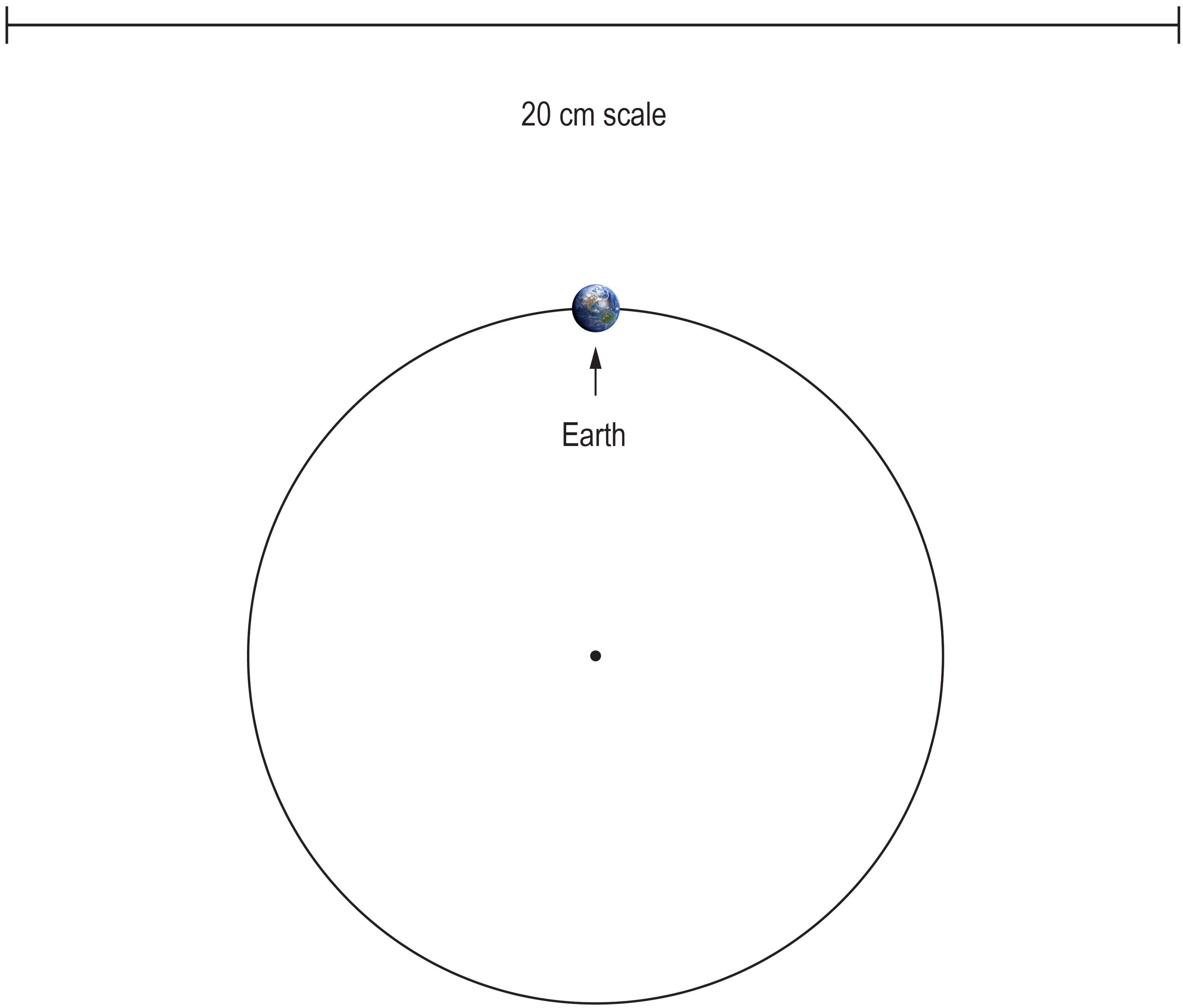


## Mars Orbit Template




Mars orbit template

# Earth Orbit Template




Earth orbit template

# Activity Three: Performance

## Educator Notes

### Learning Objectives

Students will

- Model how data (packets) can become degraded during deep space communications.
- Develop a protocol to diminish the amount of packet loss and degradation of data transmitted across networks.
- Explain Delay/Disruption Tolerant Networking (DTN), the protocol for packaging messages for delivery in the Deep Space Network (DSN).

### Challenge Overview

During the 3D (Delayed, Degraded, Delivered) Game, students will take on the roles of the NASA team developing the DSN by simulating how data transmitted across the DSN can be delayed, degraded, and delivered. This activity walks the educator and students through the ins and outs of DTN protocol by placing students in real-life DSN scenarios.

### Suggested Pacing

45 to 60 minutes

### National STEM Standards

| Science and Engineering (NGSS) | |
|---|---|
| • MS-PS4-2: Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials. (Grades 6–8)<br>*Disciplinary Core Ideas*<br>• A sound wave needs a medium through which it is transmitted. | *Science and Engineering Practices*<br>• Develop and use a model to describe phenomena. |
| **Technology (CSTA)** | |
| • 2-NI-04: Model the role of protocols in transmitting data across networks and the internet. | |
| **Mathematics (CCSS)** | |
| *Mathematical Practices*<br>• CSS.Math.Practice.MP3: Construct viable arguments and critique the reasoning of others. | |
| **Language Arts (CCSS)** | |
| *Language Arts Practices*<br>• CCSS.ELA-LITERACY.RST.6-8.7: Integrate quantitative or technical information expressed in words in a text with a version of that information expressed visually (e.g., in a flowchart, diagram, model, graph, or table). | *Language Arts Practices (continued)*<br>• CCSS.ELA-LITERACY.RST.6-8.2: Determine the central ideas or conclusions of a text; provide an accurate summary of the text distinct from prior knowledge or opinions. |

### Challenge Preparation

The Deep Space Network (DSN) is a worldwide system of sensitive antennas that communicates with interplanetary spacecraft. Signals to and from the spacecraft travel millions to billions of kilometers. To hear the spacecraft's faint signal, the antennas on Earth are equipped with amplifiers, but there are several problems. The signal becomes degraded by background radio noise (static) emitted naturally by nearly all objects in the universe, including the Sun and Earth. The background noise gets amplified along with the signal. The signal can also be degraded through absorption of the waves as a loss in sound energy. Also, the powerful electronic equipment amplifying the signal adds noise of its own. The Deep Space Network uses highly sophisticated technology, including cooling the amplifiers to a few degrees above absolute zero, and special coding techniques so the receiving system can distinguish the signal from the unwanted noise.

The educator should

- Read the introduction and background information, the Educator Notes, and the Student Handout to become familiar with the challenge.
- Print the Student Handout for each team.
- Copy the Cosmic Comic Game comic strip (one per team) at the end of the Educator Notes and cut it into individual images.

### Materials

- ☐ Cosmic Comic Game comic strip of NASA images, one set per team
- ☐ Dice or number cubes for each team
- ☐ Index cards
- ☐ Writing utensils
- ☐ Delayed, Degraded, Delivered worksheet, one per team

### Introduce the Challenge

Remind students to use school-appropriate language throughout this entire activity.

Come up with a space-themed sentence and jumble up the words. For example, "Don't turn on the thrusters until after you count to ten" could become "Turn on the ten to thrusters until after you don't count." Read the jumbled-up sentence to students and ask if they were able to understand it.

To activate prior knowledge, ask students the following questions:

- How does a text get from your phone to your friend's phone nearby?
- Why is Wi-Fi important to your everyday life?

Read the article "Space Communications: 7 Things You Need To Know" as a group, using strategies for reading comprehension (e.g., modeling by thinking aloud, using graphic organizers to assimilate information, and providing questions that require students to find evidence in the text). https://www.nasa.gov/feature/goddard/2020/space-communications-7-things-you-need-to-know

#### Engage

- Share the video "7 Minutes of Terror." https://mars.nasa.gov/resources/20049/challenges-of-getting-to-mars-curiositys-seven-minutes-of-terror/?site=msl
- Ask students the following questions:
  - Why did the team who designed the entry, descent, and landing system feel "terror" during the landing of NASA's Mars Curiosity Rover?
  - Why is there a delay in communication with humans on the Moon and/or Mars?
  - How might that impact astronauts on the Moon and Mars?
  - What might be different if a human, instead of a robot, were landing on Mars?

### Facilitate the Challenge

#### Explore

***Cosmic Comic Game***

This game is a paper-passing activity to simulate issues that can occur with data packets traveling across a network.

- Pre-cut the Cosmic Comic Game comic strip at the end of the Educator Notes and distribute the pieces (out of sequence) to small teams of no more than four students.

  Note: The educator may use other sources as long as the group of images depicts a clear sequence of events. Numerous NASA images can be found at https://www.nasa.gov/exploration/systems/sls/outreach/activities.html.
- Challenge students to work as a team to quickly organize the comic or picture pieces into the correct sequence.
- The team with the fastest time and correct order wins the round.
- After the Cosmic Comic Game, the educator will engage students with the following questions:
  - What does the model seem to be demonstrating?

  - How is this process similar to that of NASA's Deep Space Network?
  - What are some challenges NASA faces when trying to transmit and receive communications with spacecraft and satellites?
- Discuss with students how NASA communicates with spacecraft. The following videos are helpful resources to learn more.
  - For background on how the DSN operates, share the video "How Does a Spacecraft Take a Picture?" https://www.youtube.com/watch?v=5ueMGZTezfY (Video length 3:02)
  - Share the video "Mars in a Minute: Phoning Home—Communicating From Mars." https://www.jpl.nasa.gov/edu/learn/video/mars-in-a-minute-phoning-home-communicating-from-mars/ (Video length: 2:29)

### Explain

Have students select at least two of the following resources (one activity and one website) to learn more. After they have completed at least one activity and explored at least one website, have students create a graphic organizer or picture to demonstrate their mastery of how the DSN and DTN work. Students must include the following vocabulary: reflect, absorb, transmit, satellite, and signal. This will help students as they model how a signal travels in the 3D Game.

Activity resources:

- DSN Game UpLink–Downlink. https://spaceplace.nasa.gov/search/DSN/
- SCaN Coloring Page and "Color With NASA" video. https://www.nasa.gov/directorates/heo/scan/communications/outreach/students/create_with_scan
  - Optional: Educators can share their students' work on a social media platform with #NextGenSTEM.

Website resources:

- Deep Space Network *Now* website. https://eyes.nasa.gov/dsn/dsn.html
- "Building Interplanetary Internet With 'Disruption Tolerant Networking'" video. https://www.nasa.gov/feature/antarctic-selfie-s-journey-to-space-via-disruption-tolerant-networking
- DTN website. https://www.nasa.gov/directorates/heo/scan/engineering/technology/disruption_tolerant_networking

### Elaborate

***3D Game***

Students will play two rounds. Round 1 will demonstrate a signal from Earth to a spacecraft on the Moon (a distance of 382,500 kilometers, or 237,674 miles); this can be played with three to five students per team. Round 2 will demonstrate a signal from Earth to a spacecraft on Mars; the number of students per team can be doubled or tripled. The number of students per team is increased to represent the need for more relay stations to transmit a signal from Earth to Mars (a distance of 54.6 million kilometers, or 39,926,867 miles) and additional opportunities for that signal to experience degradation and delay.

Instructions:

- Divide the whole group into teams.
  - Round 1: Three to five students per team
  - Round 2: Six to ten students per team
- Give each team a Delayed, Degraded, Delivered worksheet, two dice or number cubes, and index cards.
- The first student in the team will be the DSN station sending a message to the spacecraft, which is the last student in the team. Everyone else acts as relay stations. The relay process is showing how a signal is transmitted from Earth to a spacecraft.
  - Round 1: The spacecraft is on the Moon.
  - Round 2: The spacecraft is on Mars.

- Instruct the DSN station (first student in the team) to select a physical location within the room and write a series of brief commands on index cards (one 3- to 5-word sentence/command per card) to direct the spacecraft (last student in the team) to the location.
  - For example: Walk 10 paces. Turn left at third desk. Continue straight for 2 paces. Stop at whiteboard.
- The DSN station will hand each command card in sequence to the relay team. As each relay student receives a command card, they will roll the dice, read the corresponding scenario from the Delayed, Degraded, Delivered sheet, make any instructed changes to the index card, and pass the card to the next team member. Each command card will cycle through this process until all relay students have had a turn with each command card and the command is received by the spacecraft.
- The last student (the spacecraft) will collect all the command cards and try to navigate to the location based on the revised command cards.

After both rounds have been completed, have each team examine their commands and discuss the following questions:

- How far off course was the person who followed the garbled message?
- Compare and contrast the Round 1 message to the Round 2 message. What trends did you notice?
- Why do you think that this trend occurred?
- At the end of Round 1, were you able to understand the message? At the end of Round 2, were you able to understand the message?
- Did some of the errors have a greater impact than others?

### ✓ Evaluate

- Have students develop a protocol that will allow them to overcome the various scenarios they encountered in the **Elaborate** section. The protocol must ensure that both the DSN station and the spacecraft can be confident the full message will be received.
- Guidelines for the protocol:
  - The full message must consist of a series of 3- to 5-word commands. Students may decide that as part of their protocol they want the data to arrive in packets; if so, they have the option to write each word on a different index card.
  - The location cannot be known beforehand. Only the DSN station can know the physical location within the room where the spacecraft is going.
- Some examples of protocols that students may implement:
  - Have data sent one packet at a time.
  - Double the message to ensure most of the message is delivered. For example, the message may be "Turn left at first desk," and students may choose to double each sentence: "Turn left at first desk. Turn left at first desk."
  - Student may decide to truncate commands as a protocol. For example, "Place tool on left side of capsule" would become "Place tool on left side."
- Have students test their protocol at least once with a team of no more than five students.

### Share

Have students present their protocols. Engage students with the following discussion questions or prompts:

- Did your protocol work to ensure the message was delivered and not degraded?
- Why do you believe your protocol worked or did not work?
- If you could revise your protocol, what new revisions would you make?
- Compare and contrast your protocol to the DTN protocol. The DTN protocol can be found here: https://www.nasa.gov/directorates/heo/scan/engineering/technology/disruption_tolerant_networking

As students present, be sure to check that they have covered the following concepts:

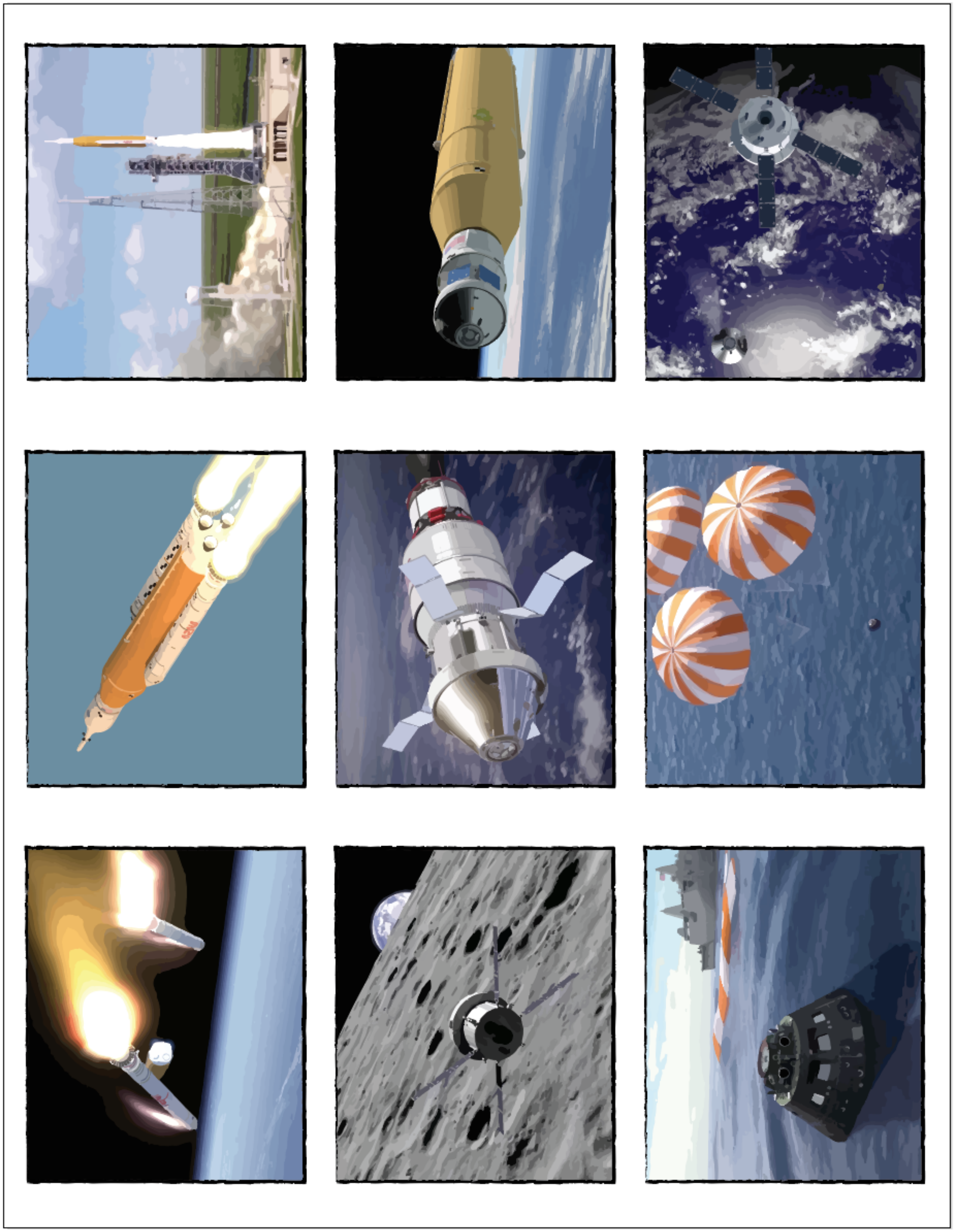
☐ Message was delivered.
☐ Students detailed the steps of their protocol.
☐ Students suggested improvements to their protocol.
☐ During the presentation, the students compared and contrasted their protocol to the DTN.

### Extensions

- Allow teams to test how many relay stations work best with their protocol to deliver the full message.
- Build Your Own Spacecraft! https://spaceplace.nasa.gov/build-a-spacecraft/en/
- Deep Space Network *Now*. https://eyes.nasa.gov/dsn/dsn.html

# Cosmic Comic Game Comic Strip

Educator: Pre-cut the Cosmic Comic Game comic strip (one set per team) and distribute the cut comic pieces sets (out of sequence) to small teams of no more than four students.



# Activity Three: Performance

## Student Handout

### Your Challenge

The Deep Space Network (DSN) is a worldwide system of sensitive antennas that communicates with interplanetary spacecraft. Signals to and from the spacecraft travel millions to billions of kilometers. That is a long journey, so you might be wondering, how does this work?

During the 3D (Delayed, Degraded, Delivered) Game, your team will take on the roles of a NASA team developing the DSN by simulating how data transmitted across a network can be delayed, degraded, and delivered. This activity walks you through the ins and outs of Delay/Disruption Tolerant Networking (DTN) protocol by placing you in real-life DSN scenarios.

### Engage

After watching "7 Minutes of Terror," discuss the following questions:

- Why did the team who designed the entry, descent, and landing system feel "terror" during the landing of NASA's Mars Curiosity Rover?
- Why is there a delay in communication with humans on the Moon and/or Mars?
- How might that impact astronauts on the Moon and Mars?
- What might be different if a human, instead of a robot, were landing on Mars?

### Explore

***Cosmic Comic Game***

This game is a paper-passing activity to simulate issues that can occur with data packets traveling across a network.

- You will be given pieces of a comic strip or an image.
- Your team will work quickly to organize those pieces into the correct sequence.

After organizing the images, think about the following questions:

- What does the model seem to be demonstrating?
- How is this process similar to that of NASA's Deep Space Network?
- What are some challenges NASA faces when trying to transmit and receive communications with spacecraft and satellites?

### Explain

How does NASA communicate with a spacecraft? Listed below are NASA resources for your team to explore. Select at least two of these resources (one activity and one website) to become familiar with the DSN, and create a graphic organizer or picture to demonstrate how the DSN and DTN work.

Activity resources:

- DSN Game UpLink–Downlink. https://spaceplace.nasa.gov/search/DSN/

## Fun Fact

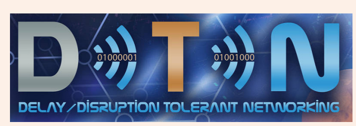
In 1997, the Texas Legislature passed a bill that allowed NASA astronauts to vote from space.

In 2020, NASA astronaut Kate Rubins performed her civic duty from space on the International Space Station, 250 miles above the Earth's surface.

Learn more: https://www.nasa.gov/image-feature/goddard/2020/how-nasa-transmits-votes-from-the-space-station

## Career Corner

In the summer of 2020, a group of NASA Space Communications and Navigation (SCaN) interns helped develop network protocols that will extend internet-like services deep into the solar system.




Learn more: https://www.nasa.gov/feature/Goddard/2020/nasa-interns-extending-internetworking-off-world

- SCaN Coloring Page and "Color With NASA" video. https://www.nasa.gov/directorates/heo/scan/communications/outreach/students/create_with_scan

Website resources:

- Deep Space Network *Now* website. https://eyes.nasa.gov/dsn/dsn.html
- "Building Interplanetary Internet With 'Disruption Tolerant Networking'" video. https://www.nasa.gov/feature/antarctic-selfie-s-journey-to-space-via-disruption-tolerant-networking
- DTN website. https://www.nasa.gov/directorates/heo/scan/engineering/technology/disruption_tolerant_networking

**Elaborate**

***3D Game***

Your teacher will assign teams to play two rounds of the 3D (Delayed, Degraded, Delivered) Game. Round 1 will demonstrate a signal from Earth to the Moon (a distance of 382,500 kilometers, or 237,674 miles). In Round 2, the number of students per team will be increased to represent the need for more relay stations to transmit a signal from Earth to Mars (a distance of 54.6 million kilometers, or 33,926,867 miles).

- Each team will receive a Delayed, Degraded, Delivered worksheet, two dice or number cubes, and index cards.
- The first student in the team will be the DSN station sending a message to the spacecraft, which is the last student in the team. Everyone else acts as relay stations. The relay process is showing how a signal is transmitted from Earth to a spacecraft.
  - Round 1: The spacecraft is on the Moon.
  - Round 2: The spacecraft is on Mars.
- The DSN station (first team member) will select a physical location in the room. Do not tell the spacecraft (the last team member) the location.
- The DSN station will write a series of brief commands on index cards (one 3- to 5-word sentence/command per card) to direct the spacecraft (last student in the team) to the location.
  - For example, if you want the spacecraft (last student) to get to the instructor's desk, you could write the following commands: Walk 10 paces. Turn left at third desk. Continue straight for 2 paces. Stop at whiteboard.
  - Remember: Each command will be on a different index card.
- The DSN station will hand each command card in sequence to the relay team. As each relay student receives a command card, they will roll the dice, read the corresponding scenario from the Delayed, Degraded, Delivered sheet, make any instructed changes to the index card, and pass the card to the next team member. Each command card will cycle through this process until all relay students have had a turn and the command is received by the spacecraft.
- The last student (the spacecraft) will collect all the command cards and try to navigate to the location based on the revised command cards.

As the team examines the original message and the message at the end of the activity, discuss the following questions:

- How far off course was the person who followed the garbled message?
- Compare and contrast the Round 1 message to the Round 2 message. What trends did you notice?
- Why do you think that this trend occurred?
- At the end of Round 1, were you able to understand the message? At the end of Round 2, were you able to understand the message?
- Did some of the errors have a greater impact than others?

**Evaluate**

- Now that you have learned how a message can be delayed, degraded, or delivered, your team will develop a protocol that will allow you to overcome the various scenarios that were encountered in the 3D Game. The protocol must ensure that both the DSN station and the spacecraft can be confident the full message will be received.

- Guidelines for the protocol:
  - The full message must consist of a series of 3- to 5-word commands that allow the spacecraft to reach a destination.
  - The DSN station will create the full message. The rest of the team will not know the message ahead of time.
- You will be allowed time to test your protocol to see if the message was delivered.

**Share**

You will present your protocol. As you prepare your presentation, think about the following discussion questions or prompts:

- Did your protocol work to ensure the message was delivered and not degraded?
- Why do you believe your protocol worked or did not work?
- If you could revise your protocol, what new revisions would you make?
- Compare and contrast your protocol to the DTN protocol. The DTN protocol can be found here: https://www.nasa.gov/directorates/heo/scan/engineering/technology/disruption_tolerant_networking

# Delayed, Degraded, Delivered

This sheet is for use with the 3D Game.

Directions: After you receive your message from the Deep Space Network (DSN) station, roll your dice or number cubes and find the sum. Use the table below to see if your message is delayed, degraded, or delivered.

| Number rolled | Scenario | Action for index card |
|---|---|---|
| 2 | Delivered – Error detection has been completed, so there is no interference with the message. | **No change; deliver to next relay station** |
| 3 | Degraded – Transmission encounters ionized gas, which impairs the link between the spacecraft and the DSN station. | **Cross out the second word; deliver to next relay station** |
| 4 | Delayed – There is no direct line of view for the spacecraft to use the available antenna at the time of message delivery. | **Delay message for 60 seconds; after 60 seconds deliver to next relay station** |
| 5 | Delivered – Coding techniques successfully prevent interference with message. | **No change in the message; deliver to next relay station** |
| 6 | Degraded – Signal-to-noise ratio (signal power versus background noise) is low, so bit errors are excessive. | **Cross out every other word; deliver to next relay station** |
| 7 | Delivered – This relay station utilizes NASA's optical terminal (like the one that will be on Artemis II), which can send in 4K (resolution of approximately 4,000 pixels). | **No change; deliver to next relay station** |
| 8 | Delayed – A solar flare interferes with radio communications and causes a message delay. | **Delay message for 30 seconds; after 30 seconds deliver to next relay station** |
| 9 | Delivered – The single antenna is unable to capture the message, so an array is used to combine two or more antennas. | **No change; deliver to next relay station** |
| 10 | Degraded – The signal is degraded by background radio noise emitted naturally by objects in the universe. | **Tear out a word in the message; deliver to next relay station** |
| 11 | Degraded – There is a period of intense space weather (density of particles increased) disrupting radio frequencies. | **Cross out a part of the first, third, and fifth words; deliver to next relay station** |
| 12 | Degraded – The technology cooling the amplifiers is not working properly, which means additional noise is being added to the message. | **Add two additional words to the end of the message; deliver to the next relay station** |

# Activity Four: Networks

## Educator Notes

### Learning Objectives

Students will

- Solve a variety of network problems using minimum spanning trees.
- Determine the shortest route to visit each destination in a network.

### Challenge Overview

Many networks link our society together, such as telephone networks, computer networks, and transportation networks, in addition to NASA's Deep Space Network (DSN). In this activity, students will find the most efficient way of getting from one place in a network to another.

### Suggested Pacing

45 to 60 minutes

### National STEM Standards

<table>
<tr><th colspan="2">Science and Engineering (NGSS)</th></tr>
<tr><td>• MS-ETS1-2: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.<br>Disciplinary Core Ideas<br>• ETS1.C: Optimizing the Design Solution</td><td>Science and Engineering Practices<br>• Asking Questions and Defining Problems<br>• Developing and Using Models<br>• Using Mathematics and Computational Thinking<br>• Crosscutting Concepts<br>• Influence of Science, Engineering, and Technology on Society and the Natural World</td></tr>
<tr><th colspan="2">Technology (ISTE)</th></tr>
<tr><td>Knowledge Constructor<br>• 3d: Students build knowledge by actively exploring real-world issues and problems, developing ideas and theories, and pursuing answers and solutions.<br>Computational Thinker<br>• 5a: Students formulate problem definitions suited for technology-assisted methods such as data analysis, abstract models, and algorithmic thinking in exploring and finding solutions.<br>• 5d: Students understand how automation works and use algorithmic thinking to develop a sequence of steps to create and test automated solutions.</td><td>Innovative Designer<br>• 4a: Students know and use a deliberate design process for generating ideas, testing theories, creating innovative artifacts, or solving authentic problems.<br>Creative Communicator<br>• 6c: Students communicate complex ideas clearly and effectively by creating or using a variety of digital objects such as visualizations, models, or simulations.</td></tr>
<tr><th colspan="2">Computer Science (CSTA)</th></tr>
<tr><td>Standards for Students<br>• 1B-NI-04: Model how information is broken down into smaller pieces, transmitted as packets through multiple devices over networks and the internet, and reassembled at the destination.</td><td>Standards for Students (continued)<br>• 2-NI-04: Model the role of protocols in transmitting data across networks and the Internet.<br>• 2AP-10: Use flowcharts and/or pseudocode to address complex problems as algorithms.</td></tr>
<tr><th colspan="2">Mathematics (CCSS)</th></tr>
<tr><td colspan="2">Mathematical Practices<br>• CCSS.MATH.CONTENT.6.EE.B.6: Use variables to represent numbers and write expressions when solving a real-world or mathematical problem; understand that a variable can represent an unknown number, or depending on the purpose at hand, any number in a specified set.</td></tr>
</table>

### Challenge Preparation

The educator should

- Read the introduction and background material, particularly the information about NASA's Deep Space Network.
- Read the Educator Notes and Student Handouts to become familiar with the activity.
- Prepare the materials listed below.

### Materials

Each student/group will need

- ☐ Student Handout: Scavenger Hunt
- ☐ Student Handout: Deep Space Neighbors

- ☐ Dry-erase board and colored dry-erase markers in black, red, and blue
- ☐ Colored pencils or markers
- ☐ 50 cotton swabs or toothpicks
- ☐ 10 buttons or pennies

### Safety

- There are no safety concerns with this activity.

## Introduce the Challenge

### Engage

- Remind students that there are many kinds of networks in their lives, such as telephone networks, computer networks, transportation networks, and even networks of friends. NASA's DSN may be much more technically complex than a friend network, but relaying a message from Mars to Earth via satellites has a lot in common with passing a note to a friend via a few other friends. One of the most fundamental problems is figuring out which friend will pass the note most efficiently.
- Pass out Student Handout Challenge 1: Scavenger Hunt. Explain that the scavenger hunt activity is a simplified explanation for how computers design complicated networks by finding ways to efficiently connect each object in the network.

## Facilitate the Challenge

### Explore

- Read the scavenger hunt directions with students.
- Allow students to work individually on the scavenger hunt and then come back together as a whole group. To scaffold instruction within this activity, consider simplifying the scavenger hunt to only a few objects to introduce the idea of networks.

### Explain

- Discuss with the group the solutions they found for the scavenger hunt challenge. Have students explain what strategies they used.
- On the board, write the following words and discuss with the group their ideas for the words' definitions. As the activity progresses, add the definitions from the lesson to the board.
  - Graph
  - Abstraction
  - Algorithm
  - Minimum spanning tree
- Give students the following directions:
  - To begin the scavenger hunt, pick one item on the scavenger hunt map. That is the starting point. The next task is to connect that location to another on the map, using the shortest path possible, and then color in the path.
  - Continue working through the scavenger hunt by connecting more items, using as few steps as possible. Items that are already linked through another path **do not** need to be connected. Sometimes it may be better to go back to a location that has already been visited in order to connect to other items, and it may be shorter to use a new path than to backtrack. Two example paths are shown here in red:

## Share With Students

### Brain Booster

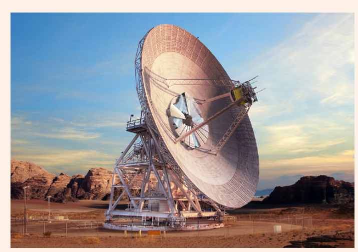
TV and movies tend to make communication in space look easy. Astronauts communicate with family and friends with crystal-clear clarity and no delay. In actuality, space communication is a challenging task, and NASA is up for the job!

Artist's rendering of tracking and data relay satellites alongside the International Space Station and the Hubble Space Telescope. (NASA)

Learn more: https://www.nasa.gov/feature/goddard/2020/space-communications-7-things-you-need-to-know

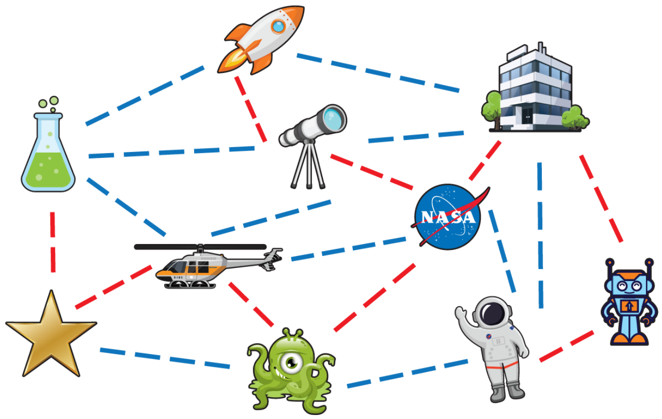
### On Location

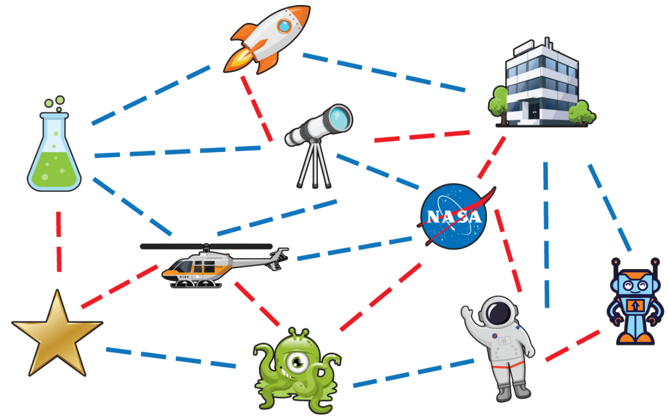
Virtually visit NASA's three Deep Space Network (DSN) antenna complexes across the world in the engaging video "Where in the World is the DSN?"



Artist's concept of Deep Space Station 23, a new antenna dish being constructed at the Goldstone, California, DSN complex. (NASA)

Learn more: https://youtu.be/Plkmm8f_4DE

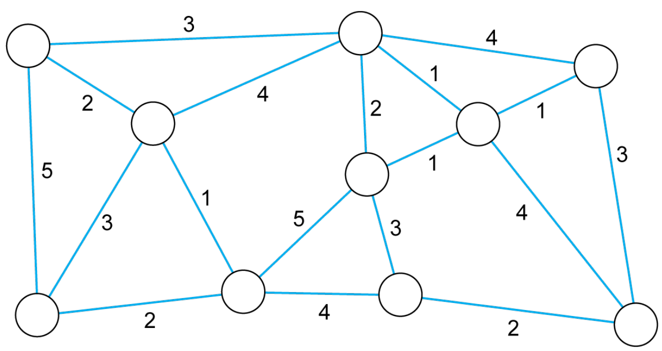



- Ask students where they would find networks of paths in real life. (Examples: Phone, computer, class schedules, bus routes, navigating a grocery store)

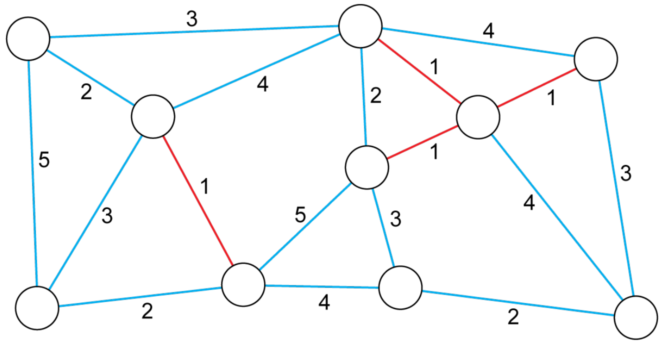
### Elaborate

- It can be very time consuming to draw items and create detailed maps like the one in the scavenger hunt activity. A quicker way to generate new maps is to use circles and lines with numbers representing the length of each path. As a first example of this type of a simple network map, draw or project the diagram below on the board. Another option is to create a digital version that students can interact with on computers—for example, in a presentation.



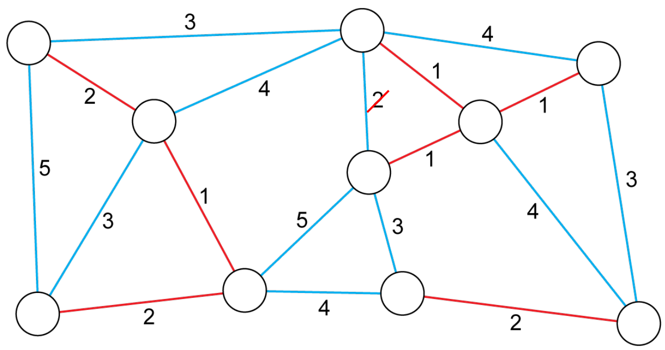

The formal name for this simpler type of map is a network *graph***.** There are many kinds of graphs; students may be more familiar with bar graphs, scatter plots, or histographs. All graphs represent data in a simpler fashion by highlighting some data and ignoring other data. This is called an *abstraction***,** and in this case, we are highlighting the distances and ignoring the object itself. The steps that are taken and repeated to solve a problem are called an *algorithm*. The algorithm demonstrated with the scavenger hunt is called a *minimum spanning tree***.** As a reminder, this algorithm focuses on always using the shortest distance available. With the scavenger hunt activity, the focus is on traveling the shortest route in order to visit all the locations on the map. However, for real-life networks, such as the DSN, a message just needs to find the shortest path to its destination; it may not need to travel along the entire network. In this way, a minimum spanning tree can be even more efficient for finding the shortest length of path from anywhere, not just from a single location. Explain to students that the next example will focus on this new, more efficient minimum spanning tree algorithm.

- In the graph above, shade in all the paths with a length of 1, because those are the shortest lengths to choose from. The completed shading is shown in red in the example that follows here:

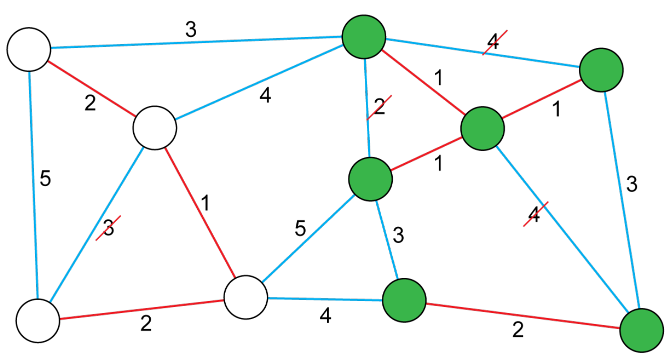



- Next, shade in the lengths of 2, *unless* the two circles have already been attached to the network through the lengths of 1.

  Note: Students may be confused to see that you are not starting in one place and drawing a connected path. Explain that since you already know the entire graph, a more effective decision can be made by selecting all the shortest lengths of paths. Also, notice that one length of 2 has been crossed through in the graph below. It is not needed because the two circles are already connected through the lengths of 1.

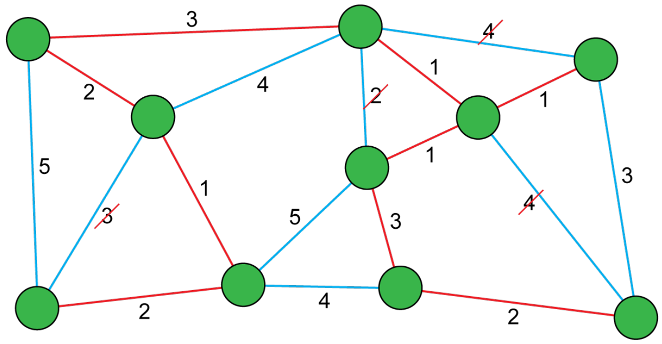



- Each circle now has at least one path leading to it. It is important to ensure that all the circles are connected to the entire network.
  - To ensure that all circles are connected, pick a circle at random to start with and fill it in (shown in the figure below with green circles).
  - Fill in every circle that can be reached directly from the starting circle using the shaded paths from the earlier exercise. For example, if starting with the circle to the top right, the circle that is one length away will be shaded in next.
  - In some cases, the circles will not be directly connected, but they will be connected in another way through the same network. That is okay! The goal is to lessen the number of steps in the minimum spanning tree.
  - If two items are connected in two different ways, eliminate the greater length by crossing it out. In this example, the length of 4 at the top of the graph is crossed out because there is another way (the length of 1) to get to the circle on the other end of that path. After connecting two more circles, another path of length 4 can be crossed out because the length of 3 is smaller.

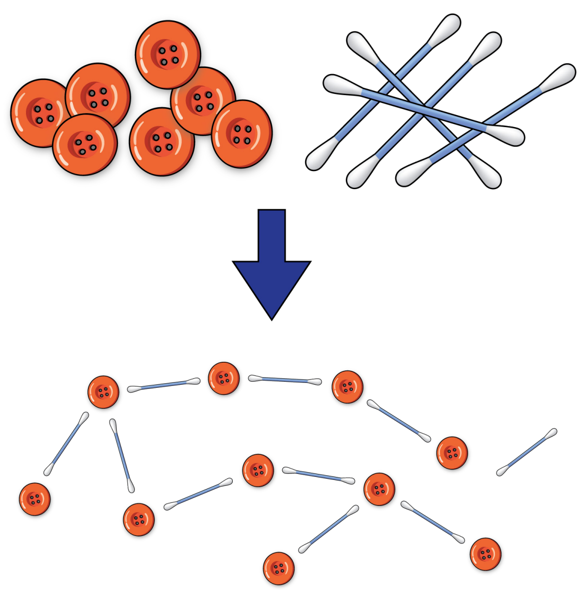



- Ask students if all the items are connected. As seen in the figure above, all the filled circles are connected in the network, but there is no completed path to the four remaining items. Make sure students understand that there are six items that are connected, and the other four items are connected to each other. Once students have connected those four to the entire network, they have completed the graph. Ask students which path they would choose. There are four ways to connect them, but it is important to choose the shortest length of path possible. Students should choose the length of 3 at the top of the graph.

- Ask students what would happen if there were two lowest length paths.
  - Answer: We could choose either of them.
- The final solution is below. Each item can now be reached in the minimal number of steps. It is a minimal solution because for *n* items (10 in this example), *n* – 1 paths (i.e., 9) are needed. Adding extra paths would be redundant and would add unnecessary steps, because only one path is needed to connect each item.




## Evaluate



- Now that students are familiar with minimum spanning trees, pass out Student Handout Challenge 2: Deep Space Neighbors.
- Instruct students to create a minimum spanning tree connecting all the satellites and antennas in the DSN.
- As a hands-on activity to this exercise and an evaluation of students' understanding, split up students into groups of two. Have each pair of students construct a connected graph using buttons or pennies and the cotton swabs or toothpicks, allowing students to choose what they prefer to work with. Have each group swap graphs with another group and try to find the minimum spanning tree of the other group's student-created graph.

## Resources

Where in the World Is the DSN? A Virtual Tour of NASA's Deep Space Communications Network (Video). https://youtu.be/PIkmm8f_4DE

Basics of Radio Astronomy. https://www2.jpl.nasa.gov/radioastronomy/radioastronomy_all.pdf

# Activity Four: Networks With NASA's Deep Space Network

## Student Handout

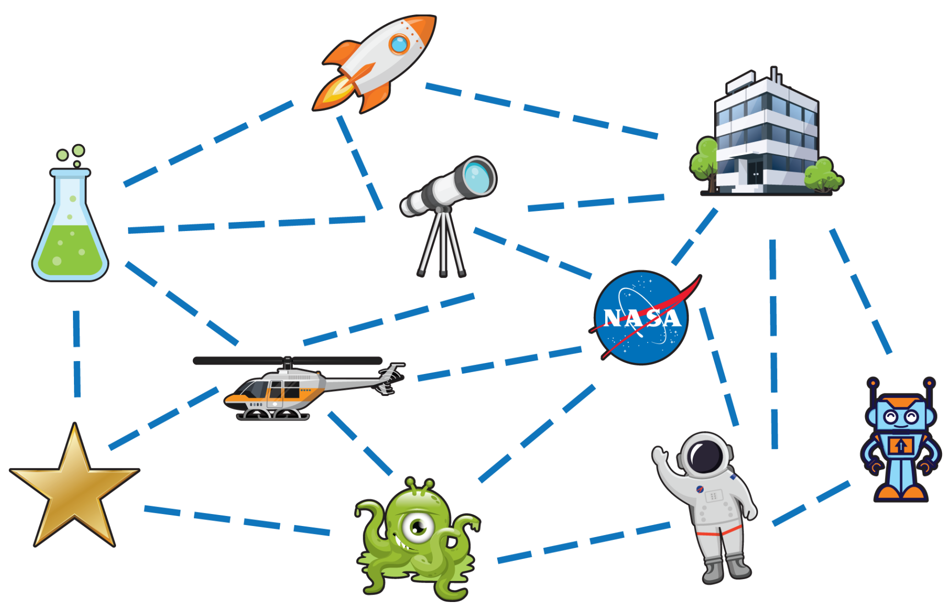
### Challenge 1: Scavenger Hunt

You have been invited to a NASA center and you have been challenged to a scavenger hunt. The scavenger hunt contains a list of items you need to find quickly. In this exercise, it is also important to take as few steps as possible when locating all 10 items. In the diagram below, you can see a map of the items and dashes connecting each item. Each dash represents a total of **20 steps**.

The scavenger hunt has two conditions:

1. You must connect all the scavenger hunt items together with the paths that you choose.
2. You must take the least number of steps possible. Remember that each dash is equal to 20 steps.

Shade in the most efficient (fewest steps) route to find all the items in the scavenger hunt.



### Fun Fact

Learn more about the Deep Space Network (DSN) with DSN Uplink–Downlink, an interactive game where you will use big antennas to send and receive information from NASA's robotic explorers in the solar system. An antenna "uplinks" instruction to the spacecraft and "downlinks" the spacecraft's images and data.

Learn more: https://spaceplace.nasa.gov/dsn-game/en/


### Career Corner

Eberhardt Rechtin is known as the "Father of the Deep Space Network." A pioneer in deep space research, he served as director of NASA's Deep Space Instrumentation Facility, the forerunner of the Deep Space Network. Prior to his career at NASA, he served in the U.S. Navy and received his doctorate in electrical engineering.

Eberhardt Rechtin directed the Deep Space Instrumentation Facility at NASA's Jet Propulsion Laboratory.

Learn more: https://history.nasa.gov/SP-4210/pages/Ch_5.htm

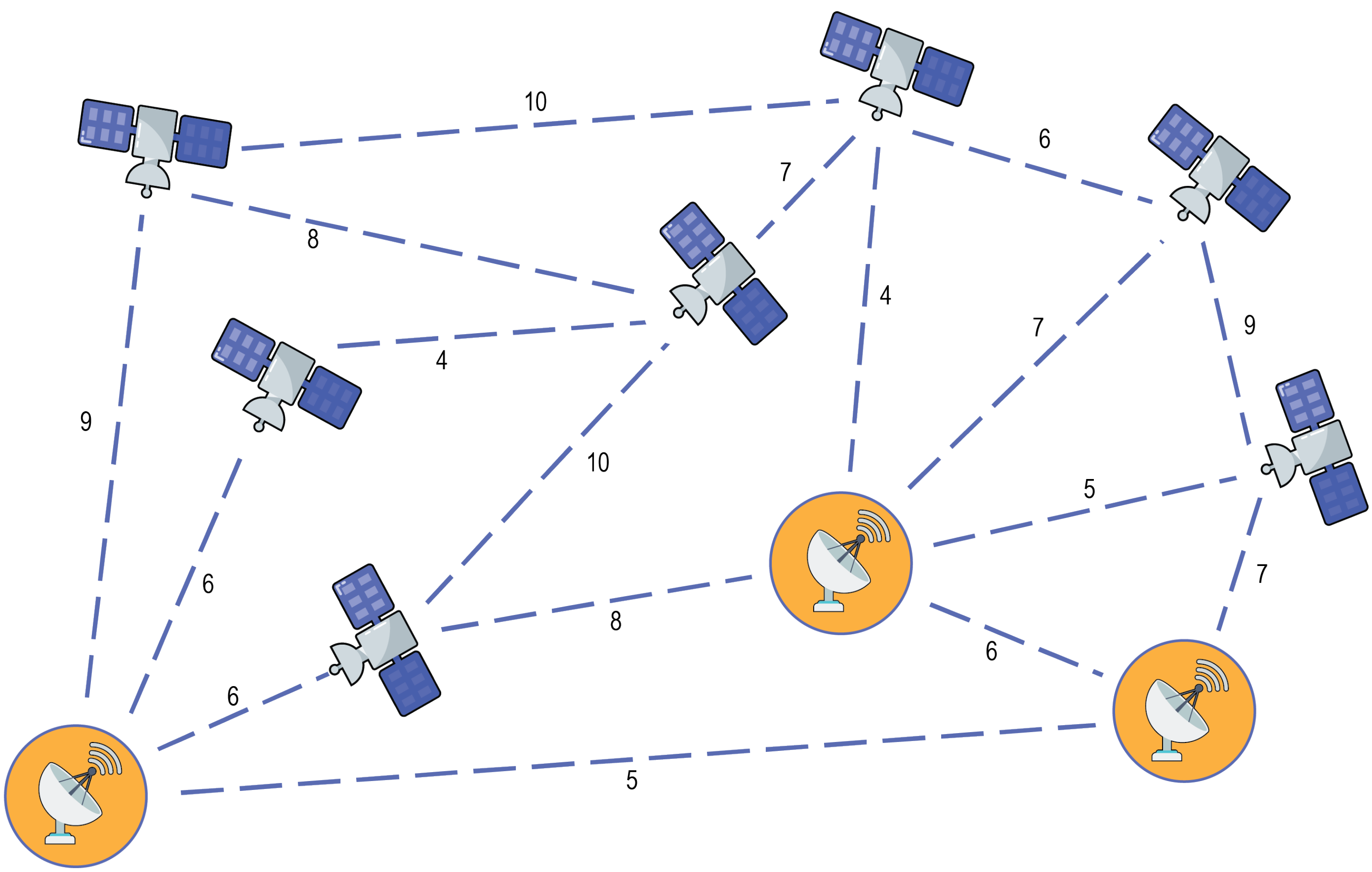
### Challenge 2: Deep Space Neighbors

NASA's Deep Space Network (DSN) is an important link in a network that communicates with all our satellites and spacecraft. Without this important network, we would lose contact with deep space satellites, like Voyager, or Mars rovers, like Perseverance and Curiosity. If we lost communication, we would not be able to send commands to our spacecraft or receive the amazing images and information that are sent back about our neighborhood, the solar system. In this activity, you will need to connect all the satellites to the giant DSN antennas in the most efficient way possible.

There are two conditions:

1. All satellites must be linked within the network
2. The network should be the most efficient. The numbers next to the paths between satellites represent distances. The farther the distance, or the bigger the number, the more degraded the message becomes, and the longer it takes to receive the message. After you complete your network, total up the distances. How does your total compare with other students' totals?

On the map below, shade in all the paths you plan on using:



# Appendix A.—Rubric for 5E Instructional Model

| 5E Step | Novice (0) | Apprentice (1) | Journeyperson (2) | Expert (3) | Level of student knowledge (Score) |
|---|---|---|---|---|---|
| **Engage** | Student does not identify any prior knowledge or connections to previous learning experiences | Student identifies irrelevant or inaccurate prior knowledge or connections to previous learning experiences | Student identifies one example of relevant and accurate prior knowledge or connection to previous learning experience | Student identifies two or more examples of relevant and accurate prior knowledge or connections to previous learning experiences | |
| **Explore** | Student does not participate in brainstorming discussion | Student participates in brainstorming discussion (asks questions, for example) but does not contribute possible hypotheses, solutions, or tests | Student contributes at least one possible hypothesis, solution, or test to brainstorming | Student contributes at least one possible hypothesis, solution, or test to brainstorming and an alternative or improvement to another student's idea | |
| **Explain** | Student does not provide explanation of observations | Student provides an explanation of observations that is inaccurate, incomplete, or lacks evidence | Student provides an accurate, complete explanation of observations based on evidence | Student provides an accurate, complete explanation of observations based on evidence and supplements their reasoning with either evidence or evidence-based explanations from others | |
| **Elaborate** | Student does not draw reasonable conclusions based on evidence | Student draws reasonable conclusions but does not utilize scientific terminology or evidence | Student draws reasonable conclusions utilizing scientific terminology and evidence | Student draws reasonable conclusions utilizing scientific terminology as well as evidence and can make reasonable predictions based on those conclusions | |
| **Evaluate** | Student does not demonstrate understanding of concept or can only repeat provided definitions | Student demonstrates an understanding of concept by providing definitions or explanations in their own words, drawings, models, etc. | Student demonstrates an understanding of concept by applying it to new questions or by analyzing new evidence | Student demonstrates an understanding of concept by explaining how evidence caused their knowledge to progress over time or by proposing new ways to use their new knowledge (such as followup experiments) | |
| | | | | **Total** | |

# Appendix B.—Glossary of Key Terms

**Absorption.** To soak something in, like water into a sponge; in the context of this guide, absorption occurs when photons from light hit atoms or molecules, which converts the light energy into vibrations

**Abstraction**. In computer science, a representation of data that focuses on the important details

**Algorithm.** Step-by-step process

**Antenna.** A structure that receives or sends electromagnetic waves such as radio waves; found on many space communications systems, from ground stations to satellites

**Artemis.** NASA's mission to land the first woman and next man on the Moon by 2024

**Binary notation.** Number system with the base of 2, which are the kinds of numbers most commonly used by computers. Digits can be 0 or 1. The binary notation of nineteen is 10011.

**Bit.** A single binary digit

**Byte.** A contiguous sequence of eight bits

**Cipher.** A coded message

**Communications.** The exchange of information from one place or person to another

**Data.** A collection of information, such as facts, numbers, measurements, photos, or observations

**Decimal notation.** Number system with the base of 10, which are the kinds of numbers most commonly used by people. Digits can be 0 through 9. The decimal notation of nineteen is 19.

**Degraded.** Reduced in quality; in communications, analog or digital signals can become degraded

**Delay.** A period of time by which an analog or digital signal is late or postponed

**Delay/Disruption Tolerant Networking (DTN).** A computer networking model and a system of rules for transmitting information (referred to as a protocol suite) that extends internet capabilities into the challenging communication environments in space, where the conventional internet does not work well

**Deliver.** Successfully send an analog or digital signal to a destination

**Graph.** A visual representation of a network of nodes in computer science

**Ground station.** A surface-based facility designed to provide real-time communication with satellites by sending and receiving radio signals

**Hexadecimal notation.** Number system with the base of 16 that uses numerals 0 through 9 and represents digits greater than 9, with letters A through F representing 10 through 15. Hexadecimal notation is commonly used by advanced computers. The hexadecimal notation of nineteen is 13.

**Minimum spanning tree.** A graph where every node is connected to the graph in the most efficient way

**Navigation.** A determination of current position in planning and following a route

**Nybble.** Four bits grouped together

**Packetizing.** Breaking up data into smaller segments (packets) for transmission across a network

**Protocol.** A procedure for carrying out the exchange or transmission or data

**Receiver.** Person or device that receives waves, electrical signals, or the like from the transmitter

**Satellite.** A spacecraft that orbits the Earth, the Moon, or another celestial body; satellites use radio signals to communicate with ground stations on Earth and with rovers on the Moon and Mars

**SCaN.** NASA's Space Communications and Navigation (SCaN) program; SCaN has antennas around the world and satellites in space to help guide spacecraft and exchange important information with all NASA spaceflight missions

**Signal.** A radio wave that has been modulated to carry information; in the context of this guide, a signal is communication with a spacecraft over a distance

**Transmission.** The sending and receiving of information by radio waves in space

**Transmitter.** The person or device sending a message or data

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