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

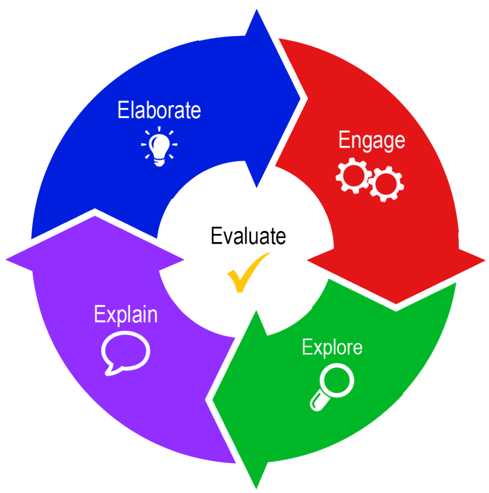
The STEM disciplines matrix shown below aligns each activity in this module to standards for teaching STEM according to four primary focus areas within each discipline. The four focus areas for science were adapted from the Next Generation Science Standards (NGSS) middle school disciplinary core ideas. 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

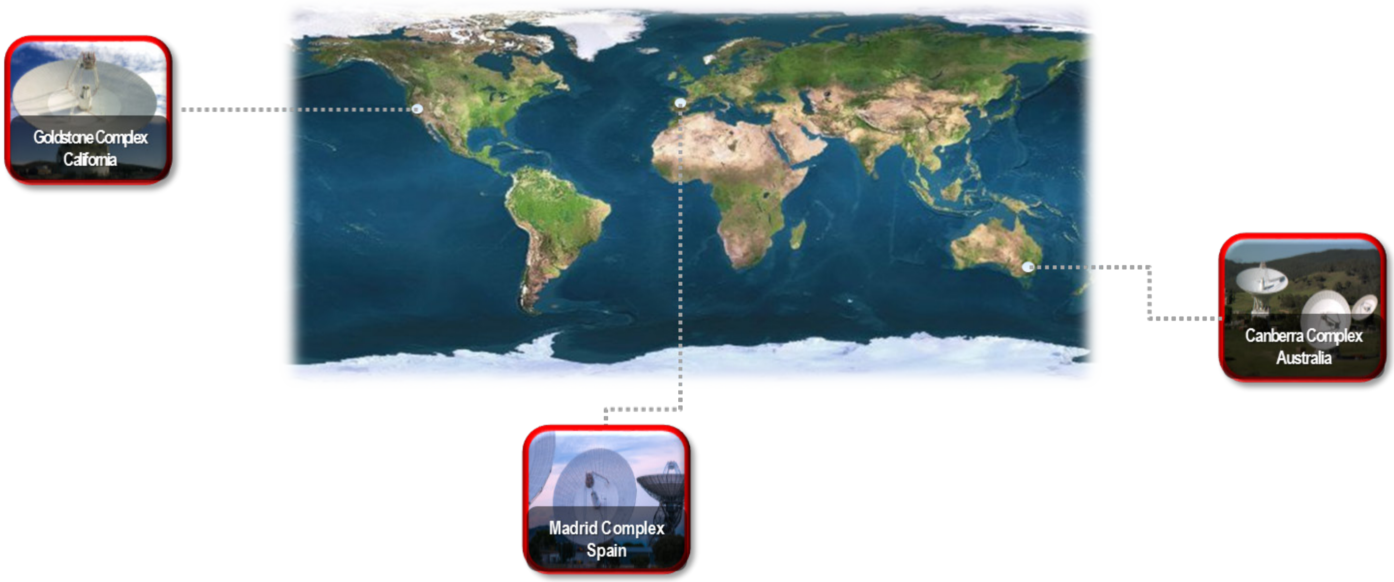
Introduction and Background (Deep Space Network)

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)	9×10^{16}
Pluto	5,000,000,000 (3,106,855,961)	2.5×10^{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

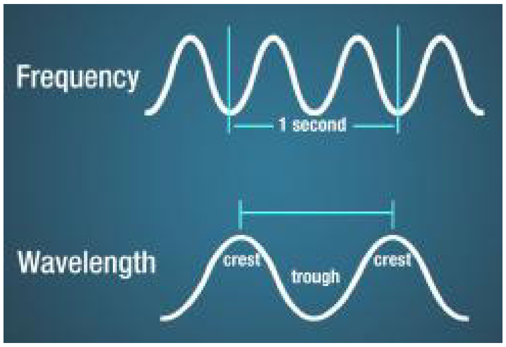
At some point, all communications (e.g., spoken words, text on a page, radio broadcasts, or laser transmissions) travel as waves through a medium. For spoken words, those waves would be sound waves, but long-distance communication is primarily based on electromagnetic waves such as visible light, infrared 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.

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!



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)

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

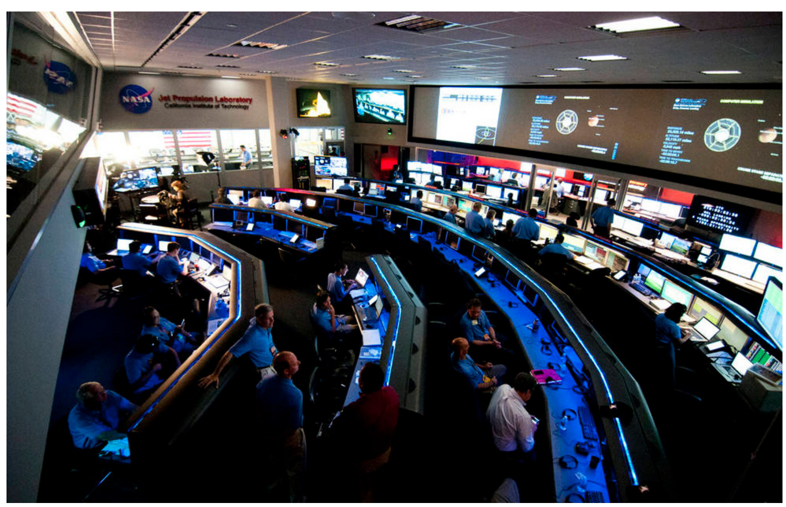
Sending messages and data gets more complicated the farther those signals have to travel. A signal might be blocked by something getting in the way, and radiation from the Sun or other celestial bodies can also interfere with the quality of transmissions. With enough of these types of complications, 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.