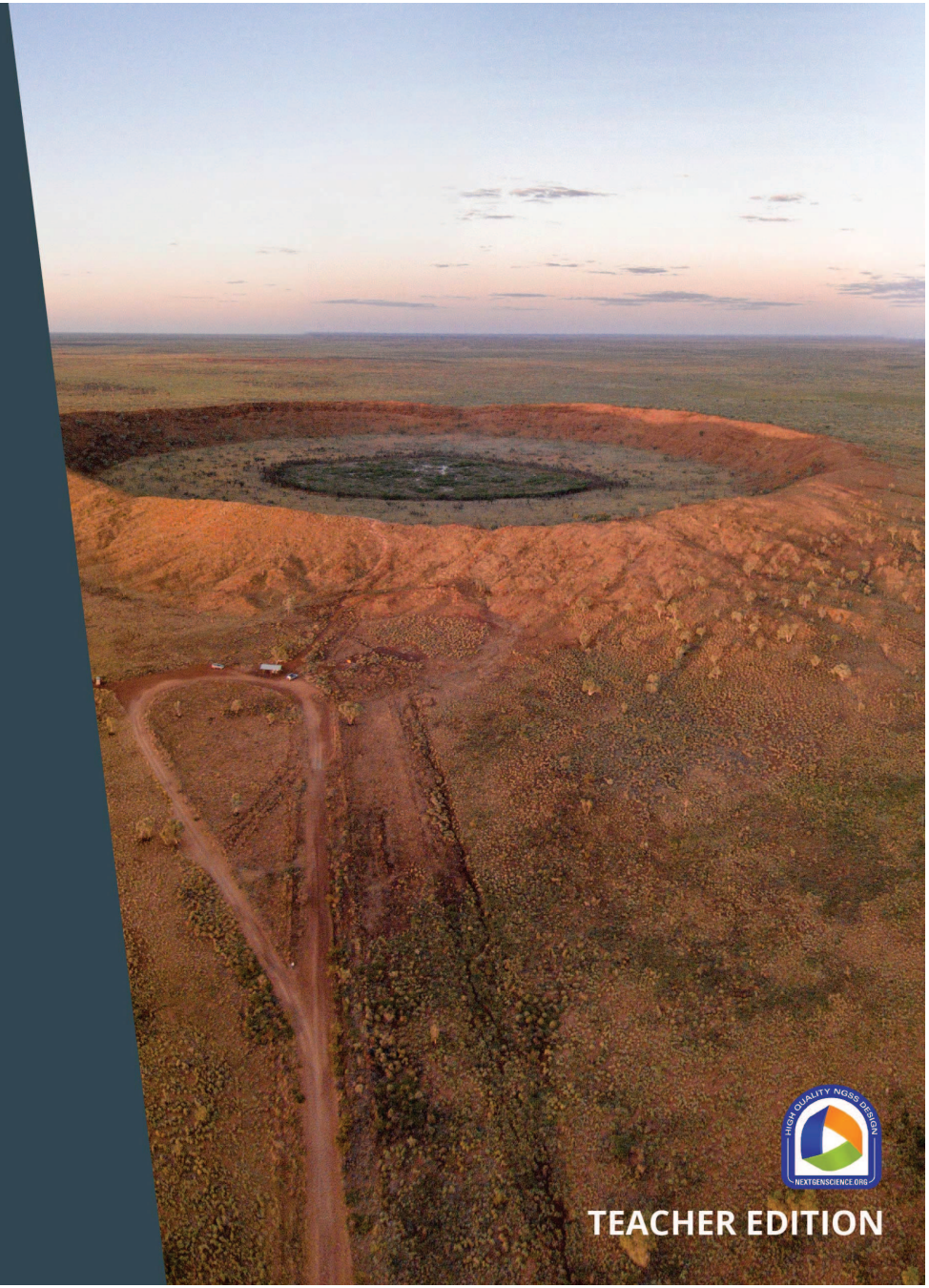
PHYSICS

Meteors, Orbits, & Gravity

How have collisions with objects from space changed Earth in the past, and how could they affect our future?



OpenSciEd

HIGH SCHOOL SCIENCE

TEACHER EDITION

How have collisions with objects from space changed Earth in the past, and how could they affect our future?

Meteors, Orbits, & Gravity: Meteors

OpenSciEd Unit P.4



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TABLE OF CONTENTS

Unit P.4 How have collisions with objects from space changed Earth in the past, and how could they affect our future?

Unit Overview		1
Unit Storyline		3
Teacher Background Knowledge		11
Home Communication		24
Lesson 1:	Why is stuff falling from the sky?	27
Lesson 2:	How far does Earth's gravity extend into space?	51
Lesson 3:	How does gravity cause only some objects to orbit?	79
Lesson 4:	Why do objects sometimes collide in space?	99
Lesson 5:	How do objects travel within their orbit paths?	117
Lesson 6:	How can force interactions in space change the orbital path of a space object?	135
Lesson 7:	What can we do if an orbiting object poses a significant risk for Earth?	143
Lesson 8:	What is the probability of a future or past meteor event impacting Earth?	149
Lesson 9:	What happened to all the meteors that reached Earth over its history?	161
Lesson 10:	What determines the size of the crater made on impact?	171
Lesson 11:	What happens to the thousands of objects the size of the Chelyabinsk meteor and smaller that enter Earth's atmosphere every year?	187
Lesson 12:	What happens when rocks hit planets or moons with minimal atmosphere?	203
Lesson 13:	Why don't we see many craters on the surface of Earth?	221
Lesson 14:	How could an impactor have killed off some types of life on Earth but not all?	239
Lesson 15:	How can we use our science ideas to explain the formation of the Moon?	255
Unit P.4 Teacher Reference Materials		263
Unit P.4 Lesson-Specific Teacher Materials		281

UNIT OVERVIEW

How have collisions with objects from space changed Earth in the past, and how could they affect our future?

This unit is designed to introduce students to the motion of objects in our solar system through the perspectives of matter, force, and energy. The learning is anchored by the appearance of a large fireball in the sky over Siberia in 2013 (the Chelyabinsk meteor). This phenomenon provides the context in which to investigate how and why objects from space sometimes collide with Earth. To figure this out, students will need to apply the concepts of Newton's universal law of gravitation, orbital motion, energy transfer with gravitational fields, and the history of Earth.

The unit is organized into two lesson sets. In **Lesson Set 1** (Lessons 1-7) students investigate how gravity between two objects changes over distance. They mathematically model gravitational forces at far distances by investigating magnetic forces at tangible distances. They then investigate how forces and tangential velocity can cause objects to move in circles and how this describes how gravity keeps objects in orbit instead of crashing into Earth or the Sun. They derive the relationship between orbital period and radius (Kepler's third law) through combining the mathematical models for gravity and circular motion, and they reason that meteors like the one they observed during the anchor are not likely to move in circular orbits. Next, they investigate noncircular orbits and learn that all orbits are elliptical (Kepler's first law), with variation in eccentricity. They reason that this variation of orbit shape can cause orbit paths to cross, creating a potential risk of collision between objects. They model the energy transfer that occurs between the Sun, an orbiting object, and the gravitational field between them to conceptualize the changes in velocity of an object in an eccentric orbit (Kepler's second law). They use this to consider how we can model the potential for an object to collide with Earth. Finally, they consider the limitation of Kepler's laws to two-body systems and explore how contact and noncontact forces can change the orbital path of space objects. Students end the lesson set wondering how these concepts of gravity and interactions with nearby objects have and will affect Earth. At the end of this lesson set, students use their ideas to explain how a kinetic impactor and a gravity tractor, two asteroid-deflection strategies, work.

In **Lesson Set 2** (Lessons 8-15) students consider Earth's history and future. They start by analyzing data about objects that recently came close to colliding with Earth and use this to predict the probability of a high-energy collision event. They return to the DQB to evaluate the questions they have answered and brainstorm additional questions based on these data. To answer these new questions, students carry out an investigation to explain which meteor property, its mass or velocity upon impact, can have a larger effect on the amount of damage it can cause. They analyze data on how small objects burn up in Earth's atmosphere, preventing them from hitting Earth's surface. They analyze evidence of cratering activity on solar system objects that do not have atmospheres and identify patterns that suggest changes in the frequency of small and large meteors hitting the Earth-Moon system over time. They also analyze evidence of cratering activity on Earth and explore geological processes that help explain the lack of large craters on Earth. They read about an especially large crater in Chicxulub that dates to the same time that there was a mass extinction event on Earth and use these ideas to explain how the impactor led to both short-term and longer-term effects that caused the extinction of only some types of organisms and not others. Finally, they return to the DQB to evaluate the questions they have answered and complete a transfer task on the formation of the Moon.

Building Toward NGSS Performance Expectations

HS-ESS1-4:
Use mathematical or computational representations to predict the motion of orbiting objects in the solar system.

HS-ESS1-6:
Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history.

HS-PS2-4:
Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

HS-PS3-1:
Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.

HS-PS3-2:
Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motion of particles (objects) and energy associated with the relative positions of particles (objects).

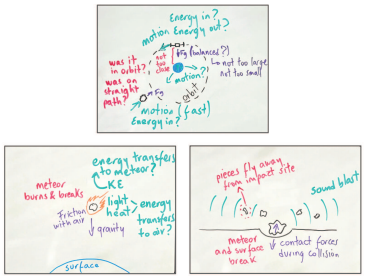
UNIT STORYLINE

Unit Question: How have collisions with objects from space changed Earth in the past, and how could they affect our future?

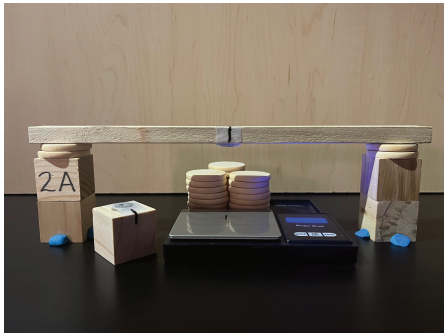
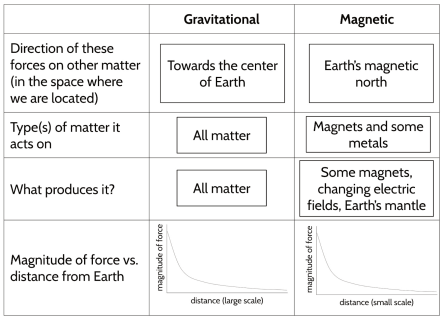
How students will engage with each of the phenomena

HANDS-ON/ LAB ACTIVITIES | VIDEOS OR IMAGES | DATA SETS | READINGS | COMPUTER INTERACTIVES

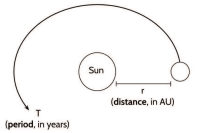
Lesson Set 1: What causes collisions between Earth and objects in space?

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 1 Lesson Set 1 3 days **Why is stuff falling from the sky?** Anchoring Phenomenon	 *A rock from space hit Siberia in 2013; it glowed brightly as it traveled through the air for a few seconds, then it exploded and damaged windows in buildings for many miles.*	We explore video of the Chelyabinsk meteor. We categorize data on related phenomena. We develop two models, one to explain the observed changes during the Chelyabinsk event, and one to explain the motion of different space objects. We record questions and ideas for investigations and data we need to answer them for our Driving Question Board. We figure out: • A rock from space broke up over Siberia in 2013, lit up the sky, and damaged buildings. • Similar phenomena have been observed in other places around the world throughout history. Sometimes pieces of this stuff hit the ground, and sometimes they do not. • Some space objects in the solar system remain in orbit, while others collide with different objects.	

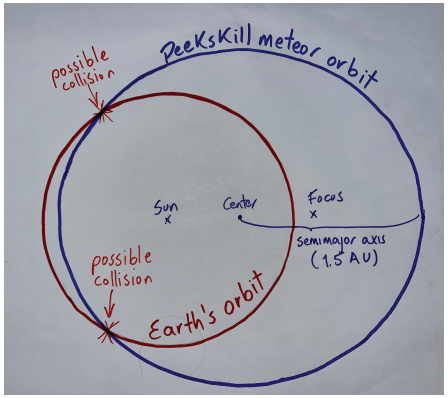
⇓ **Navigation to Next Lesson:** Since gravity pulls space objects towards each other, we wondered how it can cause some objects to move in orbit and others to hit Earth.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 2 Lesson Set 1 3 days **How far does Earth's gravity extend into space?** Investigation	 *Various tools in our lab allow us to measure the strength and direction of forces between two objects' fields when the distance between them is changed.*	We make predictions about the gravitational force experienced by objects at different distances from Earth's surface and carry out an investigation of magnetic forces versus distance. We analyze data for various objects and distances. We use mathematical models to determine the strength of the force acting on different space objects and consider whether this helps explain why some objects collide with Earth while others remain in orbit. We figure out: • When two objects interact at a distance through a field, the forces between them are equal in magnitude and opposite in direction. • Newton's law of universal gravitation mathematically models how gravitational forces depend on the masses of and distance between two objects. • The force of gravity experienced by space objects alone does not fully explain why some collide with Earth while others remain in orbit.	**Gravity-Magnetism Comparison** 

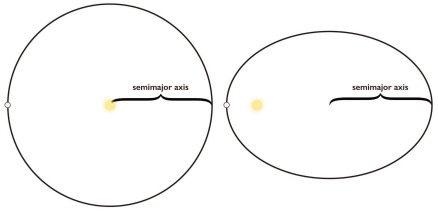
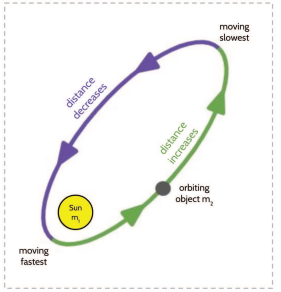
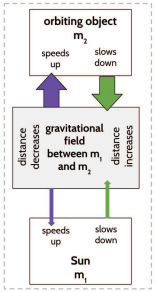
⇓ **Navigation to Next Lesson:** If we know some amount of gravity extends forever through space, what prevents the Moon and satellites from falling into Earth or Earth from falling into the Sun?

LESSON 3 Lesson Set 1 2 days **How does gravity cause only some objects to orbit?** Investigation	 *Some objects in the solar system orbit others in regular patterns of circular motion, which we can emulate in the lab using simple equipment or simulations.*	We use a simulation to figure out the relationship between velocity and force necessary for orbit. We investigate how the distance between two objects affects this relationship and identify the period of revolution of an object to predict its orbital motion. We identify a relationship between period and orbital radius. We figure out: • Some planets orbit the Sun in nearly circular orbits. • An object must have the right velocity in order to orbit a star or planet. If it is moving too fast, it will continue into space. If it is moving too slow, it will fall toward the star or planet. • The relationship between the gravitational force on an object and its velocity depends on the distance from the object it orbits. • The relationship (T^2/a^3) of orbital period (T) to radius (a) is constant for all objects orbiting the same body.	This relationship is referred to by scientists as **Kepler's third law**. $\frac{T^2}{a^3} = constant$ 

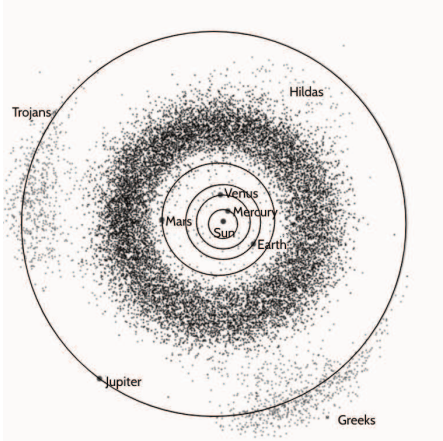
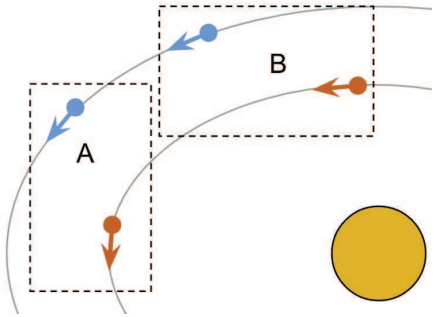
⇓ **Navigation to Next Lesson:** If objects orbit in predictable circular paths, then why do they sometimes hit each other?

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 4 Lesson Set 1 2 days **Why do objects sometimes collide in space?** Investigation	 *Objects orbit the Sun with elliptical orbits ranging from near circular to very stretched out. Sometimes orbital paths of objects cross.*	We explore elliptical orbits and their properties. We read about objects in space that may have the potential to collide with Earth and model the orbits of Earth and the Peekskill meteor to explain their collision. We wonder how to know if objects on crossing orbits will actually meet at the crossing point and collide. We figure out: • Orbits are elliptical in shape with the Sun located at one of the foci. • Objects in space are at risk of colliding if their orbit paths cross. • Asteroids, comets, and meteor showers are different types of objects in space that have the potential to collide with Earth.	

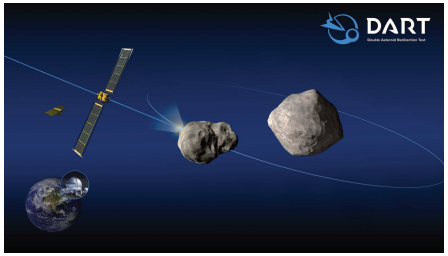
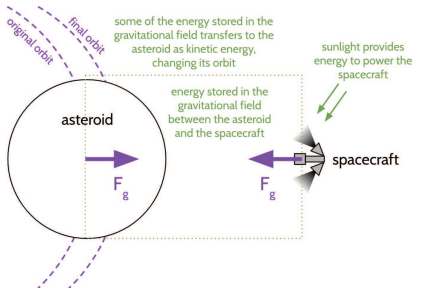
⇓ **Navigation to Next Lesson:** We figure out that orbits are elliptical in shape and that collisions are possible if two orbits cross each other in space. We wonder how we know when the objects will be at this intersection point of orbits so we can know if there will be a collision.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 5 Lesson Set 1 2 days **How do objects travel within their orbit paths?** Investigation	 *The speed of an orbiting object varies with its distance from the Sun.*	We want to know more about how to predict the motion of orbiting objects. We look at a simulation of orbits and notice that the speed of objects in elliptical orbits changes along the path. We use energy thinking to make sense of this and construct energy transfer diagrams to model this change. We make predictions about the Chelyabinsk meteor's orbit to compare with scientists' predictions next time. We figure out: • Orbiting objects move faster when closer to the Sun and slower when farther away. • Speed changes of orbiting objects are related to the distance between the orbiting object and the Sun and are due to energy transfer between the object and the Sun and the gravitational field between them.	 

⇓ **Navigation to Next Lesson:** We think that the Chelyabinsk meteor probably had a very eccentric orbit, which is why it hit Earth. We want to compare our predictions against scientists' predictions next time.

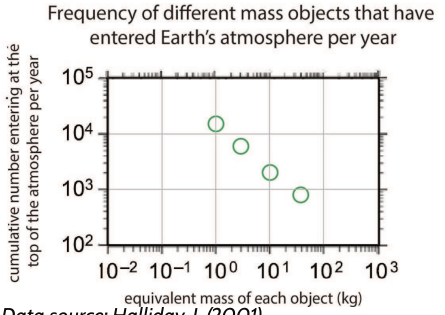
Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 6 Lesson Set 1 1 day **How can force interactions in space change the orbital path of a space object?** Investigation	 *The Chelyabinsk meteor originated from the asteroid belt before it was redirected by force interactions in space.*	We are wondering if gravitational forces can change orbital paths and consider the limitations of our two-object models. We look at an image of our solar system with the asteroid belt and make predictions as to what could have led to the redirection of the Chelyabinsk meteor from the asteroid belt towards Earth. We develop models for the two possibilities: gravitational forces from other objects or a collision with another asteroid. We figure out: • Scientists believe that the Chelyabinsk meteor was likely redirected by a combination of collisions and gravitational forces from nearby objects. • Many meteors that collide with Earth come from the asteroid belt where they could have been redirected by collisions with other asteroids or by the gravitational forces from nearby objects.	

⇓ **Navigation to Next Lesson:** We figured out that there are many different interactions between objects in our solar system and that some of these interactions can lead to collisions with Earth. We are wondering how often Earth is collided with and how collisions have shaped the planet we know today.

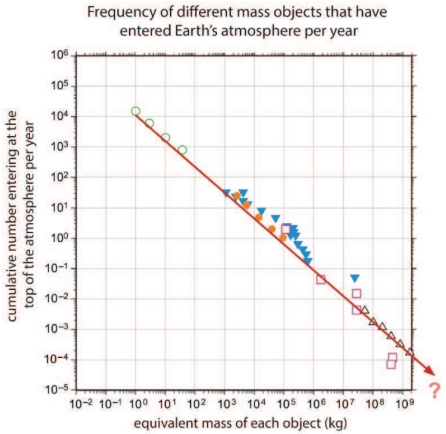
LESSON 7 Lesson Set 1 1 day **What can we do if an orbiting object poses a significant risk for Earth?** Putting Pieces Together	 *NASA and other space agencies are developing and testing strategies intended to deflect hazardous impactors on a collision course with Earth.*	We read about two strategies designed to deflect hazardous impactors on a collision course with Earth. We use data collected by scientists and some of the mathematical models we have developed in this unit to explain how these strategies work. We figured out: • Scientists are developing and testing strategies intended to deflect hazardous impactors on a collision course with Earth. • A small spacecraft traveling at high speed can have enough kinetic energy to change the orbit of an impactor. • A gravity tractor can slowly move an impactor into a different orbit by using the force of gravity acting between the spacecraft and the impactor.	

⇓ **Navigation to Next Lesson:** We wonder how often impactors like the Chelyabinsk meteor hit Earth.

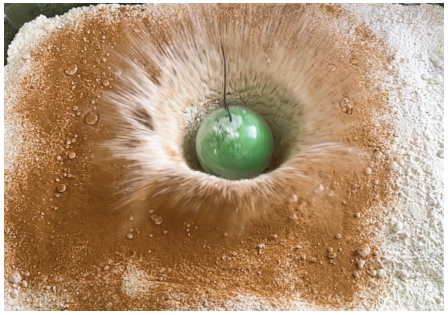
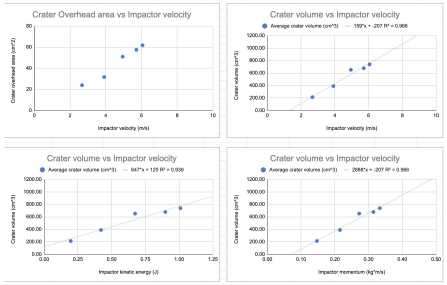
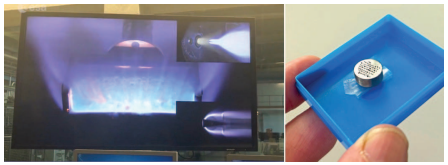
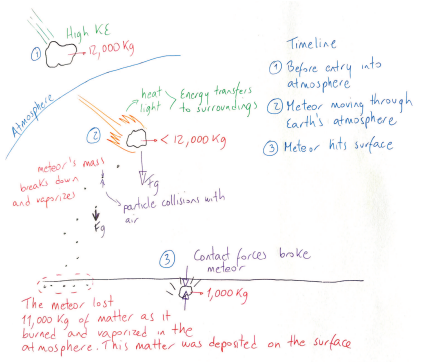
Lesson Set 2: How can we know if Earth is at risk for future large-scale, high-energy collisions?

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 8 Lesson Set 2 1 day **What is the probability of a future or past meteor event impacting Earth?** Investigation	<table><tr><th>Meteor size (kg)</th><th>Frequency per year</th><th>Frequency of a single event</th><th>Kinetic energy (in J)</th></tr><tr><td>10,000,000</td><td>0.01</td><td>1 per 100 years</td><td>2×10^{9} J</td></tr><tr><td>100,000,000</td><td>0.001</td><td>1 per 1,000 years</td><td>2×10^{10} J</td></tr><tr><td>1,000,000,000</td><td>0.0001</td><td>1 per 10,000 years</td><td>2×10^{11} J</td></tr><tr><td>1×10^{10}</td><td>0.00001</td><td>1 per 1×10^{5} years</td><td>2×10^{12} J</td></tr><tr><td>1×10^{11}</td><td>0.000001</td><td>1 per 1×10^{6} years</td><td>2×10^{13} J</td></tr><tr><td>1×10^{12}</td><td>0.0000001</td><td>1 per 1×10^{7} years</td><td>2×10^{14} J</td></tr><tr><td>1×10^{13}</td><td>0.00000001</td><td>1 per 1×10^{8} years</td><td>2×10^{15} J</td></tr><tr><td>1×10^{14}</td><td>0.000000001</td><td>1 per 1×10^{9} years</td><td>2×10^{16} J</td></tr><tr><td>1×10^{15}</td><td>0.0000000001</td><td>1 per 1×10^{10} years</td><td>2×10^{17} J</td></tr></table> *Cameras, telescopes, and sound detectors have detected many different-sized objects that have entered Earth's atmosphere over a 28-year period.*	We construct a line that best fits a graph of objects that have entered Earth's atmosphere and use it to predict the frequency of larger-mass objects reaching Earth's atmosphere. We estimate the potential damage these could inflict using kinetic energy. We argue for why we should continue to invest in DART-like technologies and what this might imply about Earth's past. We figure out: • Large meteors are rare and unlikely, but they could alter human history. • The mathematical relationship we've established should guide our future plans • While these relationships offer insights into Earth's 4.5-billion-year history, more data are needed to confirm or refute their historical predictions.	 *Data source: Halliday, I. (2001)*

⇓ **Navigation to Next Lesson:** We know that we can predict the likelihood of an impact that poses a significant risk to Earth. We wonder about potential strategies for protecting Earth from a future impact.

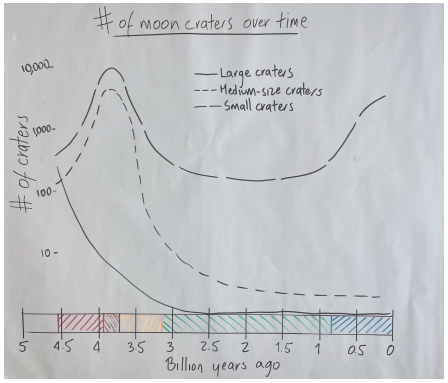
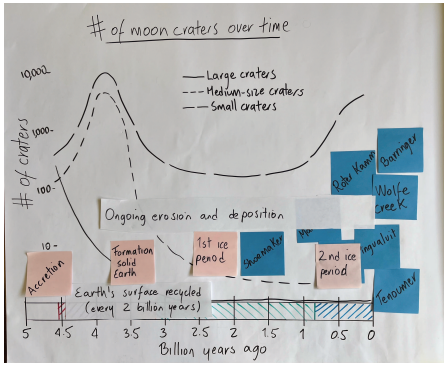
LESSON 9 Lesson Set 2 1 day **What happened to all the meteors that reached Earth over its history?** Investigation	 *The frequency of meteors that reach Earth versus their mass follows a relatively linear trend for the period of time we have observed them.*	We share initial explanations for what might have happened to all the objects of different sizes that reached Earth from space over its 4.5-billion-year history. We brainstorm factors besides mass that might affect what happens to these objects when they reach Earth. We record new questions we have and sources of data and investigations that could help us answer these questions. We figure out: • The mass of a meteor (or space object) probably affects whether anything impacts Earth's surface or whether it all burns up in the atmosphere. • There are additional factors besides mass (e.g., speed, angle, or trajectory, material of the meteor, and where it hits) that may also affect the outcome. • We are not certain that our mathematical model from the last lesson holds for earlier in Earth's history or for moons and other planets.	

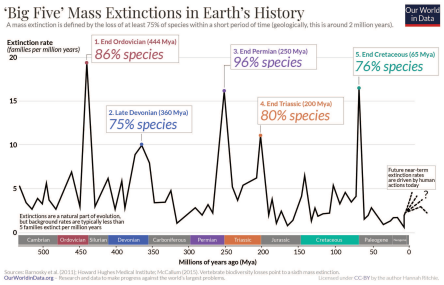
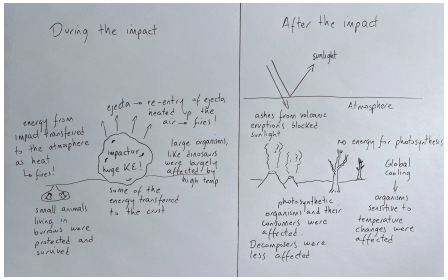
⇓ **Navigation to Next Lesson:** While we have a lot of new lines of questions and ideas for investigations, we plan on starting our next lesson with the line of investigations related to what makes meteors more damaging.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 10 Lesson Set 2 2 days **What determines the size of the crater made on impact?** Investigation	 *Dropping impactors of different masses and from different heights in flour generates craters of different sizes.*	We investigate whether a meteor's velocity or mass better predicts its crater size. We analyze our results using the coefficient of correlation to establish that the velocity of an impactor better predicts the crater's size. We learn that meteors with sufficient kinetic energy can vaporize upon surface impact. We explain the changes in matter and energy within the meteor-Earth system. We figure out: • Craters are not imprints of the objects but are larger than the object was. • Craters are surrounded by areas of ejecta. • The kinetic energy of an impactor is a good predictor of the size of a crater. • In comparison to mass, the velocity of an impactor has a stronger relationship with the size of the crater it creates. • Increasing the mass also increases the size of the crater. • Impactors with enough kinetic energy can vaporize upon surface impact.	
LESSON 11 Lesson Set 2 1 day **What happens to the thousands of objects the size of the Chelyabinsk meteor and smaller that enter Earth's atmosphere every year?** Investigation	 *High-speed wind tunnels are used to simulate what will happen to some satellites upon reentry. Some hobbyists use magnets to find small fragments of iron meteors scattered across Earth's surface.*	We analyze data from a video of a satellite being tested in a high-speed wind tunnel. We develop an explanation for why only a relatively small amount of the Chelyabinsk meteor's matter was still in solid pieces when it reached the surface. We argue that only a small amount of the matter that most frequently enters Earth's atmosphere ends up actually leaving an impact on its surface. We figure out: • As objects from space move through the atmosphere at high speeds, they collide with air particles, causing changes in both matter and energy along their paths. • All the matter that melts, vaporizes, or breaks off in solid pieces in this process will eventually end up deposited across Earth's surface. • Only a fraction of the matter that enters Earth's atmosphere leaves an impact on the surface because it either has so little mass to begin with or is in really small pieces by the time it reaches the surface.	

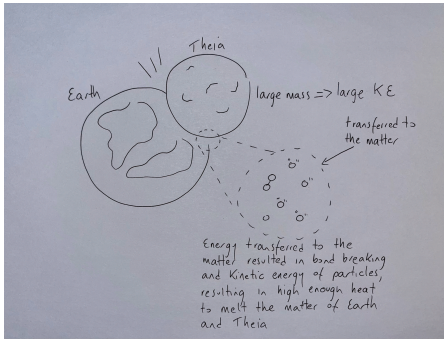
⇓ **Navigation to Next Lesson:** Since sometimes the rocks that come towards Earth hit the ground and sometimes they do not, we wondered what determines whether a rock hits the ground and how often this happens.

⇓ **Navigation to Next Lesson:** We predicted that the frequency and size of impacts from meteors would be much larger if we did not have an atmosphere, which led us to want to look at some data from planets or moons that have little or no atmosphere to see if they support or refute our predictions.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 12 Lesson Set 2 2 days **What happens when rocks hit planets or moons with minimal atmosphere?** Investigation	 *There are many craters on objects in the solar system that are varied in size and age and do not have the impactors in the craters.*	We examine images of objects in space that lack atmospheres to see what happens when objects fall into them without burning up in an atmosphere. We make observations of cratering activity on the Moon over its history and find periods with high and low cratering activity. We consider why we don't see evidence of large meteor impacts on the Moon. We figure out: • There are a lot of craters on other space objects created over billions of years. • Evidence from other space objects suggests there must have been a large number of things that came towards Earth too (many of which probably burned up in the atmosphere). • The age distribution of large craters on the Moon has decreased over time, while the age distribution of small and medium-size craters has fluctuated.	
⇓ **Navigation to Next Lesson:** We figured out that the surfaces of numerous planets and moons are dotted with craters, both large and small. We wonder why Earth's surface does not look like that.			
LESSON 13 Lesson Set 2 2 days **Why don't we see many craters on the surface of Earth?** Investigation	 *The record of terrestrial craters exhibits a pattern of relatively recent cratering activity that sharply declines after 650 million years.*	We will analyze data and find visible impact cratering is absent in over half of Earth's timeline. We will use images of terrestrial craters to observe that older ones have less-clear features. We will use an erosion model to test how the surface can change. We will read about geological processes and will use these ideas to explain differences in cratering evidence between the Moon and Earth. We figure out: • We see that visible Earth craters have been found mostly in the last 650 million years of our 4.5 billion year history. • We see that Earth's craters are less well defined than those of the Moon. • We learn about four Earth processes or mechanisms which shaped Earth's landform throughout its history. • Around 65 million years ago, a meteor with enough kinetic energy to create a crater 112 miles (200 km) in diameter collided with Earth.	
⇓ **Navigation to Next Lesson:** The historical record shows that Earth has been hit by large meteors. We wonder how an impact from an object in space could cause a mass extinction on Earth.			

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 14 Lesson Set 2 3 days **How could an impactor have killed off some types of life on Earth but not all?** Investigation	 *A layer of ~1-cm-thick sedimentary rock can be found all over the world that has a concentration of iridium in it that matches what is found in meteors and has been radioactively dated to be 65-66 million years old. Many types of fossils found in the layer below it don't appear anywhere in the layers above it.*	We analyze a graph showing mass extinctions in Earth's history. We develop a model to explain how an impactor collision leads to mass extinctions. We gather information about the Chicxulub crater formation. We use a Gotta-Have-It Checklist to revise the model to explain how some but not all types of organisms go extinct. We figure out: • The fossil record provides evidence that some types of organisms went extinct around the time of the impact (e.g dinosaurs, herbivores, terrestrial plants), while others survived. • There are competing/alternate mechanisms for how the impactor affects energy transfers and matter flows in and through other earth systems (global forests, oceans, mantle, atmosphere). • There would be longer-term effects on the energy flow to photosynthetic organisms and through food chains, due to the longer-term changes in matter in different earth systems, that would have resulted from the impactor.	

⇓ **Navigation to Next Lesson:** While we explained the effects of a 10 km-wide object colliding with Earth 65 million years ago. We now have a lot of new questions about the effects of a 6,000 km-wide object that scientists believe collided with Earth even longer ago. We plan to investigate and answer some of these questions as part of a final transfer task and assessment to wrap up the unit in the next lesson .

LESSON 15 Lesson Set 2 1 day **How can we use our science ideas to explain the formation of the Moon?** Putting Pieces Together	 *Scientists believe the Moon was formed after Theia, a planet from the young solar system, collided with Earth.*	We return to the DQB to evaluate which questions we have answered in this unit. We work through an assessment task where we assess whether the evidence from moon rocks supports scientists' ideas about the formation of the Moon from a giant impact between Earth and another planet known as Theia. We figure out: • The Moon was formed after Theia, a planet from the young solar system, collided with Earth. • Ideas about matter changes, forces acting on matter, and energy flow can be used to assess whether the available evidence supports ideas about the formation of the Moon.	

⇓ **Navigation to Next Lesson:** This is the last lesson in the unit..

LESSONS 1-15
27 days total

TEACHER BACKGROUND KNOWLEDGE

Lab Safety Requirements for Science Investigations

It is important to adopt and follow appropriate safety practices when conducting hands-on science investigations and demonstrations, whether in an instructional space (traditional laboratory or classroom) or in the field. To this end, teachers must be aware of any school or district safety policies, legal safety standards, and better professional safety practices that are applicable to the activities being undertaken.

Science safety practices in instructional spaces require engineering controls and personal protective equipment (e.g., sanitized safety goggles or safety glasses with side shields as appropriate, nonlatex aprons and gloves, eyewash/shower station, fume hood, appropriate ventilation, and fire extinguishers). **Science investigations should always be directly supervised by qualified adults, who should review safety procedures annually and also before initiating any hands-on activities or demonstrations.** Prior to each investigation, students should be reminded of the specific safety procedures they must follow. Each lesson within the OpenSciEd units includes teacher guidelines for applicable safety procedures for setting up and running an investigation as well as disassembling, disposing of, and storing materials.

Prior to the first investigation of the year, a safety acknowledgement form for students and parents/guardians should be provided and signed. You can access a model safety acknowledgement form for high school activities here: https://static.nsta.org/pdfs/SafetyAcknowledgmentForm-HighSchool.pdf

Disclaimer: The safety precautions provided for each activity are based in part on use of the specifically recommended materials and instructions as well as legal safety standards and better professional safety practices. Be aware that selecting alternative materials or procedures for these activities may affect the activity's level of safety and is therefore at the user's own risk.

Please follow these lab safety recommendations for any science investigation:

1. Wear sanitized safety goggles (specifically, indirectly vented chemical splash goggles) or safety glasses with side shields, as appropriate, a nonlatex apron, and nonlatex gloves during the setup, hands-on investigation, and take-down segments of the activity.
2. Safety goggles are required when working with liquid biological or chemical hazards (e.g., microbes, acids, bases). Safety glasses with side shields or safety goggles may be used when working with physical hazards (sharps, springs, glass, projectiles, etc.).
3. Immediately wipe up any spilled liquid (e.g., water) and/or granules on the floor, as this is a slip-and-fall hazard.
4. Follow your *Teacher Guide* for instructions on disassembling and storing materials and disposing of waste materials.
5. Secure loose clothing, remove loose jewelry, wear closed-toe shoes, and tie back long hair.
6. Wash your hands with soap and water immediately after completing the activity.
7. Never eat any food items used in a lab activity.
8. Never taste any substance or chemical in the lab.
9. Use only GFCI-protected circuits when using electrical equipment and keep away from water sources to prevent shock.
10. Use caution when working with glassware, which can shatter if dropped and cut skin.
11. Use caution when using sharp tools or materials, which can cut or puncture skin.
12. Never pour chemicals, either used or unused, back into their original container. Dispose of chemicals according to your institution's safety protocols and local environmental regulations.
13. If you get a hazardous chemical on your clothing or have a clothing fire, use the emergency shower.
14. If you get a chemical in your eye, use an eyewash station immediately.
15. Point the test tubes, beakers, or other vessels away from yourself and other people when the vessels contain reactants or other substances.
16. When diluting acids or bases, the acid or base should be added to water and not water to the acid or base.
17. Projective trajectory zones must be well defined and free of any obstacles. No participant is to be in the zone during operation of the projectile..
18. Make sure the ventilation system meets the needs relative to removal of flammable vapors produced. Also make sure there are no active flames or sparks in the work zone.



Specific safety precautions are called out within the lesson using this icon and a call-out box.

Where does this unit fall within the OpenSciEd Scope and Sequence?

This unit is the fourth in the OpenSciEd High School Physics course sequence. It is designed to build on student ideas about energy from the first and second units of the course and about forces from the second and third units of the course. In the first unit of OpenSciEd HS Physics, students developed ideas around energy transfer and conservation in the context of charged particles (electrons) colliding with other electrons (electricity) to transfer energy across great distances. In the second unit of the course, earth science phenomena that transfer energy differently across scales of time and space motivated the need for forces to explain our observations. In the third unit, students developed a more robust understanding of forces as vectors and used conservation of momentum to make predictions about the outcomes of collisions. In this fourth unit, students expand their model of forces to include forces of gravity at great distances, using ideas about fields developed in the first unit to understand the relationships between gravity and energy transfer.

In the unit that follows this one, students use energy transfer, electromagnetism, wave mechanics, and forces at a distance to explain how food heats up in a microwave and if or how this technology might be dangerous for humans. In the final unit of the course, students explore cosmology and the Big Bang, applying ideas about forces and energy from all five previous units on the largest scales.

What is the anchoring phenomenon, and why was it chosen?

This unit is anchored by a montage of video clips showing a fireball over Chelyabinsk in Siberia in 2013 that caused millions of dollars in damage and thousands of minor injuries, although thankfully nobody was killed. This phenomenon provides the context in which to investigate forces at a distance, energy transfer, and the mechanics of orbits, including Kepler's laws and Newton's universal law of gravitation. By the end of the first lesson set, students will be able to explain how different strategies of meteor deflection to protect Earth from meteor impacts work. Based on field-test data and our own tests, this phenomenon will also elicit questions about the likelihood of similar events happening in the near future. To answer these questions, students will explore multiple data sets of empirical evidence about the surface of Earth and other space objects to investigate how the frequency of these events has changed over time. Students will investigate the effects of meteor impact events from the past on Earth and other solar system bodies, including the history-altering Chicxulub event, which was most likely the primary cause of the extinction of the dinosaurs and about 75% of life on Earth at the end of the Cretaceous period. Finally, they will use their ideas to analyze the evidence that supports a theory about the formation of the Moon.

The Chelyabinsk anchoring phenomenon was chosen from a group of phenomena aligned with the target performance expectations based on the results of a survey administered to almost 1,000 students from across the country and in consultation with external advisory panels that include teachers, subject matter experts, and state science administrators. The full physics course is designed to purposefully highlight a variety of different types of phenomena. While we design to privilege the interests of students to whom we owe an educational debt, we must not essentialize minoritized groups by assuming that a trend in the data equates to homogenous interests and experiences. Providing a diverse suite of entry points into content and practices creates more opportunities for every student to connect with the content.

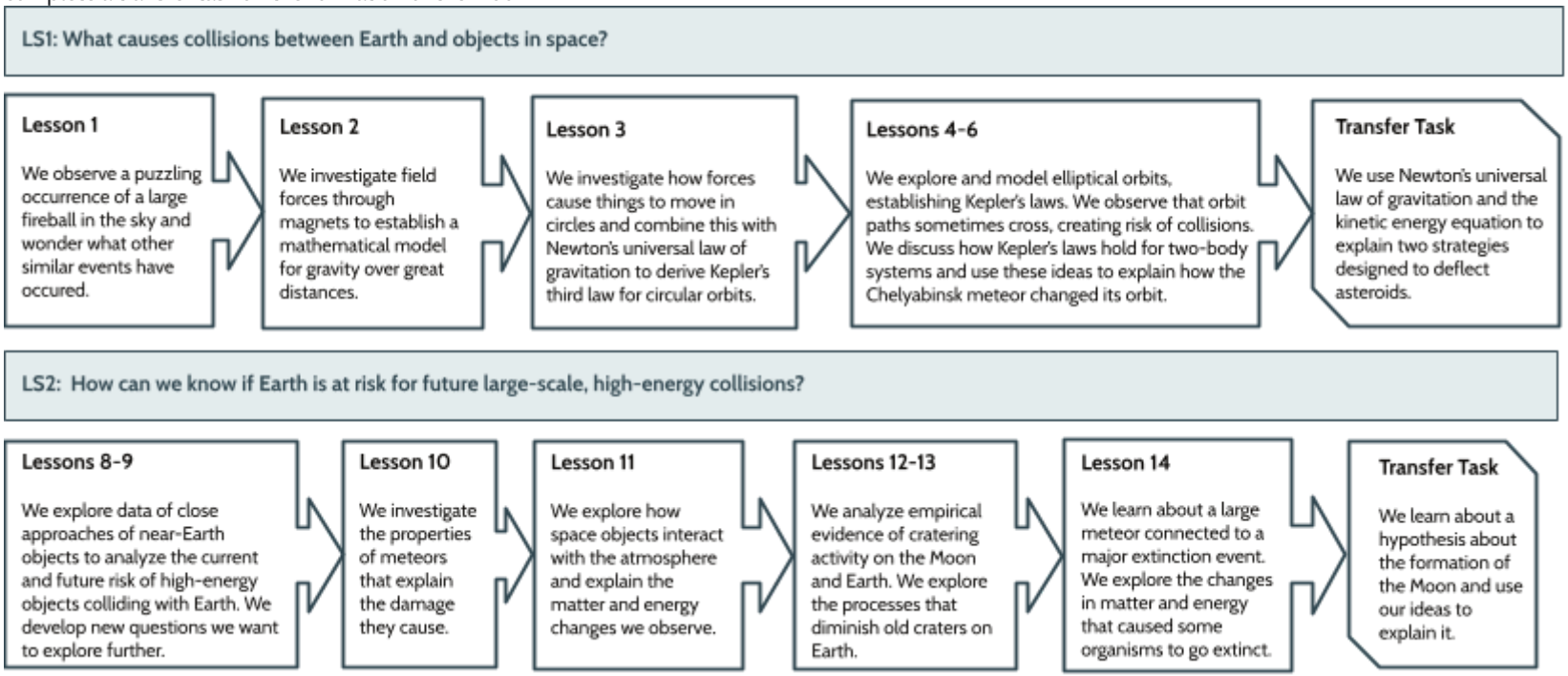
The Chelyabinsk phenomenon was chosen for the following reasons:

- Students showed high interest in explaining fireballs and related phenomena.
- Teachers and administrators saw the phenomenon as interesting and on grade band.
- Explaining the mechanics of meteors using physics concepts grounds abstract ideas about orbital motion, gravity, and energy.
- Explaining the phenomenon addresses all the DCIs in the bundle at a high school level.
- Explaining the phenomenon requires the use of mathematical thinking at a high school level.

How is the unit structured?

The unit is organized into two main lesson sets. In **Lesson Set 1** (Lessons 1-7) students investigate how gravity between two objects changes over distance. They mathematically model gravitational forces at far distances by investigating magnetic forces at tangible distances. They then investigate how forces and tangential velocity can cause objects to move in circles and how this describes how gravity keeps objects in orbit instead of crashing into Earth or the Sun. They derive the relationship between orbital period and radius (Kepler's third law) through combining the mathematical models for gravity and circular motion, and they reason that meteors like the one they observed during the anchor are not likely to move in circular orbits. Next, they investigate noncircular orbits and learn that all orbits are elliptical (Kepler's first law), with variation in eccentricity. They reason that this variation of orbit shape can cause orbit paths to cross, creating a potential risk of collision between objects. They model the energy transfer that occurs between the Sun, an orbiting object, and the gravitational field between them to conceptualize the changes in velocity of an object in an eccentric orbit (Kepler's second law). They use this to consider how we can model the potential for an object to collide with Earth. Finally, they consider the limitation of Kepler's laws to two-body systems and explore how contact and noncontact forces can change the orbital path of space objects. Students end the lesson set wondering how these concepts of gravity and interactions with nearby objects have and will affect Earth. At the end of this lesson set, students use their ideas to explain how a kinetic impactor and a gravity tractor, two asteroid-deflection strategies, work.

In **Lesson Set 2** (Lessons 8-15) students consider Earth's history and future. They start by analyzing data about objects that recently came close to colliding with Earth and use this to predict the probability of a high-energy collision event. They return to the DQB to evaluate the questions they have answered and brainstorm additional questions based on these data. To answer these new questions, students carry out an investigation to explain which meteor property, its mass or velocity upon impact, can have a larger effect on the amount of damage it can cause. They analyze data on how small objects burn up in Earth's atmosphere, preventing them from hitting Earth's surface. They analyze evidence of cratering activity on solar system objects that do not have atmospheres and identify patterns that suggest changes in the frequency of small and large meteors hitting the Earth-Moon system over time. They also analyze evidence of cratering activity on Earth and explore geological processes that help explain the lack of large craters on Earth. They read about an especially large crater in Chicxulub that dates to the same time that there was a mass extinction event on Earth and use these ideas to explain how the impactor led to both short-term and longer-term effects that caused the extinction of only some types of organisms and not others. Finally, they return to the DQB to evaluate the questions they have answered and complete a transfer task on the formation of the Moon.



What elements of the NGSS three dimensions are developed in this unit?

This unit is designed to give students the opportunity to analyze the motion of objects in our solar system through the perspectives of matter, force, and energy. In Lesson Set 1, students use mathematics, computational thinking, and algebraic thinking to develop different models that help explain the motion and interactions of space objects. Students connect to the ideas of Kepler's laws in Lessons 3-5, applying data from orbits, simulations, and mathematical modeling to their working models for the orbital motions of bodies in the solar system. Students derive Kepler's laws from data taken through indirect observations, due to the vast scale of the solar system. Students further connect to the ideas of energy transfer and conservation within their modeling of Kepler's laws.

The development of Kepler's laws by applying Newton's universal law of gravitation is also part of the use of mathematics and computational thinking, which is **intentionally developed** across this unit. Students apply algebraic thinking to consider the inverse square relationship between gravity and distance, providing a concrete context for understanding the importance of scale, proportion, and quantity. This crosscutting concept is **intentionally developed** throughout the unit as students analyze gravitational forces at a classroom scale and at a solar system scale, noticing along the way that the patterns we observe in natural systems depend on the scale at which we examine it.

Analyzing and interpreting data **is intentionally developed** throughout the second lesson set of this unit, starting in Lesson 8 when students begin looking at data about objects that recently came close to colliding with Earth. In Lesson 10, students use the correlation coefficient to analyze empirical data collected from an investigation they carry out to determine whether the mass or the velocity of an impactor better explains the damage it can cause. In the next three lessons, students analyze data related to **craters on Earth and on other solar system bodies** to identify patterns that can help explain **Earth's early history**.

Students also develop a sophisticated understanding of energy conservation and energy transfer in a system. In Lesson 5, students explore the idea of energy conservation through the use of **mathematical thinking**. They also consider how the energy stored in fields (potential energy) transfers to the orbiting object as kinetic energy. In Lesson 10, students investigate how the mass and the velocity of an object affects its kinetic energy. This is an important idea that allows students to explain **matter and energy changes in the system** caused by large meteors in Lessons 14 and 15.

This unit builds toward these performance expectations:
HS-ESS1-4 Use mathematical or computational representations to predict the motion of orbiting objects in the solar system. **HS-ESS1-6** Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history. **HS-PS2-4†** Use mathematical representations of Newton's Law of Gravitation ~~and Coulomb's Law~~ to describe and predict the gravitational ~~and electrostatic~~ forces between objects. **HS-PS3-1†** Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known. **HS-PS3-2†** Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motion of ~~particles~~ (objects) and energy associated with the relative positions of ~~particles~~ (objects). ~~†~~This performance expectation is developed across multiple courses.

Science and Engineering Practices*	Disciplinary Core Ideas*	Crosscutting Concepts*

Developing and Using Models: This unit **intentionally develops** students' engagement in this practice element:

- 2.3 Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

Analyzing and Interpreting Data: This unit **intentionally develops** students' engagement in this practice element:

- 4.1 Analyze data using tools, technologies, and/or models (e.g., computational, mathematical) in order to make valid and reliable scientific claims ~~or determine an optimal design solution~~.

Using Mathematics and Computational Thinking: This unit **intentionally develops** students' engagement in this practice element:

- 5.2 Use mathematical, computational, and/or algorithmic representations of phenomena or design solutions to describe and/or support claims and/or explanations.

The following practices are also **key to the sensemaking** in this unit:

- Asking Questions and Defining Problems
- Planning and Carrying Out Investigations
- Constructing Explanations and Designing Solutions
- Engaging in Argument from Evidence
- Obtaining, Evaluating, and Communicating Information

ESS1.B: Earth and the Solar System

- Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. (HS-ESS1-4)

ESS1.C: The History of Planet Earth

- Although active geologic processes, such as plate tectonics and erosion, have destroyed or altered most of the very early rock record on Earth, other objects in the solar system, such as lunar rocks, asteroids, and meteorites, have changed little over billions of years. Studying these objects can provide information about Earth's formation and early history. (HS-ESS1-6)

ESS2.A.2: Earth's Systems

- ~~Evidence from deep probes and seismic waves,~~ reconstructions of historical changes in Earth's surface and its magnetic field~~, and an understanding of physical and chemical processes~~ lead to a model of Earth ~~with a hot but solid inner core, a liquid outer core, a solid mantle and crust. Motions of the mantle and its plates occur primarily through thermal convection, which involves the cycling of matter due to the outward flow of energy from Earth's interior and gravitational movement of denser materials toward the interior~~. (HS-ESS2-3)

This DCI is associated with a performance expectation that is not included in the bundle for this unit, and is addressed in unit P.2.

PS2.B: Types of Interactions

- Newton's law of universal gravitation ~~and Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic~~ forces between distant objects. (HS-PS2-4)
- Forces at a distance are explained by fields (gravitational, electrical, and magnetic) permeating space that can transfer energy through space. ~~Magnets or electrical currents cause magnetic fields; electrical charges or changing magnetic fields cause electrical fields.~~ (HS-PS2-4),(HS-PS2-5)

PS3.A: Definitions of Energy

Scale, Proportion, and Quantity: This unit **intentionally develops** students' use of these crosscutting concept elements.

- 3.1 The significance of a phenomenon is dependent on the scale, proportion, and quantity at which it occurs.
- 3.2 Some systems can only be studied indirectly as they are ~~too small~~, too large, ~~too fast, or too slow~~ to observe directly.
- 3.5 Algebraic thinking is used to examine scientific data and predict the effect of a change in one variable on another (e.g., linear growth vs. exponential growth).

The following crosscutting concepts are also **key to the sensemaking** in this unit:

- Patterns
- Cause and Effect: Mechanism and Prediction
- Systems and System Models
- Energy and Matter in Systems: Flows, Cycles, and Conservation
- Stability and Change of Systems

	• At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. (HSPS3-2) (HS-PS3-3) • These relationships are better understood at the microscopic scale~~, at which all of the different manifestations of energy can be modeled as a combination of energy associated with the motion of particles and energy associated with the configuration (relative position of the particles). In some cases the relative position energy can be thought of as stored in fields (which mediate interactions between particles). This last concept includes radiation, a phenomenon in which energy stored in fields moves across space.~~ (HS-PS3-2) **PS3.B: Conservation of Energy and Energy Transfer** • Energy cannot be created or destroyed, but it can be transported from one place to another ~~and transferred between systems~~. (HS-PS3-1),(HS-PS3-4) • Mathematical expressions, which quantify how the stored energy in a system depends on its configuration (e.g., relative positions ~~of charged particles, compression of a spring~~) and how kinetic energy depends on mass and speed, allow the concept of conservation of energy to be used to predict and describe system behavior. (HS-PS3-1) • The availability of energy limits what can occur in any system. (HS-PS3-1)	

"Disciplinary Core Ideas" are reproduced verbatim from A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. DOI: https://doi.org/10.17226/13165. National Research Council; Division of Behavioral and Social Sciences and Education; Board on Science Education; Committee on a Conceptual Framework for New K-12 Science Education Standards. National Academies Press, Washington, DC. This material may be reproduced and used by other parties with this attribution. If the original material is altered in any way, the attribution must state that the material is adapted from the original.

Connections to the Nature of Science (NOS) and/or Engineering, Technology, and the Application of Science (ETS)

Connections to the Nature of Science (NOS)	
Which elements of NOS are developed in the unit?	How are they developed?
Scientific Investigations Use a Variety of Methods. Science investigations use diverse methods and do not always use the same set of procedures to obtain data.	In Lesson 3, students use a physical model to obtain data to investigate the relationship between the force of gravity acting on an orbiting object and its velocity. To investigate this relationship further, they will use a computer model and algebraic thinking.
Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena. Laws are statements or descriptions of the relationships among observable phenomena.	In Lesson 2, students will use empirical data to describe Newton's law of universal gravitation as the relationship between the mass of two objects and the distance between them. In Lesson 3, students will use their observations about the motion of space objects to develop Kepler's third law in terms of the distance between the planet and the Sun and its period of revolution.

Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena. Models, mechanisms, and explanations collectively serve as tools in the development of a scientific theory.	In Lesson 15, students will evaluate the Giant Impact Hypothesis by considering the models that scientists have developed to support it, along with mechanisms that integrate changes in energy, matter, and force within the system.

Connections to Engineering, Technology, and Applications of Science (ETS)	
Which elements of ETS are developed in the unit?	How are they developed?
Influence of Science, Engineering, and Technology on Society and the Natural World. Modern civilization depends on major technological systems. Engineers continuously modify these technological systems by applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks.	In Lesson 7, students will explore some of the strategies scientists and engineers are developing to deflect asteroids that can pose a threat to modern civilization.

How does the unit build three-dimensional progressions across the course and the program?

This unit uses and builds upon **disciplinary core ideas (DCIs)** and other science ideas that students should have previously developed in this course and in middle school.

- **Forces and Motion** (*Vehicle Collisions Unit*): Newton's second law accurately predicts changes in the motion of macroscopic objects.
- **Earth and the Solar System** (*Space Unit*): 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. Earth and its solar system are part of the Milky Way galaxy, which is one of many galaxies in the universe.
- **Types of Interactions** (*Space Unit*): Gravitational forces are always attractive. There is a gravitational force between any two masses, but it is very small except when one or both of the objects have large mass—e.g., Earth and the Sun. The solar system appears to have formed from a disk of dust and gas, drawn together by gravity.
- **Nuclear Processes** (*Earth's Interior Unit*): Nuclear lifetimes allow radiometric dating to be used to determine the ages of rocks and other materials.
- **Plate Tectonics and Large-Scale System Interactions** and **Nuclear Processes** (*Earth's Interior Unit*): Plate tectonics is the unifying theory that explains the past and current movements of the rocks at Earth's surface and provides a framework for understanding its geologic history.

This unit uses and builds upon **science and engineering practices (SEPs)** that students should have previously developed in this course:

- **Analyzing and Interpreting Data** (*Vehicle Collisions Unit*): Students have multiple opportunities to analyze data throughout this unit, especially during the second lesson set. Students are asked to use different data sets to make inferences about Earth's past and to predict its future. In Lesson 8, students interpret the logarithmic scale of a graph to predict the number, frequencies (proportions), kinetic energy, and scale of potential destruction from meteors of different sizes reaching Earth in the near future and the rate of such events in the past. To scaffold students' use of this practice, this graph is explored by sections (small, medium, and large space objects) and time periods (present, past, and future) over several lessons. In Lesson 12, students use empirical evidence of the age distribution of lunar craters to explain changes in the frequency of meteor collisions in the Earth-Moon system in the past, and in Lesson 13, they use the age distribution of terrestrial craters to make sense of geological mechanisms that have erased evidence of meteor impacts from Earth's surface. They also use this evidence of cratering activity of the Moon and Earth to make predictions about future meteor impacts. To assess students' performance in the use of this practice, they are asked to evaluate the impact of data about the composition of the Moon's crust on a theory that suggests that a giant impact between Earth and another planet led to the formation of the Moon.
- **Using Mathematics and Computational Thinking** (*Vehicle Collisions Unit* and *Earth's Interior Unit*): During the first lesson set, students derive mathematical relationships from empirical evidence, expressing them as equations and manipulating them to derive new models as well as solving for unknown values. They use mathematical thinking to develop an understanding of Newton's law of universal gravitation and how magnetic and gravitational forces between two objects change over distance. In this unit, students learn to use mathematical thinking to make sense of energy conservation in a closed system. They also continue deepening their understanding about how mathematical representations like graphs and equations are useful in identifying patterns.
- **Developing and Using Models** is a focal practice throughout the entire unit. During the first lesson set, students develop models about orbits to first describe how the distance between two space objects affects the relationship between the force of gravity acting on an orbiting object and its velocity. In Lesson 4, students continue using models to describe the shape of the orbits and predict the potential for a collision between two space objects. In Lesson 5, students integrate the ideas developed in Lessons 2-4 to model how energy transfers in a Sun-asteroid system. In Lesson 6, students continue using this practice to model how contact forces and forces at a distance help explain how the Chelyabinsk meteor changed its orbit. Students are supported through the use of diagrammatic models and algebraic thinking.

This unit uses and builds upon **crosscutting concepts (CCCs)** that students should have previously developed in this course:

- **Scale, Proportion, and Quantity** (*OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*): Patterns at a particle scale can manifest as phenomena at a local or even a global scale. The significance of a phenomenon is dependent on the scale, proportion, and quantity at which it occurs. Algebraic thinking is used to examine scientific data and predict the effect of a change in one variable on another (e.g., linear growth vs. exponential growth).
- **Energy and Matter** (*Earth's Interior Unit*, *Vehicle Collisions Unit*): This unit continues using the Matter-Energy-Forces triangle framework developed from prior units: *Unknown material with identifier: pf.* and *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*.

This unit uses and builds upon high school-level **science and engineering practices (SEPs)** and **crosscutting concepts (CCCs)** that students should have previously developed in **OpenSciEd High School Biology and Chemistry** and will continue to build in future units. The progressions of these practices and concepts across the program are as follows:

	Questions	Models	Investigations	Data	Math	Explanation	Argument	Obtaining
Biology	*Cancer Unit*	*Serengeti Unit*, *Fires Unit*	*Fires Unit*, *Natural Selection Unit*	*Natural Selection Unit*, *Cancer Unit*	*Serengeti Unit*	*Fires Unit*, *Cancer Unit*, *Natural Selection Unit*	*Speciation Unit*	*Cancer Unit*, *Speciation Unit*
Chemistry	*Polar Ice Unit*, *Oysters Unit*	*Electrostatics Unit*, *Space Survival Unit*	*Polar Ice Unit*	*Fuels Unit*	*Polar Ice Unit*, *Oysters Unit*	*Fuels Unit*	*Fuels Unit*	*Electrostatics Unit*, *Space Survival Unit*
Physics	*Electricity Unit*, *Cosmology Unit*	*Electricity Unit*, *Microwave Unit*	*Microwave Unit*	*Electricity Unit*, *Earth's Interior Unit*, *Vehicle Collisions Unit*, *Meteors Unit*	*Vehicle Collisions Unit*, *Meteors Unit*	*Electricity Unit*, *Earth's Interior Unit*, *Vehicle Collisions Unit*	*Vehicle Collisions Unit*	*Cosmology Unit*, *Microwave Unit*

	Patterns	Cause/Effect	Scale	Systems/Models	Energy/Matter	Structure/Function	Stability/Change
Biology	*Natural Selection Unit*, *Speciation Unit*	*Cancer Unit*, *Natural Selection Unit*, *Speciation Unit*, *Serengeti Unit*	*Serengeti Unit*	*Fires Unit*, *Cancer Unit*, *Serengeti Unit*	*Fires Unit*, *Serengeti Unit*	*Cancer Unit*	*Speciation Unit*, *Serengeti Unit*
Chemistry	*Electrostatics Unit*, *Space Survival Unit*	*Oysters Unit*, *Fuels Unit*	*Electrostatics Unit*, *Oysters Unit*	*Polar Ice Unit*	*Polar Ice Unit*, *Fuels Unit*	*Space Survival Unit*	*Oysters Unit*
Physics	*Cosmology Unit*, *Vehicle Collisions Unit*, *Earth's Interior Unit*	*Vehicle Collisions Unit*, *Earth's Interior Unit*	*Meteors Unit*, *Earth's Interior Unit*	*Electricity Unit*, *Vehicle Collisions Unit*, *Microwave Unit*	*Electricity Unit*, *Earth's Interior Unit*	*Earth's Interior Unit*, *Vehicle Collisions Unit*	*Electricity Unit*, *Cosmology Unit*

What are some common ideas that students might have?

Students will come into the unit with many ideas about orbits and gravity derived from previous classroom experiences, intuitive understandings of the way the world works, everyday experiences with movement, and the conversations they have had with parents, friends, and family members.

Some relevant ideas with which students may come into the unit include the following:

1. A continuous force is needed for continuous orbital motion.

2. Direction of motion in an orbit implies direction of force.
3. Rest is the natural state of objects in space.
4. Equal and opposite refers only to forces that are in balance and ceases to be true when unbalanced forces cause motion.
5. Our solar system encompasses the entire universe, and stars and galaxies orbit our Sun.
6. Gravity is caused by Earth's magnetic core.
7. Gravity is caused by Earth's atmosphere.
8. There is no gravity in space nor on other moons or planets.

It is valuable to think of ideas like these not as misconceptions that need to be erased but as productive ideas that we can use to build understanding. Not only does this help some students feel more comfortable talking about science and build a scientific identity, it improves science learning across the board.

How will I need to modify the unit if taught out of sequence?

This is the fourth unit of the High School Physics Course in the OpenSciEd Scope and Sequence. Given this placement, several modifications would need to be made if teaching this unit earlier in the Physics course. These include the following adjustments:

- If taught earlier in the school year, supplemental teaching around the nature of energy transfer through systems and how to represent it may be required.
- If taught earlier in the school year, supplemental teaching around the nature of forces, how to represent them, and Newton's second and third laws may be required.
- If taught as part of an AP Physics course, be prepared to provide students with additional support around equations that are not treated in depth. An extension opportunity to calculate energy conservation in a Sun-asteroid system has been provided.

How do I shorten or condense the unit if needed? How can I extend the unit if needed?

The following are example options to shorten or condense parts of the unit without eliminating important sensemaking:

- Lesson 3: Students can use the Circular Motion Investigation to collect qualitative data instead of taking actual measurements of the period of revolution using the physical model. This approach allows students to understand the relationship between force and velocity while saving time.
- Lessons 8 and 9: You can condense these lessons into a single lesson and use it as a re-anchor to motivate the lessons in the second lesson set.
- Lessons 12-15: These lessons primarily address Earth and Space performance expectations. If these are not a priority for your school or district, you can conclude the unit after completing Lesson 8. However, students will miss the opportunity to consider the probability of future and past impacts of space objects with our planet.

To extend or enhance the unit, consider the following:

- Lesson 1: Invite students to consider objects they have seen falling from the sky, either from personal experience or from videos. As the unit progresses, ask them to make inferences about these objects, such as their mass or velocity, to help explain the damage or lack thereof upon impact with Earth's surface.
- Lesson 7: Consider asking students to use a momentum-change perspective to explain how the kinetic impactor strategy works. This will allow you to assess the DCI PS2.A: Forces and Motion.
- Lesson 15: As an end-of-unit project, consider having students design solutions to protect a community or our planet from a collision with a space object.
- All lessons: Remove scaffolds provided with Science and Engineering Practices (SEPs) as a way to give students more independent work with the elements of these practices.

What mathematics concepts will students engage with in the unit?

This unit requires knowledge of how to solve algebraic equations and is more math intensive than *Electricity Unit* and *Earth's Interior Unit*. Note that modeling is best interpreted not as a collection of isolated topics but in relation to other standards. Making mathematical models is a standard for mathematical practice, and specific modeling standards appear throughout the high school standards.

This unit does not assume students are fluent with the mathematical practices listed below, rather, students develop these practices as part of the sensemaking. Thus, these standards are not so much prerequisites as co-requisites. If students are simultaneously developing the skills and vocabulary in math class, you can help by making explicit connections to the mathematical standards below. Co-requisite concepts from students' math classes include those shown in the table below.

Talk with the math teacher(s) to identify the strategies with which students are familiar for solving equations, including radicals. If the class is having difficulties solving for one of the variables, model how to solve one.

Category	Code	Domain and Heading	Standard	Lesson
Number and Quantity	CCSS.MATH.CONTENT.HS.N-RN.2	**The Real Number System:** Extend the properties of exponents to rational exponents.	Rewrite expressions involving radicals and rational exponents using the properties of exponents.	7
	CCSS.MATH.CONTENT.HS.N-Q.1	**Quantities:** Reason quantitatively and use units to solve problems.	Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays.	2, 7
	CCSS.MATH.CONTENT.HS.N-Q.2	**Quantities:** Reason quantitatively and use units to solve problems.	Define appropriate quantities for the purpose of descriptive modeling.	2, 5
	CCSS.MATH.CONTENT.HS.N-VM.1	**Vector and Matrix Quantities:** Represent and model with vector quantities.	Recognize vector quantities as having both magnitude and direction.	3
Algebra	CCSS.MATH.CONTENT.HS.A-SSE.1a	**Seeing Structure in Expressions:** Interpret the structure of expressions.	Interpret parts of an expression, such as terms, factors, and coefficients.	2, 5
	CCSS.MATH.CONTENT.HS.A-SSE.2	**Seeing Structure in Expressions:** Interpret the structure of expressions.	Use the structure of an expression to identify ways to rewrite it.	7
	CCSS.MATH.CONTENT.HS.A-CED.4	**Creating Equations:** Create equations that describe numbers or relationships.	Rearrange formulas to highlight a quantity of interest, using the same reasoning as in solving equations.	7
	CCSS.MATH.CONTENT.HS.A-REI.1	**Reasoning with Equations and Inequalities:** Understand solving equations as a process of reasoning and explain the reasoning.	Explain each step in solving a simple equation as following from the equality of numbers asserted at the previous step, starting from the assumption that the original equation has a solution. Construct a viable argument to justify a solution method.	8
	CCSS.MATH.CONTENT.HS.A-REI.2	**Reasoning with Equations and Inequalities:** Understand solving equations as a process of reasoning and explain the reasoning.	Solve simple rational and radical equations in one variable, and give examples showing how extraneous solutions may arise.	2
Functions	CCSS.MATH.CONTENT.HS.F-IF.4	**Interpreting Functions:** Interpret functions that arise in applications in terms of the context.	For a function that models a relationship between two quantities, interpret key features of graphs and tables in terms of the quantities, and sketch graphs showing key features given a verbal description of the relationship.	8

Statistics and Probability	CCSS.MATH.CONTENT.HS.S-ID.6c	**Interpreting Categorical and Quantitative Data:** Summarize, represent, and interpret data on two categorical and quantitative variables.	Represent data on two quantitative variables on a scatter plot, and describe how the variables are related: Fit a linear function for a scatter plot that suggests a linear association.	10
	CCSS.MATH.CONTENT.HS.S-ID.8	**Interpreting Categorical and Quantitative Data:** Interpret linear models.	Compute (using technology) and interpret the correlation coefficient of a linear fit.	10

What strategies are available to support equitable science learning in this unit?

OpenSciEd units are designed to promote equitable access to high-quality science learning experiences for all students. Each unit includes strategies which are integrated throughout the OpenSciEd routines and are intended to increase relevance and provide access to science learning for all students. OpenSciEd units support these equity goals through several specific strategies such as: 1) integrating Universal Design for Learning (UDL) Principles during the unit design process to reduce potential barriers and increase accessibility for students to engage in learning experiences; 2) developing and supporting classroom agreements that encourage a safe learning culture; 3) supporting classroom discourse to promote students in developing, sharing, and revising their ideas; and 4) specific strategies for supporting emerging multilingual students in science classrooms.

Many of these strategies are highlighted in the teacher guides in sidebar or in-line callout boxes with the headings of:

- Attending to Equity
- Supporting Emerging Multilingual Learners
- Supporting Universal Design for Learning
- Additional Guidance
- Alternate Activity
- Key Ideas
- Discussion callouts

The example callout below highlights how an activity can be modified to support a wider variety of learners.

Alternate: Consider presenting https://www.youtube.com/watch?v=ANYxkwvb8pc as an alternate or additional way to provide student access to the changes in the frequency of cratering activity over time. While this video only represents lunar impact craters that are younger than about 1 billion years old, it will help students identify patterns of large versus small craters. The creators of this video use louder and deeper notes for larger craters.

What are recommended adult-level learning resources for the science concepts in this unit?

The OpenSciEd instructional model focuses on the teacher being a member of the classroom community, supporting students to figure out scientific ideas motivated by their questions about phenomena. Students iteratively build their understanding of phenomena as the unit unfolds. To match the incremental build of a full scientific explanation across the unit, the science content background necessary for you to teach individual lessons incrementally builds too. Throughout the unit, we provide just-in-time science content background for you that is specific to the disciplinary core ideas (DCIs) that will be figured out in a lesson. Places to look for this guidance include the "Where we are going" and "Where we are not going" sections for each lesson. Also, the expected student responses, keys, and rubrics illustrate important science ideas that should be developed in each lesson. The K-12 science *Framework* is another great resource to learn more about the DCIs in this unit (**ESS1.B: Earth and the Solar System, ESS1.C: The History of Planet Earth, PS2.B: Types of Interactions, PS3.A: Definitions of Energy, PS3.B: Conservation of Energy and Energy Transfer**), including what students have learned previously and where they are headed in high school. In addition to the science content background information embedded in the lesson resources, below we provide recommended resources that can help build your understanding of phenomena and the performance expectations bundle for this unit:

- To learn more about the physics of orbits and gravity
  - https://web.archive.org/web/20120204054322/http://www.braeunig.us/space/orbmech.htm
  - https://solarsystem.nasa.gov/basics/chapter3-4/
- To learn more about cultural connections humans have made to meteors
  - https://tv.apple.com/us/movie/fireball-visitors-from-darker-worlds/umc.cmc.4kxqi7mmx247xjrdfll0lsme1

    - https://thepilgrim.co/hajr-e-aswad-black-stone/
    - https://www.hou.usra.edu/meetings/lpsc2018/pdf/1118.pdf
    - https://www.space.com/24675-winter-olympics-meteorite-medal.html
- To learn more about the Chelyabinsk meteor event
    - https://www.theguardian.com/science/2013/nov/06/chelyabinsk-meteor-russia
    - https://www.nasa.gov/feature/five-years-after-the-chelyabinsk-meteor-nasa-leads-efforts-in-planetary-defense/
    - https://www.space.com/33623-chelyabinsk-meteor-wake-up-call-for-earth.html
- To learn more about the Chicxulub meteor event and the controversy surrounding it
    - https://www.nationalgeographic.com/science/article/last-day-dinosaurs-reign-captured-stunning-detail
    - https://radiolab.org/episodes/dinopocalypse-redux
    - https://www.lpi.usra.edu/science/kring/Chicxulub/regional-effects/
    - https://www.bbc.com/news/science-environment-39922998
- To learn more about the formation of the Moon and its past
    - https://www.amnh.org/exhibitions/permanent/meteorites/meteorite-impacts/on-the-moon#:~:text=The%20craters%20on%20the%20Moon,no%20geologic%20activity%20or%20water.
    - https://news.uchicago.edu/explainer/formation-earth-and-moon-explained
- The design of this unit has been informed by different learning progressions to support students in building integrated understanding. To learn more about learning progressions and their usefulness in science teaching, review these resources:
    - https://www.edutopia.org/article/learning-progressions-science/
    - https://www.isls.org/research-topics/learning-progressions-in-science-education/
    - https://diser.springeropen.com/articles/10.1186/s43031-019-0005-x
    - https://www.nextgenscience.org/sites/default/files/resource/files/AppendixE-ProgressionswithinNGSS-061617.pdf

Guidance for Developing Your Personal Glossaries

This unit refers to two categories of academic language (i.e., vocabulary). Most often in this unit, students will have experiences with and discussions about science ideas before they know the specific vocabulary word that names that idea. After students have developed a deep understanding of a science idea through these experiences, and sometimes because they are looking for a more efficient way to express that idea, they have co-developed that definition and can add the specific term to a Personal Glossary at the back of their notebook. These "definitions we co-develop" should be recorded using the students' own words whenever possible. On the other hand, "definitions we encounter" are "given" to students in the course of a reading, video, or other activity, often with a definition clearly stated in the text. Sometimes, definitions we encounter are helpful just in that lesson and need not be recorded in students' Personal Glossaries. However, if a word we encounter will be frequently referred to throughout the unit, it should be added.

It is best for students if you create consensus definitions in the moment, using phrases and pictorial representations that the class develops together as they discuss their experiences in the lesson. When they co-create the meaning of the word, students "own" the word—it honors their use of language and connects their specific experiences to the vocabulary of science beyond their classroom. It is especially important for emergent multilingual students to have a reference for this important vocabulary, which includes an accessible definition and visual support. Sometimes defining a word is a challenge. The *Teacher Guide* provides a suggested definition for each term to support you in helping your class develop a student-friendly definition that is also scientifically accurate.

The definitions we co-develop and encounter in this unit are listed in this document and in each lesson to help prepare and to avoid introducing a word before students have earned it. They are not intended as a vocabulary list for students to study before a lesson, as that would undermine the authentic and lasting connection students can make with these words when they are allowed to experience them first as ideas they're trying to figure out.

Lesson	Words and equations with meanings we co-develop	Words and equations with meanings we encounter
L1		orbit, meteor, asteroid, comet, satellite
L2	gravitational field, Newton's universal law of gravitation: $F_g = G(m_1 * m_2)/r^2$	magnetic field
L3	Orbit, Kepler's third law: $T^2/r^3 = constant$, Period of revolution	circular motion

L4	ellipse, eccentricity, $T^2/a^3 = constant$	semimajor axis, foci, asteroid, comet
L5	SE (potential energy) = mgh	
L6		perturbation
L7		
L8		logarithmic
L9		
L10		impactor, ejecta, crater
L11		vaporize, atmosphere, micrometeorite
L12		
L13		accretion, erosion, glaciation
L14	K-Pg boundary	mass extinction
L15		

HOME COMMUNICATION

Dear Parents, Guardians, and Caregivers,

Your child's high school physics class is starting a unit called *How have collisions with objects from space changed Earth in the past, and how could they affect our future?* as part of the OpenSciEd high school science curriculum. In this unit, students investigate how gravity between two objects changes over distance and how forces and velocity can cause objects to move in orbits. They use their ideas to explain how we can deflect asteroids on a collision course with Earth.

Students will consider Earth's history and future as part of this unit. They analyze data about objects that recently collided with Earth and use this to predict the probability of a collision event. They analyze data on how small objects burn up in Earth's atmosphere and look at evidence of cratering activity on solar system objects. They also learn about a large crater in Chicxulub, Mexico, that dates to the same time that there was a mass extinction event on Earth.

Helping your student make sense of their learning

- There is no need to teach your student any related vocabulary before the unit because many words have multiple meanings and new terms are often easier to remember once students have had some experience with them.
- Encourage your student to expand their thinking by asking them to give you examples or to say more about their ideas.
- Ask how your student arrived at a particular conclusion.
- Ask your student to recall what other students have said in class and what about those ideas they agreed or disagreed with.
- Repeat, rephrase, or paraphrase what your student says as a way to clarify their ideas.

Having conversations about science

- Encourage your student's curiosity through talking about their noticings and wonderings.
- Ask your student to explain why some space objects, like the Moon or manmade satellites, can orbit Earth while others collide with our planet.
- Ask your student to explain some of the strategies that are being developed to deflect meteors and how we can predict the probability and potential damage of future collisions with space objects.

This unit begins with a montage of video clips showing a fireball over Chelyabinsk in Siberia in 2013 that caused millions of dollars in damage and thousands of minor injuries. Although thankfully nobody was killed, it can be frightening for students to learn about the potential for meteor impacts. Reach out to a counselor or support center if you are concerned about feelings or behavior your student is experiencing related to collisions with objects from space.

If you have any questions about the content of this unit or would like to discuss anything further, I encourage you to reach out to me at _____.

Best,

Estimados padres, tutores y cuidadores:

La clase de física de la escuela secundaria de su hijo está comenzando una unidad llamada *¿Cómo han cambiado la Tierra las colisiones con objetos espaciales en el pasado y cómo podrían afectar nuestro futuro?* como parte del plan de estudios de ciencias de la escuela secundaria OpenSciEd. En esta unidad, los estudiantes investigan cómo la gravedad entre dos objetos cambia a lo largo de la distancia y cómo las fuerzas y la velocidad pueden hacer que los objetos se muevan en órbitas. Utilizan sus ideas para explicar cómo podemos desviar asteroides en curso de colisión con la Tierra.

Los estudiantes considerarán la historia y el futuro de la Tierra como parte de esta unidad. Analizan datos sobre objetos que colisionaron recientemente con la Tierra y los utilizan para predecir la probabilidad de una colisión. Analizan datos sobre cómo se queman objetos pequeños en la atmósfera de la Tierra y observan evidencia de actividad de cráteres en objetos del sistema solar. También aprenden sobre un gran cráter en Chicxulub, México, que data del mismo tiempo que hubo un evento de extinción masiva en la Tierra.

Ayudar a su estudiante a darle sentido a su aprendizaje

- No es necesario enseñarle a su estudiante ningún vocabulario relacionado antes de la unidad porque muchas palabras tienen múltiples significados y los términos nuevos suelen ser más fáciles de recordar una vez que los estudiantes han tenido algo de experiencia con ellos.
- Anime a su estudiante a ampliar su pensamiento pidiéndole que le dé ejemplos o que diga más sobre sus ideas.
- Pregunte cómo llegó su estudiante a una conclusión particular.
- Pídale a su estudiante que recuerde lo que otros estudiantes han dicho en clase y qué pasa con las ideas con las que estuvo de acuerdo o en desacuerdo.
- Repita, reformule o parafrasee lo que dice su estudiante como una forma de aclarar sus ideas.

Tener conversaciones sobre ciencia

- Fomente la curiosidad de su estudiante hablando sobre sus observaciones y preguntas.
- Pídale a su estudiante que explique por qué algunos objetos espaciales, como la Luna o los satélites artificiales, pueden orbitar la Tierra mientras otros chocan con nuestro planeta.
- Pídale a su estudiante que le explique algunas de las estrategias que se están desarrollando para desviar los meteoros y cómo podemos predecir la probabilidad y el daño potencial de futuras colisiones con objetos espaciales.

Esta unidad comienza con un montaje de videoclips que muestran una bola de fuego sobre Chelyabinsk en Siberia en 2013 que causó millones de dólares en daños y miles de heridos leves. Aunque afortunadamente nadie murió, puede resultar aterrador para los estudiantes aprender sobre el potencial de los impactos de meteoritos. Comuníquese con un consejero o centro de apoyo si le preocupan los sentimientos o el comportamiento que experimenta su estudiante en relación con las colisiones con objetos del espacio.

Si tiene alguna pregunta sobre el contenido de esta unidad o desea discutir algo más, le invito a que se comunique conmigo al _____.

Sinceramente,

LESSON 1: Why is stuff falling from the sky?

PREVIOUS LESSON *There is no previous lesson.*

THIS LESSON

ANCHORING PHENOMENON

3 days



Alex Alishevskikh, CC BY-SA 2.0

We explore eyewitness video clips of the Chelyabinsk meteor. We categorize data on other related phenomena that people have observed. We develop two sets of models, one to explain the observed changes during the Chelyabinsk event and one to explain the motion of other space objects. We develop questions for our Driving Question Board, and then record ideas for investigations and data we need to answer them.

NEXT LESSON *We will predict the gravitational force experienced by objects at different distances from Earth's surface and conduct an investigation on magnetic forces versus distance. We will analyze data on gravitational forces for various objects and distances. We will use mathematical models to determine the force of gravity acting on space objects and consider whether this explains why some will collide with Earth while others will remain in orbit.*

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

1.A Develop a model using evidence from the Chelyabinsk meteor event and related phenomena to illustrate how the interactions between different parts of the system at different scales help explain the changes in matter, energy, and/or motion of orbiting objects. (SEP: 2.3; CCC: 2.2; DCI: PS2.B.1, PS3.A.2, ESS1.B.1)

1.B Ask questions that arise from careful observation of a meteor event at multiple scales and data from related events to clarify and seek additional information about the causes of the motions of orbiting objects, the effects of gravitational forces on these objects, and the consequences of their impact on our planet. (SEP: 1.1; CCC: 2.2; DCI: PS2.B.1, PS3.A.2, ESS1.B.1)

WHAT STUDENTS WILL FIGURE OUT

- A rock from space broke up over Siberia in 2013, lit up the sky, and damaged buildings.
- Similar phenomena have been observed in other places around the world throughout history. Sometimes part(s) of these rocks or other debris from space hit the ground, and sometimes they do not.
- Some space objects in the solar system remain in orbit, while others collide with different objects.

Lesson 1 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	10 min		**EXPLORE A NEW PHENOMENON** Present eyewitness video clips of the Chelyabinsk meteor event to students and record their noticings and wonderings.	A	Chelyabinsk Noticings and Wonderings poster, chart paper (optional), chart paper markers, https://youtu.be/zdxoOHVgip8?si=TP2Jx9cCJ7PsSu9f, https://youtu.be/n1TL_jaVijY?si=llY6Qsl2YO76y1QA
2	10 min		**GATHER AND COMMUNICATE INFORMATION** Guide students in gathering and sharing information on their questions using the internet.	B-C	computer
3	15 min		**DEVELOP INITIAL MODEL OF CHELYABINSK EVENT** Distribute to students a blank piece of paper to develop models that help explain what was happening to the Chelyabinsk meteor after it entered Earth's atmosphere and when a part of it hit the surface.	D-F	loose-leaf paper, colored pencils, M-E-F poster
4	8 min		**DEVELOP A CONSENSUS MODEL OF OBSERVED PHENOMENA DURING THE CHELYABINSK EVENT POSTER** Ask students to bring their models and gather in a Scientists Circle to develop a consensus model that helps explain some of the changes in matter, energy, and forces observed during the Chelyabinsk event.	G	Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster, chart paper markers (red), chart paper markers (green), chart paper markers (purple)
5	2 min		**NAVIGATE: HOME LEARNING** Brainstorm related phenomena in home learning that students can share with friends, family, and trusted adults.	H	*Home Learning*
					End of day 1
6	3 min		**NAVIGATE** Share some of the examples of related phenomena students discussed at the end of last period.	I	*Home Learning*
7	22 min		**EXPLORE RELATED PHENOMENA** Distribute to each student group a deck of 14 phenomena cards describing related phenomena for them to sort into different categories. Invite students to share the categories they sorted the cards into.	J-K	deck of 14 *Phenomena Cards* in half sheet protectors, dry-erase markers, laptop with access to https://docs.google.com/presentation/d/1VpBz-L_6TcrQFdLI3SREPHb5NrmzYs8ibUy3W0RsnDY/copy (optional), Categories of Space Objects poster, chart paper markers
8	7 min		**USE SCALE TO ORGANIZE PHENOMENA CARDS** Lead a discussion using time and space scales lenses to organize the phenomena cards. Record students' ideas using the Scale Chart poster.	L	Scale Chart poster, 3x5 sticky notes with names of phenomena cards, chart paper markers, *Phenomena Cards*

Part	Duration		Summary	Slide	Materials
9	4 min		**ASK QUESTIONS ABOUT RELATED PHENOMENA** Distribute a blank piece of paper to every student to record their questions about the related phenomena. Collect these before students leave the room.	M	loose-leaf paper
10	9 min		**DEVELOP INITIAL MODELS OF THE MOTION OF SPACE OBJECTS** Distribute to each student a blank piece of paper to develop models that help explain why some objects remain in Earth's orbit while others hit Earth.	N	loose-leaf paper, colored pencils
					End of day 2
11	5 min		**NAVIGATE: COMPARE MODELS** Return to students their initial models of the motion of space objects they developed at the end of last period. Have students compare their models with a partner.	O	initial models
12	4 min		**REFLECT ON COMMUNITY AGREEMENTS** Ask students to consider and select a focal community agreement and share with a partner the one they will focus on to reestablish community norms.	P-Q	Community Agreements poster
13	11 min		**DEVELOP A CONSENSUS MODEL OF THE MOTION OF SPACE OBJECTS** Ask students to gather in a Scientists Circle to collaboratively develop a consensus model that explains why some space objects remain in orbit around Earth while others collide with it.	R	student models developed during days 1 and 2, Initial Consensus Model: Motion of Space Objects poster, chart paper markers
14	15 min		**RECORD QUESTIONS AND ADD TO THE DQB** Facilitate the construction of a Driving Question Board by the class to establish the questions for the unit.	S-U	3x3 sticky notes, permanent marker (dark), Chelyabinsk Noticings and Wonderings poster, Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster, Initial Consensus Model: Motion of Space Objects poster, Community Agreements poster, Driving Question Board
15	8 min		**DEVELOP IDEAS FOR INVESTIGATIONS AND DATA NEEDED** Prompt students to individually do a stop and jot to develop ideas for investigations and data we need. Then ask students to share with the class.	V	Ideas for Investigations and Data We Need poster, chart paper markers
16	2 min		**NAVIGATE** Consider how gravity could cause some objects to move in orbit and others to hit Earth.	W	Driving Question Board
					End of day 3

Lesson 1 • Materials List

	per student	per group	per class
Lesson materials	• science notebook • computer • loose-leaf paper • colored pencils • *Home Learning* • initial models • student models developed during days 1 and 2 • 3x3 sticky notes • permanent marker (dark)	• deck of 14 *Phenomena Cards* in half sheet protectors • dry-erase markers • laptop with access to https://docs.google.com/presentation/d/1VpBz-L_6TcrQFdLI3SREPHb5NrmzYs8ibUy3W0RsnDY/copy (optional)	• Chelyabinsk Noticings and Wonderings poster • chart paper (optional) • chart paper markers • https://youtu.be/zdxo0HVgip8?si=TP2Jx9cCJ7PsSu9f • https://youtu.be/n1TL_jaVijY?si=lIY6Qsl2Y076y1QA • M-E-F poster • Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster • chart paper markers (red) • chart paper markers (green) • chart paper markers (purple) • Categories of Space Objects poster • Scale Chart poster • 3x5 sticky notes with names of phenomena cards • *Phenomena Cards* • Community Agreements poster • Initial Consensus Model: Motion of Space Objects poster • Driving Question Board • Ideas for Investigations and Data We Need poster

Materials preparation (20 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Test the two videos:

- https://youtu.be/zdxo0HVgip8?si=TP2Jx9cCJ7PsSu9f
- https://youtu.be/n1TL_jaVijY?si=lIY6Qsl2Y076y1QA

Access https://www.google.com/search?q=chelyabinsk+pronunciation&sca_esv=9f3a723203ad5f19&sca_upv=1&ei=-U93ZdHxPLKNwbkP7oSZmA0&oq=chelyabinsk&gs_lp=Egxnd3Mtd2l6LXNlcnAiC2NoZWx5YWJpbnNrKgIIATIREC4YgwEYkQIYsQMYgAQYigUyCxAAGIAEGIoFGJECMgoQABiABBiKBRhDMhAQABiABBiKBRhDGLEDGIMBMgsQLhiABBiKBRiRAjIKEAAYgAQYigUYQzIKEAAYgAQYigUYQzIFEAAYgAQyCRAuGAcYHhjUAjIGEAAYBxgeMiAQLhiDARiRAhixAxiABBiKBRiXBRjcBBjeBBjgBNgBAkjHvQJQAFjFLnABeACQAQCYAYYCoAGvA6oBBTAuMS4xuAEByAEA-AEBwgIQEAAYgAQYigUYkQIYRhj_AcICHBAAGIAEGIoFGJECGEYY_wEYlwUYjAUY3QTYAQHCAggQABiABBiwA8ICDhAAGIAEGIoFGIYDGLAD4gMEGAAgQYgGAZAGBLoGBggBEAEYE7oGBggCEAEYFA&sclient=gws-wiz-serp and click the speaker icon to hear the pronunciation of "Chelyabinsk".

Use *Phenomena Cards* to print 7 copies of each of the 14 phenomena cards--in color and single sided. Cut each page in half to separate the data cards and insert each of the 14 data cards into a plastic half-sheet protector. Aggregate the cards into 7 decks, 14 data cards each. You will distribute a set of phenomena cards to each pair of students. They will return these cards at the end of their class. Alternatively, you can distribute laptops to every group, and ask students to type the link on slide J to access the phenomena cards:
https://docs.google.com/presentation/d/1VpBz-L_6TcrQFdLI3SREPHb5NrmzYs8ibUy3W0RsnDY/copy
This will provide them with a digital copy of the card deck that they can organize by changing the order of the slides.

Prepare chart paper for the posters you will make in this lesson:

- Chelyabinsk Noticings and Wonderings
- Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event
- Initial Consensus Model: Motion of Space Objects
- Categories of Space Objects
- Scale Chart
- Driving Question Board
- Ideas for Investigations and Data We Need

Make sure the Community Agreements poster, developed in the *Electricity Unit*, is readily visible in the classroom. If you and your students have not yet co-developed these agreements, see the *OpenSciEd Teacher Handbook: High School Science* for guidelines.

Decide on and prepare for how you want to distribute the colored pencils to students. For the first initial model, students will each need access to multiple colors. One option is bundling colors together in boxes or with rubber bands with enough for small groups or individual students. Throughout this unit, students will be color coding. Each student should have access to at least 5-6 colors.

Post the M-E-F poster you developed from prior units: *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)* and *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*.

Lesson 1 • Where We Are Going and NOT Going

Where We Are Going

Students first developed ideas about how energy transfers are accompanied by changes in matter in the *Electricity Unit* and extended this idea in the *Earth's Interior Unit*. Students considered how forces cause changes in matter, including nonelastic, permanent deformation, in the later unit as well as in the *Vehicle Collisions Unit*. These ideas are particularly relevant to thinking about the way in which objects entering the atmosphere give off light (and heat up) as well as what causes many of them to break apart--all phenomena that students encounter evidence of in this lesson. Students also developed the idea that the momentum of an object is related to the magnitude of the forces that are produced in a collision between it and another object as well as the resulting damage to either object. This idea is particularly relevant to thinking about impact craters, which is another phenomenon there is evidence of in this lesson, and is also a phenomenon that will be investigated more deeply in Lessons 3-6.

In *OpenSciEd Unit 8.4: How are we connected to the patterns we see in the sky and space? (Space Unit)*, students developed the idea that the amount of mass and the distance between two objects affect the magnitude of the gravitational force between them. These ideas will help students make sense of how gravity can cause the types of motion exhibited by space objects.

Because this is the first lesson in a new unit, the goal is not to establish any ideas associated with the relevant DCIs but rather to elicit student ideas related to those DCIs. The DCI elements that students may bring in ideas related to in this lesson include the following:

- **PS3.A.2** At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy.
- **ESS1.B.1** ~~Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun.~~ Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system.
- **PS2.B.1** Newton's law of universal gravitation ~~and Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic~~ forces between distant objects.

Students will engage in the following practices during this lesson:

- **Developing and Using Models:** Develop, revise, ~~and/or use~~ a model based on evidence to illustrate ~~and/or predict~~ the relationships ~~between systems or~~ between components of a system.
- **Asking Questions and Defining Problems:** Ask questions that arise from careful observation of phenomena~~, or unexpected results~~, to clarify and/or seek additional information.

Students will develop two sets of initial consensus models in this lesson. The first set of models is intended to make students' ideas about matter, energy, and forces visible as they try to explain the observable changes of the Chelyabinsk meteor as it entered the atmosphere and hit Earth's surface. Students will revise these models during the second lesson set (Lessons 8-15) as they investigate what happens when objects collide with Earth or other solar system objects.

The second set of models is intended to make students' ideas visible about the role of gravity between space objects. Students will revise these models during the first lesson set (Lessons 1-7) as they investigate the relationship between gravity and the observed motion of space objects. Students will use these models to make predictions about why and how two space objects can collide.

Students will encounter several terms in this lesson: *orbit, asteroid, comet, meteorite, meteor, satellite.* It is OK to let students use these terms imprecisely in this lesson as they try them out and share their experiences. Over the next several lessons, we will co-develop meanings for these words. We recommend that you **do not** post any terms or ask students to record any words until after your class has developed a shared understanding of their meaning.

Where We Are NOT Going

We are not defining in this lesson what the differences are among asteroids, comets, meteors, or designed structures (e.g., space stations) visible in orbit. All these objects share important similarities and differences in what they look like moving across the sky, and allowing students to determine their categories that might help describe what is different about them helps provide a broader range of questions that future lessons will help answer.

LEARNING PLAN for LESSON 1

1 · EXPLORE A NEW PHENOMENON

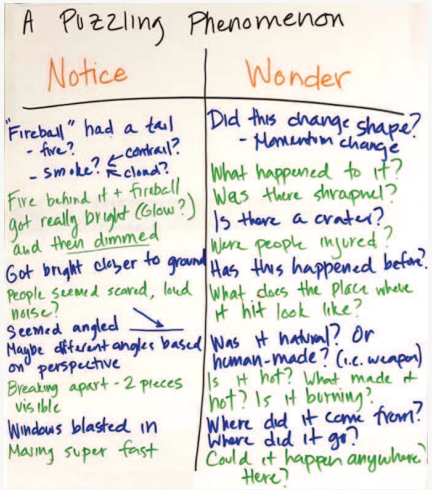
10 min

MATERIALS: science notebook, Chelyabinsk Noticings and Wonderings poster, chart paper (optional), chart paper markers, https://youtu.be/zdxoOHVgip8?si=TP2Jx9cCJ7PsSu9f, https://youtu.be/n1TL_jaVijY?si=lIY6Qsl2YO76y1QA

Notice and wonder. Present **slide A**. Say, *A few years ago in Siberia, something puzzling happened. A rock fell from the sky with no warning. Some of you may have seen videos of this event or heard of something similar happening somewhere else. I will show you two videos from this event in Siberia. The first is a series of clips from various cameras that recorded the event from different angles. The second is a brief news report related to the event.*

Play https://youtu.be/zdxoOHVgip8?si=TP2Jx9cCJ7PsSu9f and give students a minute to record their ideas in their science notebooks. Then play https://youtu.be/n1TL_jaVijY?si=lIY6Qsl2YO76y1QA and give students an additional minute to record their ideas.

Create a public record of noticings and wonderings. On a blank sheet of chart paper, or on the Chelyabinsk Noticings and Wonderings poster that you prepared ahead of time, create a T-chart to mirror the students' T-chart. Invite students to share aloud what they noticed and wondered. ✱ As they share, quickly document their ideas on the poster. One example of this T-chart is shown to the right.✱



ADDITIONAL GUIDANCE

If there are Russian speakers in your classroom, ask students privately if they would feel comfortable teaching the class to pronounce Chelyabinsk. Doing so makes the value of multilingualism explicit, showing students that the resources they bring to science learning from their cultural communities is productive for the project of figuring things out together. To hear the pronunciation of "Chelyabinsk", access https://www.google.com/search?q=chelyabinsk+pronunciation&sca_esv=9f3a723203ad5f19&sca_upv=1&ei=-U93ZdHxPLKNwbkP7oSZmAO&oq=chelyabinsk&gs_lp=Egxnd3Mtd2l6LXNlcnAiC2NoZWx5YWJpbnNrKgIIATIREC4YgwEYkQIYsQMYgAQYigUyCxAAGIAEGIoFGJECMgoQABiABBiKBRhDMhAQABiABBiKBRhDGLEDGIMBMgsQLhiABBiKBRiRAjIKEAAYgAQYigUYQzIKEAAYgAQYigUYQzIFEAAYgAQyCRAuGAcYHhjUAjIGEAAYBxgeMiAQLhiDARiRAhixAxiABBiKBRiXBRjcBBjeBBjgBNgBAkjHvQJQAFjFLnABeACQAQCYAYYCoAGvA6oBBTAuMS4xuAEByAEA-AEBwgIQEAAYgAQYigUYkQIYRhj_AcICHBAAGIAEGIoFGJECGEYY_wEYlwUYjAUY3QTYAQHCAggQABiABBiwA8ICDhAAGIAEGIoFGIYDGLAD4gMEGAAgQYgGAZAGBLoGBggBEAEYE7oGBggCEAEYFA&sclient=gws-wiz-serp and click the speaker icon. Note that the accent is on the second syllable (ya).

✱ STRATEGIES FOR THIS INITIAL IDEAS DISCUSSION

For each discussion type, the teacher takes a different stance in facilitation. Be explicit about your role in this Initial Ideas Discussion. Your role is to capture all student ideas, build excitement, and encourage as many students as possible to participate, whether the ideas they share are right or wrong.

Make space for all students to share ideas (possibly connected to experiences outside school as well). Encourage student-to-student talk with a focus on raising questions, clarifying, or adding to what someone has said, rather than debating or arguing. They may also use nods or hand signals to show they had a similar idea.

✱ ATTENDING TO EQUITY

Universal Design for Learning: The *representation* shown here of using alternating colors of markers to record separate statements students make helps them more quickly identify where one thought ends and another starts.

2 · GATHER AND COMMUNICATE INFORMATION

10 min

MATERIALS: computer, science notebook

Gather information from a search engine. Present **slide B**. Say, *I bet there is a lot on the internet about this event. Let's see if we can find additional information that can help answer some of our questions.*

Mention that you will provide each student with a computer so they can complete the first two prompts, but don't set them loose on the computers yet, as that will be distracting:

- *Record two questions you have about the Chelyabinsk meteor on February 15, 2013.*✱
- *Record your findings in your notebook.*

Before distributing a computer to every student, discuss the third prompt as a class:

- *Which government agencies, universities, research institutions, encyclopedias, or libraries might have productive websites to begin searching?*✱

Accept all answers. Distribute computers and allocate about 5 minutes for this.

SCIENCE NOTEBOOK



Keeping a science notebook allows students a space in which to reflect on and communicate their developing understandings about science ideas and to track changes in those understandings. Each student should have a binder that serves as their science notebook for the course. In this unit, this notebook will serve as a general note-taking space, contain the Progress Tracker for the unit, and organize handouts.

Communicate information. Present **slide C**. Cue students to briefly share with a partner one (or more) of the most interesting things they found out.

✱ SUPPORTING STUDENTS IN ENGAGING IN ASKING QUESTIONS AND DEFINING PROBLEMS

Social and emotional learning: If students don't have questions ready to research, encourage them to consider what people who witnessed the meteor in person might have been wondering about during and after the event. Explain that scientists ask questions about what they observe. *If you had observed an event like this in real life, what would you be wondering about?*

Giving students a chance to consider what people close to this event experienced can help support the development of students' social awareness, one of the Collaborative for Academic, Social, and Emotional Learning (CASEL) five core competencies. Social awareness describes the abilities to understand the perspectives of and empathize with others, including those from diverse backgrounds, cultures, and contexts. For more support around social and emotional learning, visit https://casel.org/.

✱ SUPPORTING STUDENTS IN ENGAGING IN OBTAINING, EVALUATING, AND COMMUNICATING INFORMATION

This is an opportunity to support students in obtaining information from credible sources. You might want to model the process of evaluating online sources. Share examples of credible and reliable sources, explaining the criteria you used for assessing their reliability. This will provide students with additional lenses for how to discern reliable information. Obtaining, evaluating, and communicating information is **not** a focus in this unit, but students will begin to apply it throughout. Students will intentionally develop this scientific practice in *OpenSciEd Unit P.5: How do we use radiation in our lives and is it safe for humans? (Microwave Unit)* and

OpenSciEd Unit P.6: Why do stars shine and will they shine forever? (Stars), using a series of scaffolds.

3 · DEVELOP INITIAL MODEL OF CHELYABINSK EVENT

15 min

MATERIALS: loose-leaf paper, science notebook, colored pencils, M-E-F poster

Develop initial models. Say, *Now that we saw a couple of videos and collected additional information, let's see if we can use our science ideas to try to explain our observations from the Chelyabinsk event.*

Mention that you want them to explain what they think was happening in the system that helps explain some of our observations. This is not about drawing what we saw, but using drawings and words to try to explain what could have led to the things we observed.

Present **slide D**. Distribute to each student a blank piece of paper and colored pencils to show what was happening to the rock
A. after the rock has entered Earth's atmosphere and
B. when a part of it (meteorite) hit Earth's surface.

Encourage them to use pictures, symbols, and words to explain both what happened over the time of the videos we saw and why it happened. Give students about 6 minutes to work on this individually.✱
Compare models. Present **slide E**. Prompt M-E-F thinking by referencing the M-E-F poster developed in *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*. Ask students to use these different perspectives to talk with a partner for 3 minutes about places in their models where they picture the matter is changing in some way, energy is being transferred, and forces are acting on objects in the system.

Use scale thinking to make sense of Chelyabinsk. Give students 2 additional minutes to discuss the second prompt:
- *Share ideas about why modeling at two scales can help us better understand these changes and force interactions. Are there any other scales we should add?*

It is unlikely that students will choose to model at a particle scale right now, but this question does open up that possibility. Some students may choose to add an additional scale when they update their models, but many students will not, and that is fine.

Update individual models. Present **slide F**. Give students 2 minutes to update their models using some of the ideas they discussed with their partner. Encourage students to use arrows, words, and colored pencils to express their thoughts. Encourage them to use their models to identify any questions they have about this phenomenon and to record those questions below their models.

Have students put their name on their paper and collect these models at the end of this day. You will give these models back on day 3. They will use the questions they included on this sheet during the construction of the Driving Question Board (DQB) on day 3 of this lesson.

✱ SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

Encourage students to use a pencil to draw their models. Mistakes made by pen are difficult to remove from the model, which might discourage some students from trying out different ideas.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: Look for students' models to accomplish the following:

- Use evidence about the Chelyabinsk event such as flashes of light, sound, smoke, or anything else they might have observed.
- Label this evidence in some way to indicate changes in matter and energy in different parts of the system (SEP: 2.3; CCC: 2.2; DCI: PS3.A.2, PS3.A.2)
- Represent forces such as gravity, friction, or other contact forces acting on the meteor and Earth's surface. (SEP: 2.3; DCI: ESS1.B.1, PS2.B.1)
- Represent two different spatial scales--one where we are zoomed out enough to see the meteor above Earth and one where the meteor is close to the surface of Earth. (SEP: 2.3; CCC: 2.2)

What to do: This is a great formative assessment opportunity to identify the ideas students are bringing to this unit to represent their thinking about changes in matter, forces acting on matter, and energy. Collect these models at the end of the day to identify the focus of students' models to represent these ideas.

Students showing ***Foundational Pieces*** will focus on descriptions of visible (macroscopic) changes in the system. For instance, they might indicate observable evidence of energy in the system, such as the meteor moving fast, fire and heat coming out of the rock, or the blast causing damage on the surface. It is likely at this point in the unit that most students will have this level of understanding.

Students with a ***Linked Understanding*** might represent force interactions between parts of the system to describe energy transfer, such as the friction between the rock and the atmosphere or the contact force between the meteor and the surface.

Students with an ***Organized Understanding*** will display particle-level interactions to account for the energy transfer in the system, such as bonds breaking at the surface or rock and air particles vibrating very fast. It is unlikely that you will have many students at this level this early in the unit. If many students have an organized understanding, be ready to challenge their ideas about matter, energy, and forces in subsequent lessons so that the class does not feel bored.

Keep note of the student distribution in each level of understanding. The goal of this unit is to get all students to use ideas at all levels to make sense of this phenomenon.

Use the questions students included in their models as a formative assessment opportunity to identify the types of questions students are asking about this phenomenon. Identify whether these questions are scientific (i.e., answerable through the gathering of evidence or about the natural world) or not.

Building toward: 1.A.1 Develop a model using evidence from the Chelyabinsk meteor event and related phenomena to illustrate how the interactions between different parts of the system at different scales help explain the changes in matter, energy, and/or motion of orbiting objects. (SEP: 2.3; CCC: 2.2; DCI: PS2.B.1, PS3.A.2, ESS1.B.1)

4 · DEVELOP A CONSENSUS MODEL OF OBSERVED PHENOMENA DURING THE CHELYABINSK EVENT POSTER

8 min

MATERIALS: Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster, chart paper markers (red), chart paper markers (green), chart paper markers (purple)

Develop a first initial consensus model. Present **slide G**. Ask students to bring their models and gather in a Scientists Circle. On the Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster, sketch and label two different views, with Earth in the view at a different scale for each:
A. a rounded arc for Earth for "after the rock has entered Earth's atmosphere"
B. a flat surface for "when a part of it (meteorite) hits the surface"

Start with frame A and then move to frame B. Set up a three-color key, using red to represent changes in matter, green to represent energy in the system or energy transfer between parts of the system, and purple to represent forces in the system.

For each frame, use the following prompts to gather as many ideas as possible:

- *What are the key parts in the system that we should include?*
- *Who added the same part? Who added a different one?*
- *Do we have evidence that matter was changing? How do we represent that?*
- *Do we have evidence that energy was changing? How do we represent that?*
- *Do we have evidence that forces were acting on parts of the system? How do we represent that?*
- *What scale would help us better understand what is causing some of these changes?*

As the class shares ideas, use the slide prompts to highlight areas of agreement or disagreement:

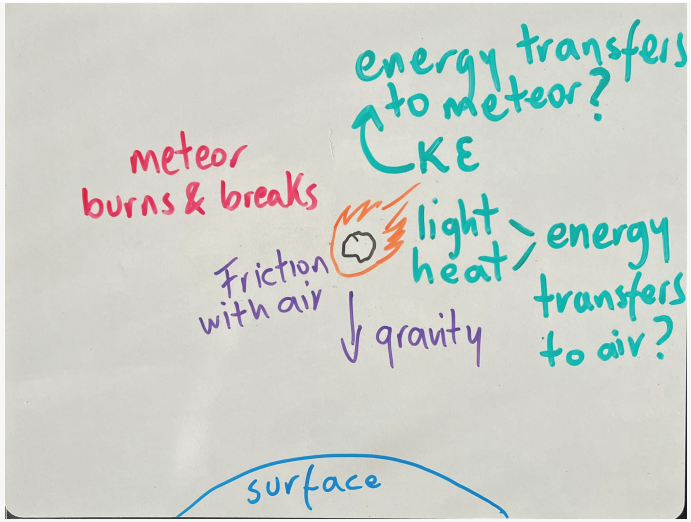
- *What do we all seem to agree on?*
- *What do we disagree on?*
- *What are some new ideas we may want to consider?*

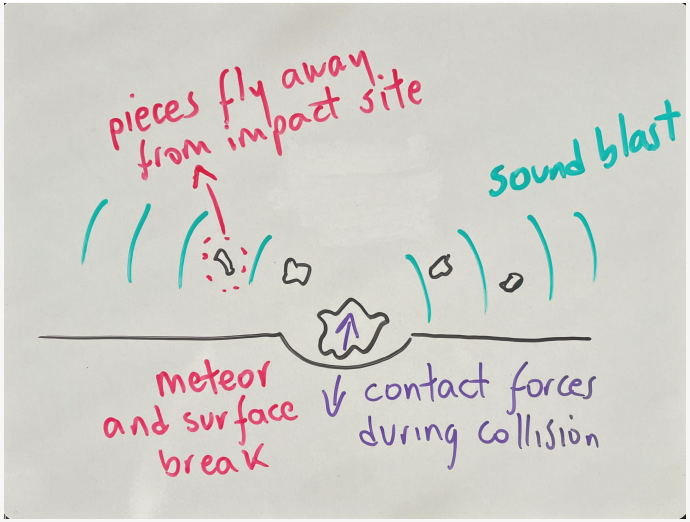
KEY IDEAS

Purpose of this discussion: Capture ideas that fall into different ways of making sense of the phenomenon from a matter, energy, and forces perspective. It's not imperative to categorize the ideas as they are shared, rather, use each category as a way to prompt for different ideas represented in the models. Indicate areas of uncertainty or competing ideas with a question mark after the idea.

Refer to *Initial Consensus Models* for key ideas to listen for related to each frame.

An example of a possible representation to build as part of developing this initial consensus model is shown below. Notice that it uses the same color code used in the M-E-F poster to represent ideas about matter, energy, or forces.


energy transfers to meteor?
KE
meteor burns & breaks
light
heat
energy transfers to air?
Friction with air
gravity
surface


pieces fly away from impact site
sound blast
meteor and surface break
contact forces during collision

5 · NAVIGATE: HOME LEARNING

2 min

MATERIALS: *Home Learning*

Make connections to related phenomena in a Home Learning. Present **slide H**. Pass out *Home Learning*. Say, *I bet there is a lot we can learn from your stories and the stories of those in your families and communities. Let's gather some of these stories for next time.* Ask students to spend time describing what happened in Chelyabinsk with friends, family, or a trusted adult, and then discussing the prompts on the handout:

- *What examples have you seen or heard about that*
    - *looked like this happening in the sky?*
    - *included something from space that fell to Earth?*
    - *could help us understand what happened with the Chelyabinsk event?*

Say, *We will share some of our ideas next time!*

Collect the Chelyabinsk event models before students leave the classroom.

End of day 1

6 · NAVIGATE

3 min

MATERIALS: *Home Learning*

Share examples of related phenomena. Present **slide I**. Use the slide prompts to elicit a few ideas from the Home Learning:

- *What other examples have you or the people you talked to seen or heard about that*
    - *looked like the Chelyabinsk meteor happening in the sky?*
    - *included something from space that fell to Earth?*
    - *could help us understand what happened with the Chelyabinsk event?*

Example responses may include things like the following:

- shooting star(s)
- space junk
- rockets falling from space
- asteroid that killed the dinosaurs
- a sacred rock or crater ✱

Say, *I have some information about some of the events you shared and some additional events. Let's see how they compare to the Chelyabinsk meteor.*

✱ ATTENDING TO EQUITY

Make space here for students to bring in stories about meteors that are spiritual or mythical in nature, in addition to concrete observations.

Many cultures throughout history have had strong spiritual connections to meteors and things that fall from space. For example, in ancient Greece, meteors were thought to be arrows shot by the gods. In ancient Rome, they were seen as portents of war or disaster. In China, meteors were believed to be dragons or other mythical creatures. In ancient Egypt, the god Bes was believed to be a protector against meteors. In Japan, the god Amaterasu was said to have created the world from a meteor. And in Aztec culture, the god Huitzilopochtli was associated with meteors.

These beliefs are not a thing of the past, rather meteors are still held sacred. In some Indigenous American cultures, meteors are still seen as signs of good luck or spiritual guidance. And the Black Rock, a likely meteorite located in the Kaaba in Mecca, is one of the most sacred objects in Islam. The cultural connections that students bring are a reminder of our shared human fascination with the night sky, and of how people around the world. Honor these stories in the classroom, and help students see that the project of making sense of phenomena may look different across cultures, but it connects us all.

7 · EXPLORE RELATED PHENOMENA

22 min

MATERIALS: science notebook, deck of 14 *Phenomena Cards* in half sheet protectors, dry-erase markers, laptop with access to https://docs.google.com/presentation/d/1VpBz-L_6TcrQFdLI3SREPHb5NrmzYs8ibUy3W0RsnDY/copy (optional), Categories of Space Objects poster, chart paper markers

Orient to the Chelyabinsk card. Say, *In a moment you will start exploring cards of 14 different space objects and phenomena. Let's take a moment to look at one of these cards.* Present **slide J**. Organize students into pairs. Distribute the Chelyabinsk card to every pair of students and give them a minute to quickly familiarize themselves with the information presented in the card.

Ask, *What information contained on the card seems confusing or new to us?* Accept all answers. If students don't raise any questions, use the following prompts:

- *What do we know about what an orbit is?*
- *Is everyone familiar with the words* orbit *and* revolve*? How can we define these terms in our own words?*
- *Do we recognize the units being used?*

ALTERNATE ACTIVITY

Distribute laptops to every group, and ask students to type the link on slide J: https://docs.google.com/presentation/d/1VpBz-L_6TcrQFdLI3SREPHb5NrmzYs8ibUy3W0RsnDY/copy This will provide them with a digital copy of the card deck that they can organize by changing the order of the slides.

Sort the cards into categories. Display **slide K**. Distribute the remaining phenomena cards to students and dry-erase markers. Read the instructions on the slide out loud to guide students' work during this task:

- *Sort the cards into different categories.*
- *In your notebook, record the categories you sort them into as well as the wonderings that emerge.*
- *Repeat this process as much as the time permits.*

Encourage students to annotate the cards placed in the half sheet protectors using dry-erase markers to highlight information they find relevant. Give them around 10 minutes for this task.

Discuss categories as a class. Invite students to share the categories they sorted the cards into. Use the following prompts to gather as many voices and ideas as possible:

- *Who else sorted the cards into a similar category?*

- *Who sorted the cards into a different category?*
- *Were there any cards that you felt didn't fit well into any category? Why or why not?*
- *Were there any cards that sparked a debate or discussion with your partner about which category they belonged to?*
- *Did you find any patterns or connections between certain cards that influenced your categorization?*

Use the Categories of Space Objects poster to keep a record of the categories students share. Keep this poster visible for the rest of the lesson, as it will support later discussions about productive categories that can help us explain the risk space objects pose on Earth. This table might look like the example below. The "Status" category is in bold text to highlight the importance of discussing the existence of objects that are in orbit for long periods of time, while other objects collide with Earth. Explaining this category will be the focus of the first lesson set of this unit.

Categories of Space Objects	
Category	**Example**
Orbit	Orbiting the Sun: Chelyabinsk meteor, Comet Hale-Bopp Orbiting Earth: ISS, Skylab
Natural vs. man made	Natural: Chelyabinsk meteor, Peekskill meteor, Halley's Comet Man made: ISS, Skylab
Type of space object	Comets: Halley's, Hale-Bopp Satellites: ISS, Skylab, Mir, Vanguard Meteor: Chelyabinsk Meteor shower: Leonid, Perseids Asteroid: Ryugu Meteorite: Willamette, Ensisheim, Sikhote-Alin, Peekskill
Status	In orbit: Vanguard, Halley's Comet Collided: Chelyabinsk meteor, Mir, Peekskill meteor

ADDITIONAL GUIDANCE

Scientists use different terms to describe the space rock's position in its trajectory. When the rock is still in space, scientists call it a meteoroid. When meteoroids enter a planet's atmosphere at high speed and burn up, the resulting fireballs are called meteors. These space rocks can come from asteroids, comets, or other solar system objects. Regardless of their origin, they create meteors in our atmosphere. If a space rock survives its trip through the atmosphere and reaches the ground, it is called a meteorite. In this unit, we will use the term "Chelyabinsk meteor" rather than "Chelyabinsk meteorite" because the phenomenon we are investigating is centered around the observations of this object colliding with our atmosphere. While we also use the term "meteorite" to refer to similar phenomena, such as the Peekskill meteorite, we do not expect students to distinguish between meteorites and meteors.

8 · USE SCALE TO ORGANIZE PHENOMENA CARDS

7 min

MATERIALS: Scale Chart poster, 3x5 sticky notes with names of phenomena cards, chart paper markers, *Phenomena Cards*

Use scale to organize phenomena cards. Say, *Some of the objects we explored so far orbit the Sun, while others orbit our planet. Some objects have been in orbit for thousands of years, while others were in orbit for short periods of time. Sometimes it is helpful to keep track of things that happen at different scales to make sense of any connections between them.* Display the Scale Chart poster. Say, *Let's see how these phenomena compare across time and space scales.*

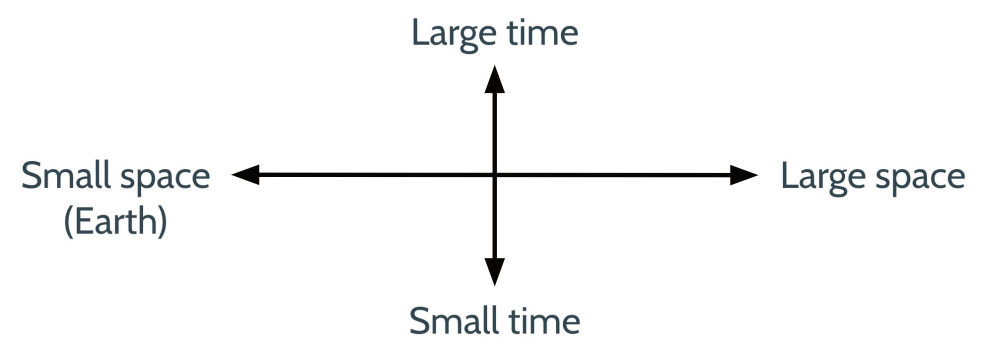
Discuss the scale of phenomena. Present **slide L**. Begin by asking students to consider the spatial scale of the phenomena presented in the cards and then discuss the time scale of these phenomena. You can ask the following questions:

- *What information presented in the cards can give us ideas about how much distance these objects travel?*
- *What information presented in the cards can give us ideas about the duration of each of these phenomena?*

Look for students to mention the following ideas:

- The object that space objects orbit (e.g., Earth, the Sun) and the distance from it can give us ideas about the distance these objects travel (space scale).
- The time it takes to orbit the Sun or Earth gives us information about the scale of time.

Sort cards based on space and time scales. On the Scale Chart poster, first draw a horizontal line to represent the space scale. Once students have shared their ideas to sort the cards from this perspective, draw a vertical line to represent the time scale. Use the sticky notes with the names of the phenomena cards and arrange them based on the ideas students share.



The objective of this activity is to assist students in recognizing the similarities and differences in the time and space scales among various space objects. Additionally, it will help prompt scale-related questions, such as why some objects remain in orbit for longer periods while others only last a few years. This activity also aims to encourage ideas about the properties of space objects that might explain the differences in scale.

ADDITIONAL GUIDANCE

The Scale Chart was originally developed during *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)* to support student sensemaking across different time and space scales. This tool is intended to help students identify connections of different phenomena across different scales as students build more-sophisticated explanations throughout the unit.

9 · ASK QUESTIONS ABOUT RELATED PHENOMENA

4 min

MATERIALS: loose-leaf paper

Record questions about related phenomena. Say, *Sorting these cards may have raised different questions. Let's record these on a piece of paper. We will come back to these questions and explore how we can answer them.* Present **slide M**. Distribute a blank piece of paper to each student and give students a couple of minutes to record their questions. Collect these questions as an exit ticket before students leave the room. You will return them to students on day 3.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: Questions to clarify and seek additional information about
- the causes of the motion of orbiting objects (SEP: 1.1; CCC: 2.2; DCI: PS2.B.1, ESS1.B.1)
- the causes of observed effects from various orbiting objects on Earth's systems (SEP: 1.1; CCC: 2.2; DCI: PS3.A.2)

What to do: Use the questions developed by students as a formative assessment opportunity to identify the types of questions students are asking about these phenomena. Identify whether these questions are scientific (i.e., answerable through the gathering of evidence or about the natural world) or not. If students seem to struggle with this task, use the following prompts:
- *Think about whether there's anything you would like to know about some of the phenomena we explored today.*
- *What did you notice or wonder while sorting the cards?*

Collect these questions before students leave, as you will use them to build the DQB during day 3.

Building toward: 1.B.1 Ask questions that arise from careful observation of a meteor event and data from related events to clarify and seek additional information about the causes of the motions of orbiting objects, the effects of gravitational forces on these objects, and the consequences of their impact on our planet. (SEP: 1.1; CCC: 2.2; DCI: PS2.B.1, PS3.A.2, ESS1.B.1)

Say, *Chelyabinsk is not the only space object that has collided with Earth. We have examples in our cards of other space objects that have collided with Earth, while other objects have remained in orbit for a very long time. Let's see if we can model how the interactions between Earth and other objects can help explain whether they remain in orbit or collide with our planet.*

10 · DEVELOP INITIAL MODELS OF THE MOTION OF SPACE OBJECTS

9 min

MATERIALS: loose-leaf paper, science notebook, colored pencils

Develop initial models of space objects interacting with Earth. Present **slide N**. Distribute a blank piece of paper and colored pencils to each student to show what might have been happening in outer space that helps explain
A. why some objects remain in orbit.
B. why some objects hit Earth.

Give students the remaining time to work on this individually. Encourage them to use their model to identify any questions they have about these phenomena. Collect these models at the end of the class.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: This is a second formative assessment that will provide you with evidence of students' ideas about forces at a distance and changes in motion. Look for students' models to

- represent forces acting on the meteor and how they can cause some objects to stay in orbit and others to hit Earth. (SEP: 2.3;CCC: 2.2; DCI: ESS1.B.1, PS2.B.1)
- represent some differences in the force interactions occurring between Earth and orbiting objects as the distance between them changes. (SEP: 2.3; CCC: 2.2; DCI: ESS1.B.1, PS2.B.1)

In addition, look for students to include

- questions to clarify and seek additional information about interactions within the system that can cause different types of motion of space objects. (SEP 1.1; CCC: 2.2; DCI: ESS1.B.1, PS2.B.1)

What to do: Remind students that forces have both magnitude and direction. Encourage them to show in their models how the magnitude and direction of forces acting on objects in the system might lead some to remain in orbit while causing others to collide with Earth. Suggest they begin with two objects, considering the force interactions between them, and then incorporate any additional objects they believe interact within the system. This is not the moment to evaluate the accuracy of students' models. Instead, encourage them to highlight areas of uncertainty in their models and ask questions that can help illuminate those areas.

Collect these models at the end of the class. You will return these models to students the next day.

Building toward: 1.A.2 Develop a model using evidence from the Chelyabinsk meteor event and related phenomena to illustrate how the interactions between different parts of the system at different scales help explain the changes in matter, energy, and/or motion of orbiting objects. (SEP: 2.3; CCC: 2.2; DCI: PS2.B.1, PS3.A.2, ESS1.B.1)

Building toward: 1.B.2 Ask questions that arise from careful observation of a meteor event and data from related events to clarify and seek additional information about the causes of the motions of orbiting objects, the effects of gravitational forces on these objects, and the consequences of their impact on our planet. (SEP: 1.1; CCC: 2.2; DCI: PS2.B.1, PS3.A.2, ESS1.B.1)

End of day 2

11 · NAVIGATE: COMPARE MODELS

5 min

MATERIALS: science notebook, initial models

Compare models. Present **slide O**. Return to students their initial models of the motion of space objects they developed at the end of last period. Give students 5 minutes to compare their models with a partner and discuss the following questions:

- *What are the key parts in the system that help explain why some space objects fall from the sky while others do not?*
- *How can the interactions between these parts cause some space objects to fall from the sky while others do not?*
- *What scale (large scale, particle-level scale) would help us better understand these phenomena?*

12 · REFLECT ON COMMUNITY AGREEMENTS

4 min

MATERIALS: Community Agreements poster

Select a focal community agreement. Remind students we are about to share our models with one another and come to consensus as a class, which is a task that relies on everyone attending to multiple community agreements. Display **slide P**. Ask students to reflect on the two questions on the slide:

- *Which agreements do you think might be particularly challenging to follow if we are out of practice?*
- *Which do you think we need to intentionally work at more to get better at?*

Ask them to choose one community agreement that they will personally work on for the rest of the class.

Share the community agreement(s) selected. Display **slide Q**. Have students share with a partner the community agreement they chose and why it is important for them.✱

ADDITIONAL GUIDANCE

OpenSciEd Community Agreements are introduced and co-developed over several lessons in the first unit of the Physics course, the *Electricity Unit*. If you have not taught a previous OpenSciEd unit with this group of students, consider spending time right now co-developing these agreements and discussing how they can support our work together before moving on.

✱ ATTENDING TO EQUITY

Universal Design for Learning: It is important to use the community agreements to begin to cultivate an equitable learning community that promotes trusting and caring relationships that foster student *engagement*. One of the reasons that OpenSciEd uses the term *community agreements* is to highlight that there is not **just one** way to collaborate. Establishing norms is a powerful tool for equity in the classroom when done collaboratively and thoughtfully. But be aware that ideas such as *safe, respectful, polite, nice,* and *kind* are culturally embedded and thus can mean different things in different communities. For examples of inclusive community agreements that support equitable spaces, visit https://www.theequitylab.org/blog/why-start-with-agreements.

13 · DEVELOP A CONSENSUS MODEL OF THE MOTION OF SPACE OBJECTS

11 min

MATERIALS: student models developed during days 1 and 2, Initial Consensus Model: Motion of Space Objects poster, chart paper markers

Develop a second initial consensus model. Present **slide R**. Ask students to bring their models and their science notebook and gather in a Scientists Circle. Sketch Earth on the Initial Consensus Model: Motion of Space Objects poster by drawing a circle in the center of the paper, with sufficient room around it to represent orbiting objects later. Decide with the class whether they want to start by modeling an object that remains in orbit or one that hits Earth, ideally Chelyabinsk. To gather as many ideas as possible, encourage students to use their models as the class explores the following prompts:

- *What are the key parts in the system that we should include?*
- *Who added the same part? Who added a different one?*
- *What interactions between these parts help explain the motion of this object?*
- *What scale would help us better understand objects that move in similar ways to this object?*

As the class shares ideas, use the slide prompts to highlight areas of agreement or disagreement:

- *What do we all seem to agree on?*
- *What do we disagree on?*
- *What are some new ideas we may want to consider?*

Once the motion of the first object has been modeled, continue with the second object.

KEY IDEAS

Purpose of this discussion: Develop an initial consensus model to capture the ideas we agree and disagree on regarding the role of gravity over distance in space.

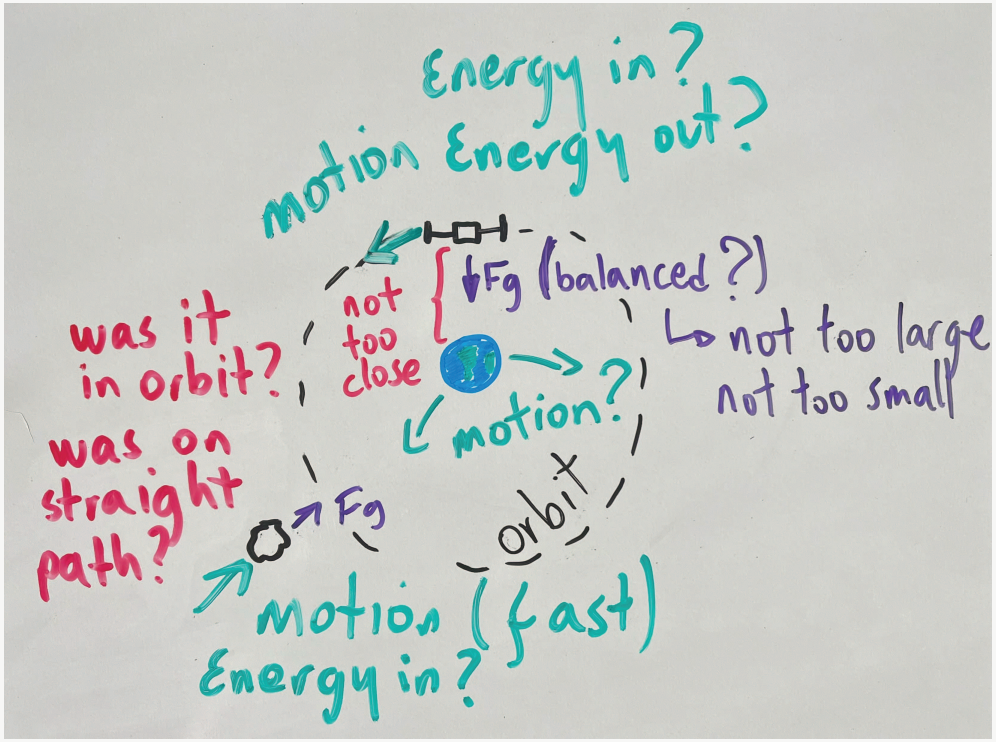
Listen for these ideas:

- The magnitude of gravity changes over distance.
- The proximity of an object to Earth might affect its orbit.

Possible areas of disagreement or controversy

- **The role of distance in gravity:** While some students might be familiar with the decrease in the force of gravity over distance, field-test teachers reported that students considered gravity to increase with distance.
- **The causes of the motion of orbiting objects:** While students might be familiar with the orbital motion of space objects, they might struggle to explain why these objects move in this manner.

An example of a possible representation to build as part of developing this initial consensus model is shown below.



14 · RECORD QUESTIONS AND ADD TO THE DQB

15 min

MATERIALS: 3x3 sticky notes, permanent marker (dark), Chelyabinsk Noticings and Wonderings poster, Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster, Initial Consensus Model: Motion of Space Objects poster, Community Agreements poster, Driving Question Board

Identify questions that can help move our thinking forward. Present **slide S**. Make sure the Chelyabinsk Noticings and Wonderings poster, the Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster, and the Initial Consensus Model: Motion of Space Objects poster are visible to all students.

Give students back the models of the Chelyabinsk event they developed during day 1 and their exit ticket. Read the slide prompts out loud to guide students through this task:
Look back at the questions you included in

- *your initial models of the Chelyabinsk event,*
- *your initial models of the motion of space objects, and*
- *your questions about related phenomena.*

Identify the questions that you think will help us understand and explain

- *the Chelyabinsk event and related phenomena.*
- *why some objects remain in orbit and why some hit Earth.*

Record initial questions. Present **slide T**. Distribute a few sticky notes and 1 marker to each student. Give students this time to record 1 question per sticky note in marker (with initials on back in pencil). Give students a few minutes to complete this activity.

Build the Driving Question Board. Display **slide U**. Review the protocol for sharing, calling on, linking in, and clustering questions on the Driving Question Board (DQB). Continue until everyone has shared at least one question. If students still have additional questions, shift to giving them an additional minute to add them silently to the DQB, sorting into clusters if they know where they go or simply putting them on the edge for now, which the class can work on clustering later.

Use the Community Agreements poster to ensure an orderly discussion.

15 · DEVELOP IDEAS FOR INVESTIGATIONS AND DATA NEEDED

8 min

MATERIALS: science notebook, Ideas for Investigations and Data We Need poster, chart paper markers

Develop ideas for investigations and data we need. Display **slide V**. Prompt students to take 3 minutes to stop and jot down ideas for kinds of investigations we could carry out and/or what additional sources of data might we need to figure out the answers to our questions.

Ask students to share these ideas with the class as you make a public record of them on the Ideas for Investigations and Data We Need poster to refer to across later lessons.

ADDITIONAL GUIDANCE	**Collect all student models developed during this lesson.** In Lesson 6, you will return the models developed during day 2 for a self-reflection opportunity. In Lesson 11, you will return the models on frames A and B to students for a self-reflection opportunity.

16 · NAVIGATE

2 min

MATERIALS: Driving Question Board

Navigate. Present **slide W**. Use the DQB to point out some of the questions students had related to the possibility of a meteor hitting Earth and/or related to why some space objects fall to Earth while others remain in orbit. Mention that our models suggest gravity plays an important role in how these objects move and interact with Earth. Ask students to turn and talk with the following prompt:

- *How could gravity cause some objects to orbit and others to hit Earth?*

Suggest starting our next lesson by sharing our ideas and trying to make progress on the role of gravity.

LESSON 2: How far does Earth's gravity extend into space?

PREVIOUS LESSON

We explored eyewitness video clips of the Chelyabinsk meteor. We categorized data on other related phenomena. We developed two sets of models, one to explain the observed changes during the Chelyabinsk event and one to explain the motion of different space objects. We developed questions for our Driving Question Board and recorded ideas for investigations and data we need to answer them.

THIS LESSON

INVESTIGATION

3 days





We make predictions about the gravitational force experienced by objects at different distances from Earth's surface and carry out an investigation of magnetic forces versus distance. We analyze data on gravitational forces for various objects and distances. We use mathematical models to determine the strength of this force acting on different space objects and consider whether this helps explain why some objects collide with Earth while others remain in orbit.

NEXT LESSON

We will use a simulation to figure out what conditions are necessary for orbit. We will investigate how to quantify how force relates to other variables in circular motion. We will analyze how planets move. We will connect the circular motion and universal gravitation equations and identify the relationship between period and orbital radius.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2



WHAT STUDENTS WILL DO

2.A Use simple limit cases and mathematical representations to describe patterns in the change of magnitudes of magnetic and gravitational forces on two objects caused by changes in their distances from each other. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1, PS2.B.2)

2.B Apply techniques of algebra to solve for the gravitational force between Earth and another space object using Newton's law of universal gravitation. (SEP: 5.3; CCC: 3.5; DCI: PS2.B.1, PS2.B.2)

WHAT STUDENTS WILL FIGURE OUT

- All matter produces gravitational fields.
- Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space.
- When two objects interact through a field force like gravity or magnetism, the forces between them are equal in magnitude and opposite in direction.
- Newton's law of universal gravitation mathematically models how gravitational forces depend on the masses of and distance between two objects.
- The force of gravity experienced by space objects alone does not fully explain why some collide with Earth while others remain in orbit.

Lesson 2 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	3 min		**NAVIGATE** Revise some of the main ideas the class had about how gravity affects different space objects.	A	Initial Consensus Model: Motion of Space Objects poster (created in Lesson 1), 1-N spring scale
2	12 min		**CONSIDER HOW DISTANCE AFFECTS FORCE OF GRAVITY** Compare gravitational force measurements for two masses and two heights. Instruct students to sketch their predictions for the relationship between the force of gravity experienced by objects and distance. Discuss the challenges of investigating this relationship in the classroom.	B-G	*Predicting Force Relationships*, 20-g impactor, 40-g impactor, 1-N spring scale, 3x3 sticky notes in 2 colors
3	10 min		**COMPARE NONCONTACT FORCES: GRAVITY AND MAGNETISM** Document the similarities and differences between gravitational and magnetic fields. Instruct students to use a graph to predict how the magnitude of the magnetic force experienced by two magnets changes as the distance between them increases.	H-K	*Predicting Force Relationships*, compass, Gravity-Magnetism Comparison poster, half sheets of paper, chart paper markers, transparent tape
4	17 min		**INVESTIGATE THE MAGNITUDE OF MAGNETIC FORCE ACTING ON TWO MAGNETS** Orient the class to the equipment used to collect magnetic force data. Analyze results from a video demonstration in which the relative forces on two magnets are measured using this equipment.	L-P	Newton's Third Law for Forces at a Distance poster, Gravity-Magnetism Comparison poster, 3x3 sticky notes, chart paper markers, https://youtu.be/fBvELBBHH_4, fine point permanent marker
5	3 min		**NAVIGATE** Distribute a piece of paper to every student to complete an exit ticket.	Q	piece of 8.5" x 11' paper
					End of day 1
6	2 min		**NAVIGATE** Use the slide prompts to revise some of the main ideas developed last time about the magnitude of the magnetic field acting on two magnets. Review ideas from the exit ticket.	R-S	
7	15 min		**CARRY OUT AN INVESTIGATION** Orient to the procedures and class spreadsheet and use these to collect and graph data on force versus distance for a magnet pair combination condition.	T-U	This Class Period's Magnetic Force Data spreadsheet, Magnetic Force vs. Distance Investigation
8	14 min		**ANALYZE AND INTERPRET DATA** Compare patterns in the magnetic investigation graphs across groups.	V-W	This Class Period's Magnetic Force Data spreadsheet, Newton's Third Law for Forces at a Distance poster
9	14 min		**ANALYZE GRAPHS AND MAKE PREDICTIONS** Analyze a gravitational force versus distance graph. Identify variables that affect gravitational force.	X-Z	*Comparing Gravitational Forces*, Newton's Third Law for Forces at a Distance poster
					End of day 2

Part	Duration		Summary	Slide	Materials
10	6 min		**NAVIGATE** Review graphs students annotated on *Comparing Gravitational Forces* last time.	AA-BB	*Comparing Gravitational Forces*, Newton's Third Law for Forces at a Distance poster
11	18 min		**USE MATHEMATICAL THINKING** Identify the variables in the universal law of gravitation and use it to make predictions for different mass interactions at different distances.	CC-HH	*Calculating Gravitational Forces*, calculator
12	8 min		**DEVELOP A MODEL** Add to the Gravity-Magnetism Comparison poster.	II	M-E-F poster, Gravity-Magnetism Comparison poster, transparent tape, sketches of the nonlinear trends for the graphs
13	5 min		**NAVIGATE** Navigate into the next lesson by considering the differences in the motion of objects caused by gravity and magnetism.	JJ	
14	8 min		**ELECTRONIC EXIT TICKET** Complete an exit ticket to explain what the universal law of gravitation predicts for the changes in a variable at one scale related to changes in another variable at a different scale.	KK	copy of https://docs.google.com/forms/d/1jFVInZdCB4gqYLqNoVqq_S1jMYIgPuauX76VAgkv8Ns/copy, *Calculating Gravitational Forces*, calculator

End of day 3

Lesson 2 • Materials List

	per student	per group	per class
Magnetic Force vs. Distance Investigation materials	• *Magnet Investigation Procedure*	• magnet beam • magnet base • 2 beam supports • digital scale (accurate to 0.01 g) • 30 game chips • computer • copy of https://docs.google.com/spreadsheets/d/1ZM2CXwmMM1Ehmt_2L2ftqZvYifZY9FIy71daRdsti8c/copy	
Lesson materials	• *Predicting Force Relationships* • piece of 8.5" x 11' paper • science notebook • *Comparing Gravitational Forces* • *Calculating Gravitational Forces* • calculator • copy of https://docs.google.com/forms/d/1jFVInZdCB4gqYLqNoVqq_S1jMYIgPuauX76VAgkv8Ns/copy	• compass	• Initial Consensus Model: Motion of Space Objects poster (created in Lesson 1) • 1-N spring scale • 20-g impactor • 40-g impactor • 3x3 sticky notes in 2 colors • Gravity-Magnetism Comparison poster • half sheets of paper • chart paper markers • transparent tape • Newton's Third Law for Forces at a Distance poster • 3x3 sticky notes • https://youtu.be/fBvELBBHH_4 • fine point permanent marker • This Class Period's Magnetic Force Data spreadsheet • M-E-F poster • sketches of the nonlinear trends for the graphs

Materials preparation (120 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole-punch all handouts so they can be added to students' science notebooks.

Print one copy of *Magnet Investigation Procedure* for each student in your largest class period. These will be reused across all periods.

Prepare 20-g and 40-g impactors used during day 1. See *Making Impactors* for how to create these.

Prepare the necessary equipment for the lab stations and magnetic force demonstration.

Review the related video: https://youtu.be/fBvELBBHH_4. You will pause this video at a few key points on day 1 to discuss and predict with your students what is happening in the system.

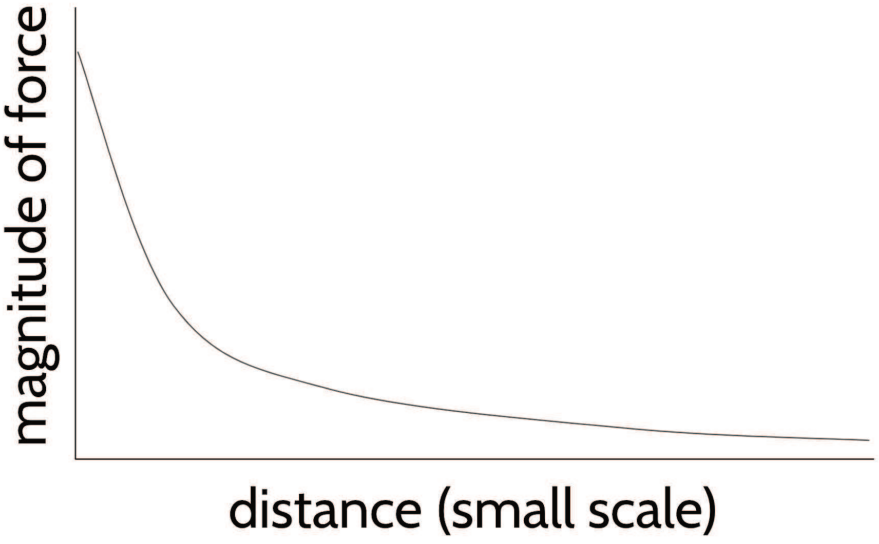
Create a copy of the exit ticket for your students to complete at the end of the second period of this lesson, using this link https://docs.google.com/forms/d/1jFVInZdCB4gqYLqNoVqq_S1jMYIgPuauX76VAgkv8Ns/copy.

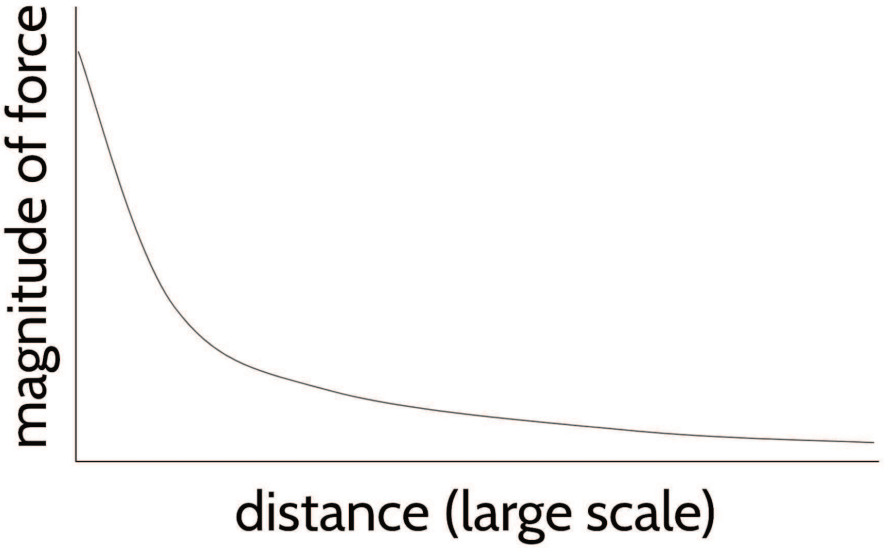
Create a copy of this spreadsheet for each class period you have: https://docs.google.com/spreadsheets/d/1ZM2CXwmMM1Ehmt_2L2ftqZvYifZY9FIy71daRdsti8c/copy. This will be referred to as *This Class Period's Magnetic Force Data* spreadsheet going forward. You will share with students, on **slide T,** the URL of the copy of the spreadsheet you spin off for their class. This will be referred to as the URL for this class's copy of the *Magnetic Force Data* spreadsheet in the remainder of this *Teacher Guide*.

Review the related teacher reference spreadsheet to see the kind of data that students will get from this investigation: https://docs.google.com/spreadsheets/d/1ZM2CXwmMM1Ehmt_2L2ftqZvYifZY9FIy71daRdsti8c/copy.

Prepare chart paper for the posters you will make in this lesson:

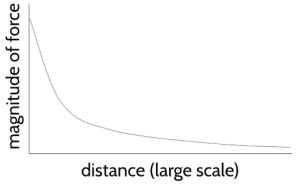
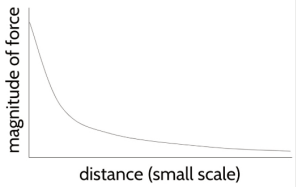
1. Gravity-Magnetism Comparison (You will reuse this poster across classes. Prepare enough blank half sheets of paper to add in each of the cells of the first three rows of this poster for all classes. Tape these half sheets to each cell in the first three rows of the table during class discussion to capture students' ideas at different points in the lesson. This will allow you to remove these annotations between classes and reuse the rows, columns, and cells of the underlying poster for the next class). Draw each of the images below on a separate half sheet of paper. You can also print these images using *Lesson 2 Posters*. You might want to create a poster for each class to avoid adding and removing these half sheets.





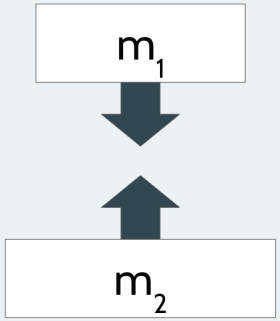
2. Newton's Third Law for Forces at a Distance

Gravity-Magnetism Comparison

	Gravitational	Magnetic
Direction of these forces on other matter (in the space where we are located)	Towards the center of Earth	Earth's magnetic north
Type(s) of matter it acts on	All matter	Magnets and some metals
What produces it?	All matter	Some magnets, changing electric fields, Earth's mantle
Magnitude of force vs. distance from Earth		

Newton's Third Law for Forces at a Distance

When two pieces of matter (m_1 and m_2) interact through a field force like gravity, magnetism, or electricity, the forces between them are equal in magnitude and opposite in direction.



Posters developed in this lesson

See *Lesson 2 Posters* to see the posters developed in this lesson.

Make sure the Initial Consensus Model: Motion of Space Objects poster created in Lesson 1 is placed on a visible area of the classroom, as you will use it to support the navigation into this lesson.

Day 2

Magnetic Force vs. Distance Investigation

- **Group size:** 5 students per group
- **Setup:** Prepare 6 lab stations as outlined in *Magnet Investigation Stations*. If you have small classes, you will only need to prepare stations 1A, 2A, and 3A.
- **Notes for during the lab:** Avoid additional weight or force on the digital scales beyond those provided in the lab. They can be damaged if the weight placed on them exceeds their maximum range of 500 g.
- **Disposal:** Materials are all reusable and do not need to be thrown away.
- **Storage:** All materials can be stored and reused for next year or for other investigations. The digital scales may not automatically shut off, so make sure to power them down at the end of the class.

Lesson 2 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently engage students in the following elements of this science and engineering practice:

- **Using Mathematics and Computational Thinking**

5.2: Use mathematical, ~~computational, and/or algorithmic~~ representations of phenomena ~~or design solutions to describe and/or~~ support ~~claims and/or~~ explanations.
5.3: Apply techniques of algebra and functions to represent and solve scientific and engineering problems.
5.4: Use simple limit cases to test mathematical expressions, ~~computer programs, algorithms, or simulations of a process or system~~ to see if a model "makes sense" by comparing the outcomes with what is known about the real world.
This lesson is designed to coherently engage students in the following crosscutting concepts (CCC):

- **Patterns:** Mathematical representations are needed to identify some patterns.
- **Scale Proportion and Quantity:** Algebraic thinking is used to examine scientific data and predict the effect of a change in one variable on another (e.g., linear growth vs. exponential growth).

Throughout the first lesson set of this unit, students will use mathematical representations and algebraic thinking to explore the relationship between different variables. In this lesson, students will explore the relationship between the magnitude of distance forces and distance. Students will see nonlinear relationships in the data they collect in this lesson related to magnetic and gravitational forces and distance. The trends they will see may remind them of their prior work in *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*, where they developed an equation that showed that *y* values approach zero, but never reach it, as *x* values increase. In Lesson 3, they will continue using algebraic thinking to examine the exponential relationship between the distance of a planet from the Sun and its period of revolution. In Lesson 5, students will use mathematical representations to make sense of energy transfer between the gravitational field and the object and prove that energy is conserved in a closed Sun-asteroid system. They create a mathematical model to show how energy flows as the asteroid experiences orbital motion.

While the next lesson will have students using algebraic equations and expressions as well, this is the only lesson where they will use mathematical thinking in the context of Newton's law of universal gravitation before the mid-unit transfer task in Lesson 7. To provide additional practice, students will calculate the force between Earth and some of the space objects they explored in Lesson 1. This lesson also provides the only opportunity to reason about the magnitude of gravitational force when the distance between two masses approaches infinity. An exit ticket at the end of this lesson was designed to gather additional evidence about students' grasp of Newton's law of universal gravitation.

Students develop and use different additional ideas related to scale, proportion, and quantity in this lesson that will continue to build in the next lesson set. They work as a class to describe similarities and differences between magnetic and gravitational forces and describe the relative differences in magnitude of these forces and the scale over which they tend to influence the behavior of matter. And they explore why some mathematical relations that might appear linear at a smaller scale (gravitational force versus height) are actually nonlinear when you study them at larger scales. This lesson revisits these elements of this CCC:

- *The significance of a phenomenon is dependent on the scale, ~~proportion, and quantity~~ at which it occurs.*
- *Patterns observable at one scale may not be observable ~~or exist~~ at other scales.*

In Lessons 8 and 9, students will focus on the proportion and quantity at which a phenomenon (meteors entering the atmosphere) occurs.
Students develop these pieces of the DCIs in this lesson:

- PS2.B.1 Newton's law of universal gravitation a~~nd Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic~~ forces between distant objects.
- PS2.B.2 Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space ~~that can transfer energy through space. Magnets or electrical currents cause magnetic fields; electrical charges or changing magnetic fields cause electrical fields.~~

This lesson emphasizes the generality of Newton's law of universal gravitation for distance forces. Though it is a middle school DCI, it is also one that students may not have collected direct evidence for in the context of distance forces. And it is one that can be very counterintuitive in the context of gravity. In Lesson 6, students will apply ideas from Newton's universal law of gravitation throughout to explain the change in orbit of the Chelyabinsk meteor.

Students will encounter or co-develop definitions for the following words in this lesson: *gravitational field, magnetic field.* They also develop Newton's law of universal gravitation. **Do not** post any words or ask students to add them to their personal glossary until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

In this lesson, we are not exploring how gravitational fields can transfer energy through space because it is likely not a question that students asked during Lesson 1. We will delve into this concept in Lesson 5, driven by the need to understand the changes in motion of space objects in orbit for making more-accurate predictions about potential space collisions.

LEARNING PLAN for LESSON 2

1 · NAVIGATE

3 min

MATERIALS: Initial Consensus Model: Motion of Space Objects poster (created in Lesson 1), 1-N spring scale

Navigate. Present **slide A**. Say, *Last time we figured out that some space objects can fall from the sky while others remain in space*. Then ask students to turn and talk about the prompts on the slide.

After about one minute, bring students together to discuss the prompts as a whole class.

Suggested prompt	Sample student response
Is the force of gravity acting differently on these objects? If so, how?	Gravity might be stronger on some of the objects that hit Earth. Larger objects experience a larger force of gravity.
What is different about these objects that might help us understand the difference in their motion due to gravity?	Some objects are very far away. Gravity might be weaker on them.

If students don't mention the role of distance, point to the Initial Consensus Model: Motion of Space Objects poster you built in the first lesson and suggest that we also considered that gravity was acting differently on objects closer to Earth than those farther away. You can ask, *Would the force of gravity change as we move farther away from Earth's surface?* Accept all responses.

Motivate taking force measurements. Say, *It seems we think that the distance from Earth's surface and the amount of mass of objects affect how gravity acts on them*. Suggest that we take some measurements of objects at various heights to be able to say more about this relationship. Show students the spring scale and remind them that it can be used to measure the force on an object.

2 · CONSIDER HOW DISTANCE AFFECTS FORCE OF GRAVITY

12 min

MATERIALS: *Predicting Force Relationships*, 20-g impactor, 40-g impactor, 1-N spring scale, 3x3 sticky notes in 2 colors

Take force measurements. Present **slide B**. Start with the 20-grams impactor you will use, mentioning it will represent a space object. Ask for two student volunteers. Have one hold the spring scale 0.5 m above the ground and hang the 20-g impactor. Have the other student report the force of gravity acting on it. Record this on the board in a two-column table (Distance above Earth's surface, Force of gravity on a 20-g object/on a 40-g object). Have them repeat the measurement while holding the spring scale at approximately 2 meters above the ground. Add these values as a second row in the table. Suggest we use an object with a larger mass since it is a property we know is affected by gravity. Do this measuring and recording process again for the 40-g impactor.

ADDITIONAL GUIDANCE

Scientists use the term *impactor* to refer to an object, such as a comet or asteroid, that collides with a planet, moon, or other space object. Throughout the unit, we will refer to these 20-g and 40-g capsules as *impactors*. However, it is not necessary to establish this term as a class. We will define the term *impactor* in Lesson 10.

Make predictions about larger distances with an elbow partner. Ask students to turn and talk with the prompt: *How would the force reading compare if we took another measurement many kilometers above Earth's surface?* Cue students to take one minute to discuss their predictions with an elbow partner. Then share responses. Accept all predictions.

Add a "?" for the force value for each column in this new row.

Distance above Earth's surface	Force of gravity (in N)	
	on a 20-g object	on a 40-g object
0.5 m (0.0005 km)	~0.20	~0.40
2.0 m (0.0020 km)	~0.20	~0.40
Many km	?	?

Plot the data collected on gravitational force. Present **slide C**. Distribute *Predicting Force Relationships*. Say, *Let's set up a graph together, and then you can use it to make predictions about these different forces. Let's plot the data we collected together on the first graph at the top of your handout.*

Make sense of the *x*-axis by asking, *Where is Earth's surface located in this graph?*
Look for students to suggest that it is located at the left end of the *x*-axis, the 0.

Complete the key on the slide by placing two sticky notes over the boxes on the screen to indicate which color will represent which mass object. Then place a sticky note in each of the locations corresponding to the data you collected, using the correct sticky note colors as indicated in the key. The sticky note for each mass will be basically on the *y*-axis because the data are so close to zero at this scale. One will be at (~0,0.2) and the other will be at (~0,0.4). Emphasize that since the *x*-axis scale is in kilometers, this scale makes it hard to plot the *x* values so we could distinguish any difference between a point at 0.0005 kilometers and a point at 0.0020 kilometers, but if the class would prefer, you can add a second sticky note on top of each of the first ones.

Add to the graph. Present **slide D**. Cue students to add the data points for both masses to the first graph on their handout and then draw a solid line for the change in gravity over distance for one mass and a dotted line for the change in gravity over distance for the other mass to show their predictions for how the gravitational forces on these two objects would compare for the distances from Earth's surface shown on the graph. Give students a minute to do this.

Compare results. Display **slide E**. Give students two minutes to turn and talk with the prompts:

- *Share something that was similar and/or different across the two lines you drew.*
- *Based on your predictions, how does the distance (r) between the object and the surface of the planet affect the strength of the gravitational force (F_g) on it?*

Invite students to share some of their predictions. Draw some of the predictions students made on the whiteboard. Elicit as many predictions as possible with these prompts:

- *Who has a different prediction?*
- *Who made a similar prediction?*

If students suggest drawing a line with a negative slope that intersects the *x*-axis at some point, say, *This plot suggests that if we move an object far enough from Earth, the gravity that Earth exerts on this object will become zero. Does everyone agree?* It is not important at this point whether most of the class agrees with that prediction.

Write a question on the board that reads: **How does the distance (r) between the object and the surface of the planet affect the strength of the gravitational force (F_g) on the object?**

Gather students' ideas about forces between two objects. Present **slide F**. Remind students that we learned in the *Vehicle Collisions Unit* that whenever two objects interact, there are forces acting on *both* objects. Then make a poll about the following question:

Do you think an object at some distance from Earth's surface will

A. *exert no gravitational force on Earth?*
B. *exert an equal gravitational force on Earth as Earth exerts on the object?*
C. *exert a lower gravitational force on Earth than Earth exerts on the object?*

Accept all answers. Suggest we investigate first the magnitude of the force of gravity experienced by two objects. Write a second question on the board that reads: **How does the force of gravity from Earth to a space object compare to the force of gravity from the space object to Earth?**

Use scale thinking. Present **slide G**. Consider the limitations of our current setup to investigate the role of distance on gravity with the first prompt:

- *Why might it be challenging to study the effect of distance on gravity at the scale we are investigating in the classroom?*

Look for students to say that we would need to go really high above the surface of Earth, which is very difficult and even dangerous.

Compare Earth's magnetic field and gravitational field. Say, *It sounds like the logistics of investigating gravity will be tricky because the scale we believe we need to investigate this question is too large. Let's consider another noncontact force that can help us explore this question on a smaller scale.*

- *What other forces do we know about that act at a distance like gravity, without the two objects having to touch?*

Look for students to suggest electricity and/or magnetism. If they do not, ask, *Have any of you ever tried holding a magnet near another magnet? It acts at a distance, right, without the magnets having to touch.*

Then ask, *How is magnetism different from gravity*? Accept all ideas here but look for students to suggest that magnetism is stronger than gravity and that magnetic forces can push in addition to pull. Then say, *It sounds like we think magnetism is not the same as gravity at all, but it might be just similar enough that we can draw some conclusions about these types of forces that act at a distance. And it's definitely easier to study in the classroom.*

3 · COMPARE NONCONTACT FORCES: GRAVITY AND MAGNETISM

10 min

MATERIALS: *Predicting Force Relationships*, compass, Gravity-Magnetism Comparison poster, half sheets of paper, chart paper markers, transparent tape

Document similarities and differences between these two types of fields. Present **slide H**. Display the Gravity-Magnetism Comparison poster. Tape a blank half sheet of paper to each cell in the first three rows of the table on the Gravity-Magnetism Comparison poster to capture what the class agrees upon. Complete the cells in the 3 rows during this discussion.

Organize students into pairs. Distribute a compass to each pair of students and ask the second prompt: *In what direction are the forces from Earth's magnetic field acting in our room?*

Ask students which direction the red end (N) of the magnetic needle is pointing. Students should point to the north. Then ask how this compares to gravity. Students should say that gravity points downwards. Elicit 1-2 ideas with the next prompt: *What type of matter does each force act on?* Look for students to say that magnetism acts on some metals and magnets, while gravity acts on all matter.

Continue this discussion with the prompt:

- *What produces each force?*

Look for students to say that all matter produces gravity due to its mass, while magnets, changing electric fields, and Earth's mantle generate magnetic fields.

If you used these prompts, this is how the poster would look like at this point:

Gravity-Magnetism Comparison

	Gravitational	Magnetic
Direction of these forces on other matter (in the space where we are located)	Towards the center of the Earth	Earth's magnetic north
Type(s) of matter it acts on	All matter	Magnets and some metals
What produces it?	All matter	Some magnets, changing electric fields, Earth's mantle

Consider magnetic force versus distance. Present **slide I**. Say, *We are using magnets because we are more familiar with how the distance between them can affect how they interact.* Ask students to turn and talk with the prompt: *How does distance affect the magnitude of the magnetic field experienced by two magnets?*

After one minute, ask for volunteers to share their ideas with the class. Look for students to suggest that when magnets are close, the force is very strong, but as the distance increases, the force decreases rapidly.

Add to graph. Present **slide J**. Ask students to use the second graph of the *Predicting Force Relationships* handout to make a prediction about how the magnitude of the magnetic force on one magnet changes over distance between two magnets. Give them a minute to sketch their prediction on their graph.

Compare results. Display **slide K**. Give students two minutes to turn and talk with the prompts:

- *Share something that was similar and/or different between your graphs.*
- *How do your magnetic force versus distance predictions compare with the gravity versus distance predictions?*

Invite students to share some of their answers to the second prompt. Accept all answers.

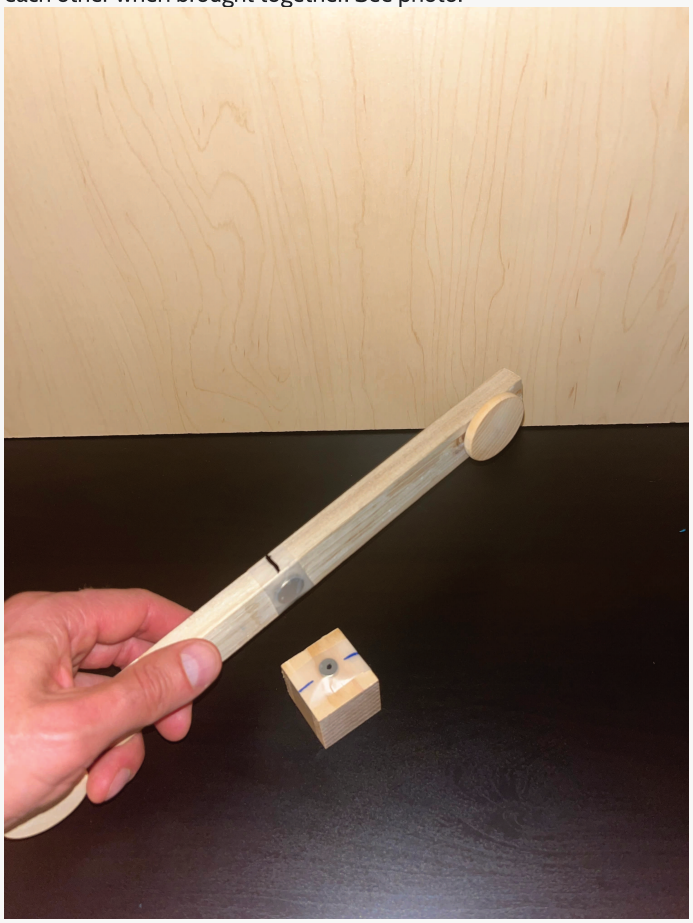
Motivate collecting some data. Say, *We are interested in investigating how gravity affects space objects, but we know we cannot study it directly because the scale required for that is too large. Instead, we will use magnets to collect data on a smaller scale—the scale of our classroom—and compare it to data collected by others for gravitational forces at a larger scale, where we are unable to collect the data ourselves.*\

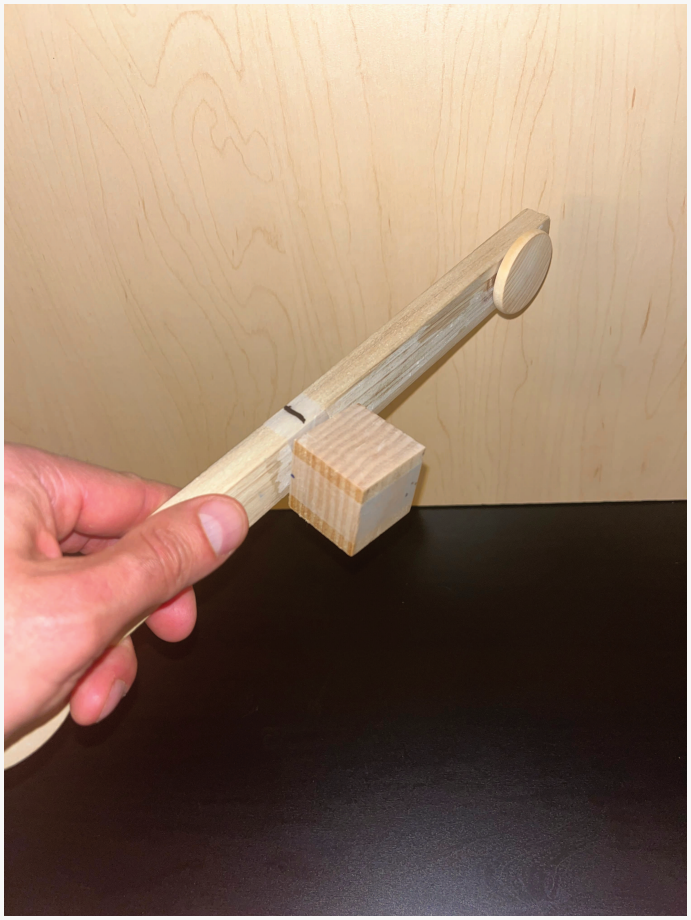
4 · INVESTIGATE THE MAGNITUDE OF MAGNETIC FORCE ACTING ON TWO MAGNETS

17 min

MATERIALS: Newton's Third Law for Forces at a Distance poster, Gravity-Magnetism Comparison poster, 3x3 sticky notes, chart paper markers, https://youtu.be/fBvELBBHH_4, fine point permanent marker

Orient to equipment students will use. Display **slide L**.
Explain that there is a large magnet glued to a wood beam and a small magnet glued to a wood cube. Then mention that the magnets stick to each other when brought together. See photo.





Remind students that we have two questions we want to investigate:

1. the role of distance on noncontact forces
2. the magnitude of the force experienced by each object

Make sense of the magnets with the prompt:

- *What do the large and small magnets represent in the Earth-meteor system we are trying to understand?*

Look for students to suggest that the large magnet represents Earth while the small magnet represents a meteor.

Make predictions. Say, *Let's say we could hold the large and small magnets at a fixed distance from each other so that we could detect a pull on at least one of them. Then let's make some predictions about how the attractive forces in the system would compare at that distance.* Display **slide M**. Give students half a minute to read through the four possible options. Then take a poll on these options:

A. *Only one of these magnets will experience a force.*
B. *The force acting on the larger magnet will be stronger than that acting on the smaller magnet.*
C. *The force acting on the larger magnet will be weaker than that acting on the smaller magnet.*
D. *Both magnets will experience equally strong forces.*

Analyze the results of a demonstration using a video. Say, *Let's orient to a setup that will allow us to take measurements of any additional forces in the system due to magnetic interactions while also removing the effect of the gravitational forces on the matter.*

ALTERNATE ACTIVITY

While the directions for doing this demonstration using a video are outlined here, if you have more time you could do a live version of it. Alternate directions for that are included in *Alternate Live Demonstration*. You will need the following materials for this demonstration:

- Base magnet cube with small magnet (see *Magnet Investigation Stations*)
- Magnet beam with large magnet (see *Magnet Investigation Stations*)
- 2 beam stands (see *Magnet Investigation Stations*)
- 3 digital scales
- 3 x 3 sticky notes
- Fine point permanent marker

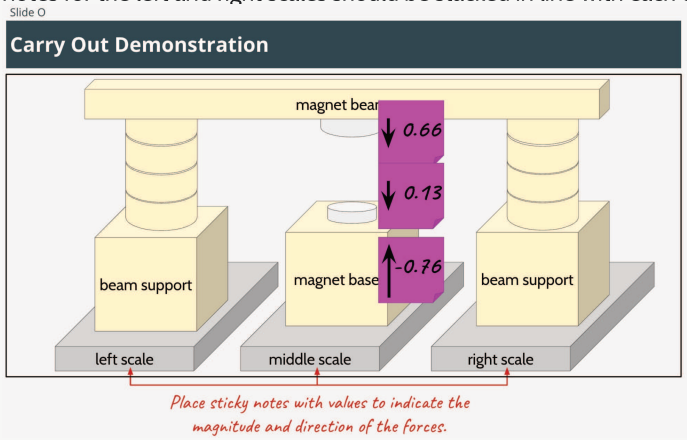
Present **slide N**. Play https://youtu.be/fBvELBBHH_4 and pause it at these time points to discuss these questions as a class:

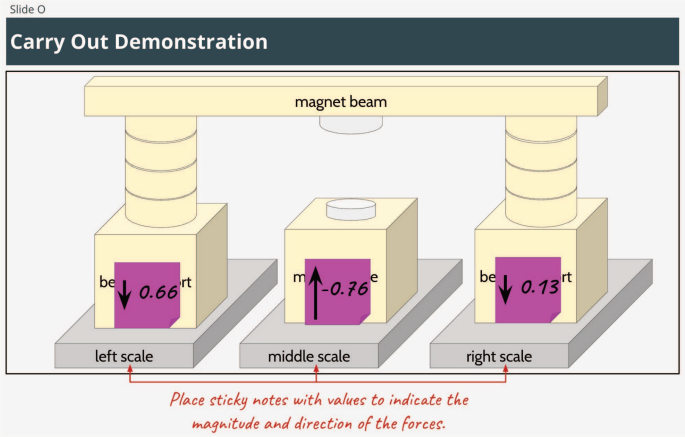
Pause at 0:14	**Prompt:** *How can we get the scales to register zero force from gravity?* Look for students to say that you can tare the scale. Establish that tarring the scale takes away the value the scale would register from any weight on it, so it in effect removes the contribution of the force of gravity on any masses on the scale when you tare it. Then continue the video.
Pause at 0:40	**Prompt:** *What will the scales report if the large magnet holder is resting on two scales instead of one?* Look for students to say that the readings of both scales together should add up to the reading of the single scale
Pause at 2:32	Compare the values recorded on the 3 sticky notes. **Prompt:** *What do you notice about the magnitude of the three force values?* Look for students to say that the sum of the two magnitudes from the left and right scales is (approximately) equal to and opposite the magnitude registered on the middle scale.

Suggest that we develop a diagrammatic representation of these forces in the system to try to make sense of what part of the system they are acting on.

Add data to a system diagram. Display **slide O**. Use three sticky notes to record the force values reported on each scale in the video. Place the sticky notes of the measures from the scales on top of the projected image of the slide at the corresponding scale locations where each value was registered. Remind students that the force of gravity was zeroed out of each part of this system. Ask students what the forces being registered on each scale are from. Students will say from the magnets.

Move the sticky notes. Relocate the sticky notes on the projection of **slide O** to show which magnet they each correspond to. The two sticky notes for the left and right scales should be stacked in line with each other.





ALTERNATE ACTIVITY

If students have experience performing operations on vectors in their math class, you could make a connection to that in what you did just now. You can say that you added the vectors together from force measures on the two scales on the left and right, end-to-end, which helps us recall that the magnitude of a sum of two vectors is the sum of the magnitudes, but only when they are in the same direction.

Make sense of results. Present **slide P**. Use the first two prompts to explore the meaning of the results:

- *What can we say about the magnitude of the forces acting on the two magnets?*
- *What question(s) do these results help answer?*

Listen for the following ideas:

- The forces acting on both magnets are equal in magnitude.
- This helps us answer the question about how the forces acting on two magnets compare.

Connect to experiences with Newton's third law in a prior unit. Say, *These values provide us evidence that the downward forces on the top magnet must be equal in magnitude and opposite in direction as the upward forces on the bottom magnet. This is happening here where we have magnets of different masses.*

Use the last prompt to elicit 1-2 student ideas:

- *What are some other examples where we have seen two objects interacting and producing **equal and opposite forces** on each other?*

Students should remember that we saw this in every collison we studied in our *Vehicle Collisions Unit* too.

Say, *It may be surprising to see evidence of that same relationship here again when the forces are noncontact forces. Let's keep track of this idea.*

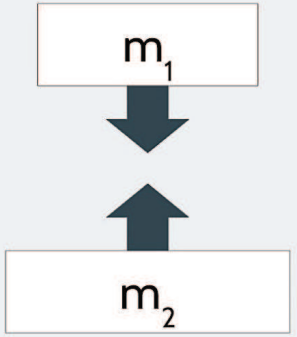
Post this relationship. Add the Newton's Third Law for Forces at a Distance poster next to the Gravity-Magnetism Comparison poster. Emphasize that this relationship is sometimes referred to as Newton's third law and is something that holds for any force interaction between 2 pieces of matter (m_1 and m_2) that is the result of a field that is produced between them (gravity, magnetism, electric).

Gravity-Magnetism Comparison

	Gravitational	Magnetic
Direction of these forces on other matter (in the space where we are located)	Towards the center of Earth	Earth's magnetic north
Type(s) of matter it acts on	All matter	Magnets and some metals
What produces it?	All matter	Some magnets, changing electric fields, Earth's mantle
Magnitude of force vs. distance from Earth		

Newton's Third Law for Forces at a Distance

When two pieces of matter (m_1 and m_2) interact through a field force like gravity, magnetism, or electricity, the forces between them are equal in magnitude and opposite in direction.



ADDITIONAL GUIDANCE

While Newton's third law is a middle school DCI, it is also one that students may not have collected direct evidence for in the context of distance forces. And it is one that can be very counterintuitive in the context of gravity (e.g., do objects falling to Earth really pull on Earth?). Reemphasizing the generality of this relationship here can help prime students to apply this to all gravitational interactions by the end of the lesson.

ALTERNATE ACTIVITY

Extension Opportunity: This is the first reference to electric fields in the lesson. In subsequent activities, some additional brief references are made to these forces, but they are not treated as something that Earth produces that would affect its interactions with space objects. If, however, some students raise this possibility or are wondering, you could provide them this article to explore further outside of class. The article explores these possible force interactions between Earth's ionosphere and meteors: Svetsov, V. V. (2002). Petrophysics hints at unexplored impact physics. In *Geological and Biological Effects of Impact Events* (pp. 265-295). Berlin, Heidelberg: Springer Berlin Heidelberg.

5 · NAVIGATE

3 min

MATERIALS: piece of 8.5" x 11' paper

Provide materials for an Exit ticket. Display **slide Q**. Distribute a piece of paper to every student. Ask them to answer the prompt on the slide:
How many scales do we need to investigate the role of distance on the magnitude of the magnetic force acting on both magnets?

A. *one scale*
B. *two scales*
C. *three scales*

Use the results from the video to support your answer.

Remind students to put their name on their paper. Collect these exit tickets before students leave the classroom.

ADDITIONAL GUIDANCE

This exit ticket is intended to help you gather evidence about students' ideas about the relationship described in Newton's third law. Based on the results from the video, students should infer that it is not necessary to measure the force acting on both magnets, since the force is equal. Therefore, look for students to suggest that we need one scale (most efficient) or two scales.
You will use this question the next time, so you can discuss each answer option with the class.
Consider returning these exit tickets the next day to give students a chance to reflect back on their answers.

End of day 1

6 · NAVIGATE

2 min

MATERIALS: None

Remind the class where we left off. Present **slide R**. Use the slide prompts to remind students of some of the main ideas developed last time:

- *What did we figure out last time about the magnitude of the magnetic field acting on the magnets in our setup?*
- *What other type of force were we trying to make sense of?*

Look for the following ideas:

- We figured out that the magnitude of the magnetic field acting on the magnets is the same.
- We were trying to make sense of the force of gravity.

Consider experimental setup. Present **slide S**. Say, *Last time we completed an exit ticket about the number of scales we would need to gather data to investigate the role of distance on the magnitude of the magnetic force acting on both magnets.*

Go through each possibility, as this will ensure that every student understands the connection between Newton's third law and the need of just one scale.

Some students might suggest that we need the three scales because that is what was done during the demonstration to measure the forces acting on the magnets. Ask these students:

- *How did the forces acting on both magnets compare?*
- *If the forces are equal, would we know the force acting on the upper magnet if we measure only the force acting on the lower magnet?*

If some students suggest we need two scales to measure the force on the upper magnet, ask them:

- *Could we get the same data if we measure the force acting on the lower magnet?*

Say, *Let's investigate the role of distance of the magnitude of the magnetic force acting on the magnets.*

7 · CARRY OUT AN INVESTIGATION

15 min

MATERIALS: Magnetic Force vs. Distance Investigation, science notebook, This Class Period's Magnetic Force Data spreadsheet

Orient to the investigation procedures. Display **slide T**. Distribute *Magnet Investigation Procedure*. Give students about a minute and a half to individually read the procedure and then ask if students have any questions about it.

Orient to the spreadsheet. Open the related *This Class Period's Magnetic Force Data* spreadsheet, orienting students to the tabs at the bottom that correspond to the groups that will be assigned. Use any tab to show how entering a value into the second column automatically calculates the force in newtons in the third column while also automatically updating that point on the graph. Delete the values in the second column you just entered.

Assign groups. Organize the class into small groups of 4-5 students and provide them a computer. Ensure that at least one group is assigned to each of the three conditions (1A, 2A, 3A). Use the group letter and number combinations shown below to name each group. Ask students to record in their science notebook their assigned pair of magnets, on which to collect force vs. distance data. Direct groups to use the spreadsheet tab that corresponds to their group name. You don't need to assign groups 1B, 1C, 2B, 2C, 3B and/or 3C if you have a smaller class.

- Group 1A: Large magnet below and large magnet above
- Group 2A: Large magnet below and small magnet above
- Group 3A: Small magnet below and large magnet above
- Group 1B: Large magnet below and large magnet above (optional)
- Group 2B: Large magnet below and small magnet above (optional)
- Group 3B: Small magnet below and large magnet above (optional)
- Group 1C: Large magnet below and large magnet above (optional)
- Group 2C: Large magnet below and small magnet above (optional)
- Group 3C: Small magnet below and large magnet above (optional)

Carry out the investigation. Display **slide U**. Share the URL for the copy of *This Class Period's Magnetic Force Data* spreadsheet you created. Instruct students to use one of the investigation stations you created, and have them carry out their assigned investigation condition. Rotate around the room and assist as needed.

ADDITIONAL GUIDANCE

It is OK if after 8 minutes students have finished collecting only a portion of their data. Collecting even half of the data will provide sufficient evidence to identify the nonlinear structure to the pattern in force versus distance.

8 · ANALYZE AND INTERPRET DATA

14 min

MATERIALS: science notebook, This Class Period's Magnetic Force Data spreadsheet, Newton's Third Law for Forces at a Distance poster

Analyze and interpret graphs. Display **slide V**. Give students a few minutes to consider the slide prompts and record their ideas in their science notebook:

Look through other groups' graphs in the last tab of the spreadsheet.

- *What patterns do these graphs help us identify?*✱
- *What happens to the force if we double the distance?*
- *Does the position of the magnets have an effect on the magnitude of the forces acting on them?*

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING PATTERNS

This prompt is another instance of using the following crosscutting concept: Mathematical representations are needed to identify some

Record your ideas in your science notebook.

Facilitate a Building Understandings Discussion. Project *This Class Period's Magnetic Force Data* spreadsheet for students to reference as you discuss the patterns in the data and the slide prompts.

KEY IDEAS

Purpose: The prompts on the slide are intended to support a Building Understandings Discussion to (1) establish the inverse square relationship between the magnitude of the magnetic force and distance and (2) use evidence to support Newton's third law of motion.

Key ideas

- The pattern follows an inverse square relationship.
- If you double the distance, the magnetic force between them decreases by a factor of four.
- The positions of the magnets do not have an effect on the magnitude of the forces acting on them, as the results from groups 2A/B/C and 3A/B/C look similar.

As you discuss the last prompt, use the Newton's Third Law for Forces at a Distance poster. Note that you could flip the diagram upside down and the diagram would still predict what we are seeing in our results, that the frame of reference for which magnet was where didn't affect the forces that were produced on both.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment

- Use the graphs from the investigation results to describe the overall pattern in the changes of the magnetic force's magnitude acting on two magnets due to increases in the distance between them. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1)
- Describe how, when the distance is doubled, the magnetic force decreases by more than half, indicating that this pattern does not follow a linear inverse relationship. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1)
- Use the results from investigations 2A and 3A to conclude that the positions of the magnets do not influence the magnitudes of the forces acting on them. (SEP: 5.2, 5.4; DCI: PS2.B.1)

What to do: If students are struggling to explain whether the positions of the magnets have an effect on the magnitude of the forces acting on the magnets, ask them to compare the results from groups 2A/2B/2C and 3A/3B/3C. Remind them that group(s) 2A/2B/2C investigated the changes in the forces by using a large magnet at the bottom and a small magnet at the top, while group(s) 3A/3B/3C used the large magnet at the top and the small magnet at the bottom.

Building toward: 2.A.1 Use simple limit cases and mathematical representations to describe patterns in the change of magnitudes of magnetic and gravitational forces on two objects caused by changes in their distances from each other. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1, PS2.B.2)

Reference the crosscutting concept of scale. Present **slide W**. Use the slide prompt to consider the influence of scale:

- *Do we think the pattern between magnetism and distance at this scale is similar to that of gravity at a larger scale? If so, how would the force of gravity vs. distance graph look?* ✱

Accept all answers.

patterns. It reinforces the notion that although we initially had an idea about how distance affected the magnitude of the magnetic force experienced by two magnets, plotting our results on a graph enabled us to discern a more-nuanced relationship that does not follow a linear pattern. This suggests that while increasing the distance between two magnets results in a decrease in the magnetic field, this force does not seem to reach zero, regardless of how far apart these magnets are.

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING PATTERNS

The image used on the slide represents the same Scale Chart used in *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*. This is a tool to help students consider the scales at which different phenomena occur and to see how patterns of data at one scale compare and relate to phenomena at other scales.

9 · ANALYZE GRAPHS AND MAKE PREDICTIONS

14 min

MATERIALS: *Comparing Gravitational Forces*, Newton's Third Law for Forces at a Distance poster

Describe the data. Say, *In recent decades, NASA has launched spacecraft equipped with gravitometers. These have allowed them to map Earth's gravitational field far above Earth as well as above the Moon. The data on the next slide are derived from mathematical relationships that scientists had discovered even before they had those data, but they were further validated by the data they have since collected.*

ADDITIONAL GUIDANCE

The missions that are referred to here are GRACE (for Earth) and EBB and FLOW (for the Moon). The gravity data students are analyzing in subsequent slides and handouts are derived from the universal law of gravitation, though, rather than directly from the data collected on these missions. This distinction is for teacher background knowledge only, as we want students to discover many of the variables and relationships that make up the universal law of gravitation, from the data they are about to analyze, before telling them that such a law has already been derived.

Analyze a gravitational force versus distance graph together as class. Display **slide X**. Discuss for a couple of minutes the patterns students notice in this graph.

Look for the the following ideas:

- The force gets close to zero but does not reach zero.
- It is nonlinear.
- It has a similar shape as the magnetic force versus distance graph.

Make predictions. Display **slide Y**. Give students three minutes to discuss the questions on the slide with a partner:

- *How would the graph for a 3-times-larger mass (60 g) compare?*
- *How would a graph of the force of gravity on either object (20 g or 60 g) compare if we measured it as we moved it away from the center of the Moon?*

Encourage students to use ideas from the Newton's Third Law for Forces at a Distance poster. Don't take time to share these predictions as a whole class.

ADDITIONAL GUIDANCE

The x-axis of the graph displayed in **slide X**, and *Comparing Gravitational Forces*, uses the distance from the center of Earth, not the distance from Earth's surface. Tell students that when scientists talk about the distance between two space objects, they often use the concept of the center of mass because it provides a reference point that simplifies calculations and helps to understand the dynamics of the system.
The distance from the center of mass of two objects will be used for the remainder of the lesson.



Analyze gravitational force versus distance graphs for different masses. Distribute *Comparing Gravitational Forces*. Display **slide Z**. Instruct students to follow the directions on the slide:

- *Annotate any patterns you notice in the data.*
- *Answer the following question in your handout:*
    - *Based on the patterns you noticed in the data, does the force of gravity on an object become zero when its distance from Earth's surface is sufficiently large?*

Give students about 5 minutes for this. Collect *Comparing Gravitational Forces* at the end of the period.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- The *y* value decreases and approaches zero but does not reach zero as the *x* value increases. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.2)
- There is a relationship (directly proportional) between the mass of an object and the strength of the gravitational forces on it (e.g., three times as much mass produced three times as much force whether it was measured on or above Earth or the Moon). (CCC: 1.4; DCI: PS2.B.1)
- Earth produces larger gravitational forces than does the Moon. (SEP: 5.2; DCI: PS2.B.1)

What to do: If students' annotations are underdeveloped, ask them to reannotate in a new color to identify any quantitative relationships in the graphs that are predicted by the universal law of gravitation on *Calculating Gravitational Forces*. Ask them to return these annotated handouts at the end of day 3.

Building toward: 2.A.2 Use simple limit cases and mathematical representations to describe patterns in the change of magnitudes of magnetic and gravitational forces on two objects caused by changes in their distances from each other. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1, PS2.B.2)

End of day 2

10 · NAVIGATE

6 min

MATERIALS: *Comparing Gravitational Forces*, Newton's Third Law for Forces at a Distance poster

Review annotated graphs from last time. Present **slide AA**. Return each student's *Comparing Gravitational Forces* handout. Ask them to compare their annotated graphs with a partner and discuss the prompt:

- *How does the distance (r) between an object and the center of the planet or the Moon affect the strength of the gravitational force (F_g) on it?*

After a minute or two, invite students to share their ideas. Listen for the following idea:

- Greater distance from its center of mass results in smaller-magnitude forces.

Present **slide BB** and continue the discussion about the relationship between mass, distance, and gravity:

- *How does the mass of the object (m_1) affect this force (F_g)?*
- *How does the mass of the planet or Moon (m_2) affect this force (F_g)?*

Listen for the following ideas:

- More mass results in stronger forces on it.
- Three times as much mass produced three times as much force whether it was measured on or above Earth or the Moon.
- Less mass produces weaker forces.
- More mass produces stronger forces.

Connect to Newton's third law. Reference the relationship shown on the Newton's Third Law for Forces at a Distance poster. Say, *The same relationship we discovered for magnets holds true for gravity. The gravitational field produced between the planet or the Moon and the object above it pulls both on the object and on the Moon or planet with an equal magnitude of force on each. Let's compare how scientists describe this relationship mathematically using these variables we identified.*

11 · USE MATHEMATICAL THINKING

18 min

MATERIALS: *Calculating Gravitational Forces*, calculator

Orient to an equation-based mathematical model of our system. Display **slide CC**. Distribute *Calculating Gravitational Forces* to every student. Read the text on the slide:

- *This equation is one that scientists have developed to predict the relationships we identified. It is referred to as the universal law of gravitation.*

Have students find this equation on their handout and annotate it using arrows and labels to identify the variables as you identify them as a class. ✱
This is how a discussion about this mathematical model might play out using the strategy highlighted in the sidebox:

Suggested prompt	Sample student response
Based on our work on the prior slides, what did we say F_g represented?	The force of gravity.
What did we say m_1 represented?	The mass of an object.
What did we say m_2 represented?	The mass of the planet or Moon.
What did we say r represented?	The distance between the planet or Moon and the object.

Emphasize, if needed, that r is the distance between the center of mass for both objects. So for Earth this would be the distance from its center to the center of the other object.

Identify what G represents. Say, *The only symbol we have not identified in the equation is G. Let's look at what that represents now.* Display **slide DD**. Use the slide to emphasize that G is a constant and is used to convert units and we can use any of the constants listed, depending on what units we measure in. Explain that G is sometimes referred to as the "universal gravitational constant". ✱
Make predictions using the equation. Display **slide EE**. Say, *Let's think about what this equation would predict would happen when we change some of these variables by one order of magnitude, which is a factor of ten*.

Give students a minute and a half to discuss with a partner the related predictions on the slide. Then quickly share these with the class.

Suggested prompt	Sample student response
How would ten times as much mass for m_1 affect the gravitational force, F_g, on the masses in the system?	It should be ten times as strong.
How would ten times the separation distance, r, between the masses affect the gravitational force, F_g, on both masses?	It should be 1/100th as strong.
How would doing both of these changes--ten times the mass for m_1 and ten times the distance--and ten times as much mass for m_2 affect the gravitational force?	It should have no effect. It should all cancel out.

✱ SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

This is a general strategy to consider using in the introduction of any new symbolic expression or equation:

1. Describe what we notice in the structure of an expression or an equation.
2. Interpret the parts of it (terms, factors, and coefficients).
3. Map those parts to analogous parts of the real-world system(s) it represents (in a diagrammatic form).
4. Describe the qualitative relationships between any two variables in the equation or expression.

Engaging in these steps can support students in building a stronger mental model of an equation or an expression as being a type of descriptive model for a set of relationships in the real-world before shifting to solving the equation or rearranging its terms. You will see this strategy is used in Lessons 4 and 7 of this unit. It was also used in the last three prior units.

✱ SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

Talk with the math teacher to identify examples to refer to where students documented the steps in solving a simple equation. Or you can refer to the prior work students did with this in the *Vehicle Collisions Unit* to recall how helpful this was for students to identify computational errors in some of that prior work.

Use the universal law of gravitation to make predictions for different conditions. Present **slide FF**. Say, *We started this lesson wondering about how gravity could act differently on different space objects. Let's see if we can use some of our ideas to see if this can help us explain why some objects remain in orbit while others collide with Earth.*

Organize the class into groups of 4 students. Provide each student a calculator. Point out the space objects for the conditions students are calculating and the data to use for their calculations. Assign each member of the group a condition to solve for. The solving task should take about 3 minutes.✱

ADDITIONAL GUIDANCE

The masses of and distances between the space objects and Earth included in this handout are the same masses and distances presented in *Phenomena Cards*. For Vanguard 1 and the Mir Station, the closest and farthest distances from Earth are given, as described in *Phenomena Cards*.

Differentiation opportunity: Since Vanguard 1 and the Mir station require calculating F_g twice, assign these two space objects to students who are proficient at solving equations.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: Documentation of all the steps to using the universal law of gravitation to solve for gravitational force between two objects (SEP: 5.3; CCC: 3.5; DCI: PS2.B.1, PS2.B.2)
This could look like the following:

- writing the universal law of gravitation and the known variables, values, and units for G, m_1, m_2, and r
- substituting the known values into the corresponding location or order for the variables in the general equation
- performing the related calculations using order of operations
- reporting a predicted force value (F) in newtons

See *Key: Calculating Forces* for sample answers.

What to do: If the students don't document all the algebraic steps for this assessment opportunity, remind them that you will be looking for documentation of these steps for their assigned condition on *Calculating Gravitational Forces*. If you feel students need additional practice, assign them the remaining conditions to solve on *Calculating Gravitational Forces*. Collect their work and provide feedback that can help students identify areas of strength and growth on the use of this mathematical model. Both feedback and additional practices will help students prepare for carrying out similar calculations on the mid-unit transfer task.

Building toward: 2.B Apply techniques of algebra to solve for the gravitational force between Earth and another space object using Newton's law of universal gravitation. (SEP: 5.3; CCC: 3.5; DCI: PS2.B.1, PS2.B.2)

Check answers. Display **slide GG**. Have students check their solutions.

This is one of the first opportunities in this unit where students are engaging in this common core standard for math in this unit: *Explain each step in solving a simple equation as following from the equality of numbers asserted at the previous step, starting from the assumption that the original equation has a solution. ~~Construct a viable argument to justify a solution method~~ (CCSS.MATH.CONTENT.HSA-REI.A.1).*

✱ SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

This is one of the first opportunities in this unit where students are engaging in this common core standard for math: *Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas~~; choose and interpret the scale and the origin in graphs and data displays~~ (CCSS.MATH.CONTENT.HS.N-Q.1).*

Attending to units used in the context of the problem and any appropriate constants when using equations or expressions is something that students will need to do in Lessons 3 and 4, are doing here in this lesson, and will need to do again in the transfer task in Lesson 7. You may want to remind your students that this is something they attended closely to in their prior work in the *Polar Ice Unit* and the *Oysters Unit*.

Space object	Mass	Distance from Earth	F_g between Earth and object
International Space Station (in orbit)	$4.45 * 10^5$ kg	409 km	$1.06 * 10^{15}$ N
Vanguard 1 (in orbit)	1.46 kg	Closest: 654 km	$1.36 * 10^9$ N
		Farthest: 3,969 km	$3.68 * 10^7$ N
Mir space station (collided with Earth)	$1.30 * 10^5$ kg	Closest: 296 km	$5.89 * 10^{14}$ N
		Farthest: 421 km	$2.91 * 10^{14}$ N
Skylab (collided with Earth)	$7.5 * 10^4$ kg	435 km	$1.57 * 10^{14}$ N
The mass of Earth is $5.97 * 10^{24}$ kg.			

Connect results to the anchor. Present **slide HH**. Ask students to look at their results as they discuss the slide prompts with their group:

- *Which space object experiences the greatest gravitational pull from Earth?*
- *Which space object experiences the least gravitational pull from Earth?*
- *Do our force calculations help us explain why some objects fall from the sky while others remain in orbit?*

After a couple of minutes, invite them to share. Listen for the following ideas:

- The International Space Station is experiencing the largest force.
- Vanguard 1 experiences the least pull from Earth.
- The results do not really help explain why some space objects remain in orbit while others collide with Earth because the objects that have collided with Earth, Mir and Skylab, are not experiencing the greatest pull from Earth.

12 · DEVELOP A MODEL

8 min

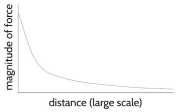
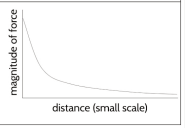
MATERIALS: M-E-F poster, Gravity-Magnetism Comparison poster, transparent tape, sketches of the nonlinear trends for the graphs

Add to the Gravity-Magnetism Comparison poster. Display **slide II**. Say, *Now that we have figured out how the magnitudes of these forces change over distances, let's add sketches of the nonlinear trends of both of these forces as distances get bigger and bigger.*

Add the prepared sketches of the nonlinear trends for the graphs to the corresponding row in the Gravity-Magnetism Comparison poster.

Reference the matter and force leg of the M-E-F poster. Point to the M-E-F poster and the leg between matter and forces that say "Fields generated by matter result in forces.". Say, *We have mainly used a force lens and a matter lens in our work so far. From that, we now know gravity is produced by interactions between all matter and it acts on all matter, and masses and distance are what affects its strength.*

Gravity-Magnetism Comparison

	Gravitational	Magnetic
Direction of these forces on other matter (in the space where we are located)	Towards the center of Earth	Earth's magnetic north
Type(s) of matter it acts on	All matter	Magnets and some metals
What produces it?	All matter	Some magnets, changing electric fields, Earth's mantle
Magnitude of force vs. distance from Earth		

And when we think about those fields extending throughout space, we start to realize that even at really really far distances, those forces get smaller and smaller and approach zero but never reach zero.

13 · NAVIGATE

5 min

MATERIALS: None

Navigate into the next lesson. Present **slide JJ**. Ask, *If we know some amount of gravity extends forever through space, what prevents the Moon and satellites from falling into Earth or Earth from falling into the Sun?*

Accept all answers. Say, *Let's make progress toward answering this question next time.*

14 · ELECTRONIC EXIT TICKET

8 min

MATERIALS: copy of https://docs.google.com/forms/d/1jFVInZdCB4gqYLqNoVqq_S1jMYIgPuauX76VAgkv8Ns/copy, *Calculating Gravitational Forces*, science notebook, calculator

Complete an electronic exit ticket. Display **slide KK**. Give students time to individually complete the exit ticket in the Google Form, copied from https://docs.google.com/forms/d/1jFVInZdCB4gqYLqNoVqq_S1jMYIgPuauX76VAgkv8Ns/copy. Allow them to use their ideas on *Calculating Gravitational Forces*, their science notebook, and a calculator.
Collect *Calculating Gravitational Forces* as students leave the classroom.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: See *Exit Ticket Key*

What to do: See *Exit Ticket Key*

Building toward: 2.A.3 Use simple limit cases and mathematical representations to describe patterns in the change of magnitudes of magnetic and gravitational forces on two objects caused by changes in their distances from each other. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1, PS2.B.2)

Additional Lesson 2 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

Number Quantity

CCSS.MATH.CONTENT.HS.N-Q.1 **Quantities:** Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays.

Students will use the universal law of gravitation equation to calculate the force of gravity acting on objects that have fallen on Earth and objects that remain in orbit. This requires them to choose and interpret units consistently.

CCSS.MATH.CONTENT.HS.N-Q.2 **Quantities:** Define appropriate quantities for the purpose of descriptive modeling.

As students use the universal law of gravitation equation to calculate the force of gravity acting on objects at different distances from Earth, they need to define the units for the constant G.

Algebra

CCSS.MATH.CONTENT.HS.A-SSE.1a **Seeing Structure in Expressions:** Interpret parts of an expression, such as terms, factors, and coefficients.

As students use the universal law of gravitation equation, they need to interpret what the terms mean in a two-object system.

CCSS.MATH.CONTENT.HS.A-REI.2 **Reasoning with Equations and Inequalities:** Solve simple rational and radical equations in one variable, ~~and give examples showing how extraneous solutions may arise.~~

As students use the universal law of gravitation equation to calculate the force of gravity acting on objects that have fallen on Earth and objects that remain in orbit, they will need to solve radical equations in one variable.

LESSON 3: How does gravity cause only some objects to orbit?

PREVIOUS LESSON

We made predictions about the gravitational force experienced by objects at distances from Earth's surface and carried out an investigation of magnetic forces versus distance. We analyzed data on gravitational forces for various objects and distances. We used mathematical models to determine the strength of this force acting on space objects and considered whether this helped explain why some collide with Earth while others remain in orbit.

THIS LESSON

INVESTIGATION

2 days





We use a simulation to figure out the relationship between velocity and force necessary for orbit. We conduct an investigation to explore how the distance between two objects affects this relationship and identify the period of revolution of an object as a lens to predict its orbital motion. We connect the circular motion and universal gravitation equations and identify the relationship between period and orbital radius.

NEXT LESSON

We will look at the orbits of objects that are not planets because planets do not seem to be at risk of colliding with each other. We will explore the elliptical nature of orbits and model orbits of objects that may be at risk of colliding with Earth.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2



WHAT STUDENTS WILL DO

3.A Use different models, including a physical manipulative and a computer simulation, to generate data supporting an explanation for how space objects can remain in stable orbits and how their orbits can change. (SEP: 2.6; CCC: 7.1; DCI: ESS1.B.1)
3.B Use algebraic thinking to examine scientific data generated with a computer model to predict the effect of changes in the radius (a) on the period of revolution of an object in orbit around the Sun. (SEP:2.6; CCC: 3.5; DCI: ESSB.1)

WHAT STUDENTS WILL FIGURE OUT

- Some planets orbit the Sun in nearly circular orbits.
- An object must have the right velocity in order to orbit a star or planet. If it is moving too fast, it will continue into space. If it is moving too slow, it will fall toward the star or planet.
- The relationship between the gravitational force on an object and its velocity depends on the distance from the object it orbits.
- The relationship (T^2/a^3) of orbital period (T) to radius (a) is constant for all objects orbiting the same body.

Lesson 3 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	3 min		**NAVIGATE** Review some of the main ideas about the interactions between two objects in space. Problematize the role of gravity to explain the motion of space objects	A-B	
2	11 min		**USE SIMULATION TO INVESTIGATE HOW VELOCITY AND GRAVITY AFFECT THE MOTION OF SPACE OBJECTS** Introduce students to https://www.openscied.org/simulation/gravity-orbits. Use this simulation as a class to explore the relationship between gravitational force and velocity to make sense of the motion of space objects.	C-E	computer (optional), https://www.openscied.org/simulation/gravity-orbits
3	2 min		**MAKE PREDICTIONS ABOUT CHANGES IN VELOCITY** Have students make predictions about the changes in velocity of an orbiting object due to changes in its distance from the object it orbits.	F	
4	18 min		**USE A PHYSICAL MODEL TO INVESTIGATE THE ROLE OF DISTANCE IN ORBITAL MOTION** Demonstrate the experimental setup. Discuss the variables needed to investigate how distance affects the velocity of an orbiting object. Distribute materials to each group for gathering data on the period of revolution.	G-K	Scissors, Circular motion set up (see *Circular Motion Setup*), Circular Motion Investigation
5	6 min		**DEVELOP AN EXPLANATION ABOUT THE STABILITY AND CHANGE OR ORBITS** Give students enough time to write an explanation about how the relationship between distance, gravitational force, and velocity affects the motion of space objects.	L	*Investigating Circular Motion*
6	5 min		**NAVIGATE** Discuss the information we need about any space object to predict its orbit. Consider how this information can help us predict the potential of space objects to collide with Earth.	M-N	
					End of day 1
7	3 min		**NAVIGATE** Revisit the ideas we ended our last class with.	O	
8	12 min		**MODEL PLANETARY ORBITS** Distribute computers to explore the relationship between the radius of a circular orbit and its period of revolution using the PhET Kepler's Laws simulator.	P	*Kepler's Third Law*, device with access to https://www.openscied.org/simulation/keplers-laws/, headphones (optional), https://www.openscied.org/simulation/keplers-laws/

Part	Duration		Summary	Slide	Materials
9	15 min		**EXAMINE THE MATHEMATICAL RELATIONSHIP BETWEEN THE PERIOD OF REVOLUTION AND THE SIZE OF THE ORBIT** Use a simulation to gather data for the period of revolution, T, and the size of the orbit, a, for planets in our solar system. Derive Kepler's third law by establishing the exponential relationship between variables.	Q-U	*Kepler's Third Law*, device with access to https://www.openscied.org/simulation/keplers-laws/, https://www.openscied.org/simulation/keplers-laws/
10	10 min		**UPDATE PERSONAL GLOSSARIES AND INTRODUCE PROGRESS TRACKER** Introduce the Progress Tracker for the unit and have students set it up and fill it out for the first time. Give students time to update their Personal Glossary.	V-W	*Progress Tracker*, three colored pencils of different colors
11	5 min		**NAVIGATE** Have students complete an exit ticket to reflect on how this lesson connects to the unit question.	X	8.5"x11" copy paper

End of day 2

Lesson 3 • Materials List

	per student	per group	per class
Circular Motion Investigation materials	• *Investigating Circular Motion* • sanitized safety glasses with side shields • calculator	• 10 washers • fishing line • plastic tube • plastic capsule • carabiner • stopwatch • permanent marker.	
Lesson materials	• science notebook • *Investigating Circular Motion* • *Kepler's Third Law* • device with access to https://www.openscied.org/simulation/keplers-laws/ • headphones (optional) • *Progress Tracker* • three colored pencils of different colors • 8.5"x11" copy paper	• computer (optional) • device with access to https://www.openscied.org/simulation/keplers-laws/	• https://www.openscied.org/simulation/gravity-orbits • Scissors • Circular motion set up (see *Circular Motion Setup*) • https://www.openscied.org/simulation/keplers-laws/

Materials preparation (60 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch all handouts so they can be added to students' notebooks.

Test https://www.openscied.org/simulation/gravity-orbits and https://www.openscied.org/simulation/keplers-laws/ before the lesson.

General safety protocols for demonstrations and hands-on activities:

- Wear sanitized safety glasses with side shields or indirectly vented chemical splash goggles during the setup, hands-on, and takedown segments of the activities.
- Secure loose clothing, wear closed-toe shoes, and tie back long hair.
- Hand sanitizer wipes must be provided for participant use at the completion of the activities.
- Follow procedures set up by the instructor for disposal of materials.
- Make sure there are no fragile items in the activity zone, especially in the area where the orbiting object is being swung.
- Lightly tug on orbiting objects when assembling them to ensure that they are properly attached (see *Circular Motion Setup*).
- Use caution when working with glass or plastic - sharp ends can cut/puncture skin.
- Wash hands with soap and water or use hand sanitizer wipes immediately after completing this activity.

Day 1: Circular Motion Investigation

- **Group size:** 5
- **Setup:** Prepare 8 stations. To each station, include a circular motion setup (see *Circular Motion Setup*), 10 washers, a stopwatch, and a computer.
- **Notes for during the lab:** Assign a station to each group. Emphasize that students should focus on the relative "feel" of the circular motion setup.

- **Safety:** Wear safety goggles throughout. Lightly tug on orbiting object before beginning to ensure that they are properly attached.
- **Disposal:** All materials may be reused.
- **Storage:** Have students wrap the string around their circular motion setup so it does not get tangled in storage. Store washers separately from setups.

See *Circular Motion Setup* for additional guidance on how to prepare these materials.

Lesson 3 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently build ideas related to the following disciplinary core idea:

- **ESS1.B.1: Earth and the Solar System.** Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. ~~Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system.~~

While building these ideas, students rely on the model of universal gravitation developed in Lesson 2. The extension of this law to observations of our solar system also relies on experiences in middle school with ideas about regular orbital movements in the solar system, developed in OpenSciEd in *OpenSciEd Unit 8.4: How are we connected to the patterns we see in the sky and space? (Space Unit)*.

This lesson is designed to coherently build ideas related to the following crosscutting concept (CCC):

- **Stability and Change:** Much of science deals with constructing explanations of how things change and how they remain stable.

Stability and change will be a lens that students will use throughout this unit. In this lesson, explaining the motion of orbiting objects will require students to pay attention to the conditions that cause an object to move in an orbit (stability) and the conditions that cause an object to exhibit other types of motion (change). By using a forces perspective as a lens to make sense of orbital motion, this lesson builds on students' prior experiences they had in *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*, where they explored the stability and change of a system from an energy perspective. During the second lesson set (Lessons 8-15), students will continue using this crosscutting concept to explain the changes of Earth's surface (Lesson 13), the extinction of some species but not others caused by the Chicxulub impactor (Lesson 14), and the formation of the Moon from a giant impact (Lesson 15).

This lesson is designed to coherently build ideas related to the following science and engineering practice (SEP):

- **Developing and Using Models:** Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems.

Developing and using models is a focal practice throughout the entire unit. During the first lesson set, students will develop models about orbits to first describe how the distance between two space objects affects the relationship between the force of gravity acting on an orbiting object and its velocity (this lesson). In Lesson 4, students will continue using models to describe the shape of the orbits and predict the potential for a collision between two space objects. In Lesson 5, students will integrate the ideas developed in Lessons 2-4 to model how energy transfers in a Sun-asteroid system. In Lesson 6, students will continue using this practice to model how contact and forces at a distance help explain how the Chelyabinsk meteor changed its orbit. Students will be supported through the use of diagrammatic models and algebraic thinking.

Students will encounter or co-develop definitions for the following words in this lesson: orbit, period of revolution, circular motion. They also develop an equation for Kepler's third law. **Do not** post any words or ask students to add them to their Personal Glossary until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

Students do not fully develop all of Kepler's laws in this lesson. They simply figure out the general structure of Kepler's third law (often summarized as the square of the orbital period being proportional to the cube of the semimajor axis, described here as period squared divided by radius cubed being constant). In Lesson 4, students will figure out that this orbit is always an ellipse, rather than a perfect circle (Kepler's first law), and replace radius in the third law with the length of the semimajor axis. In Lesson 5, students use their ideas about forces and energy transfer to explain the mechanism behind Kepler's second law (the "law of equal areas").

LEARNING PLAN for LESSON 3

1 · NAVIGATE

3 min

MATERIALS: None

Problematize the motion of objects in space due to gravity. Present **slide A**. Use the slide prompts to motivate investigating the role of gravity on the motion of space objects:

- *What did we figure out last time about the interaction between two objects in space?*
- *What would our models predict should happen to all matter in space?*

Listen for the following ideas:

- The mass and the distance between two objects influence the force of gravity acting on them.
- Objects in space should move in a straight line towards each other, or all objects in space should be coming closer to each other.

If students suggest that some objects will orbit other objects, problematize the idea by pointing out that gravity acts in the direction of the center of an object, so this does not suggest orbital motion. If students suggest that objects will move in a straight line, problematize this idea by asking if that's how objects in space are actually moving. Ask, *Why doesn't the Moon smash into Earth or fly off into space if that is true?*

Elicit student ideas about the motion of space objects. Present **slide B**. Encourage students to share their thoughts on the movement of celestial bodies to motivate them in explaining how gravity can cause these types of motion. Use the following prompts for this:

- *Do we have evidence of how objects move in space?*
- *Can we explain how gravity can cause objects to move in these ways?*

Accept all ideas. Say, *Our models of gravitational force between two bodies do not help us explain why objects in space sometimes move in orbits and sometimes they don't, so we need to investigate this further.*

Emphasize that we cannot investigate the variables affecting the motion of objects in space directly because the system is too large and the changes are observable at timescales that we cannot afford. Suggest we use a simulation to explore the conditions needed to cause the motion we have seen about space objects.

2 · USE SIMULATION TO INVESTIGATE HOW VELOCITY AND GRAVITY AFFECT THE MOTION OF SPACE OBJECTS

11 min

MATERIALS: science notebook, computer (optional), https://www.openscied.org/simulation/gravity-orbits

Orient students to the simulation. Present **slide C**. Use the slide image to introduce the variables that can be manipulated in the simulation the class is about to use. Ask students to turn and talk with the prompt:

- *What variables should we manipulate to investigate the motion of space objects?*

Accept all answers. Suggest we try testing some of these ideas with the simulation.

Use simulation to explore variables affecting the motion of an orbiting object in space. Present **slide D**. Mention that you are about to display the simulation, changing some of the variables the class thinks will affect the motion of space objects. Read aloud the slide prompts to guide students' work to record their observations:

- *In your notebook, use words and drawings to describe the resulting motion of the satellite.*

✱ SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

Remind students that both velocity and forces are vectors, and, as such, they need to pay attention to changes in both direction and magnitude.

- *For every type of motion of the satellite, annotate any relevant changes in the magnitude and direction of the force and velocity vectors you observe.*✱

Display https://www.openscied.org/simulation/gravity-orbits. Use the simulation to manipulate the variables the class thinks will cause changes in the motion of the satellite. The suggested sequence below can help the class explore these variables. After changing each variable, give students enough time to observe and record the motion of the satellite and the changes in force and velocity in the system.

1. Zoom out to expand the visual area in which the satellite moves. Use the settings shown on **slide C**, and run the simulation for a few seconds. Pause the simulation and ask a few volunteers to share their observations, highlighting the changes in the direction of the gravitational force and velocity.
2. Change the velocity of the satellite by clicking on the arrow and dragging the cursor closer or away from the satellite.
3. Click the reset button located on the top part of the settings panel. Ask students what would need to be changed in the system to alter the magnitude of the gravitational force acting on the system. They should say that changing the distance between the planet and the satellite. Move the satellite closer to the planet, and run the simulation.
4. Reset the simulation and now move the satellite farther away from the planet
5. Reset the simulation again, and change the mass of the satellite. Hit the run button, and let students record additional observations.

ADDITIONAL GUIDANCE	**Troubleshooting:** PhET simulations are developed in HTML5, which allows it to run on any browser, regardless of the device and operating system. If you are experiencing issues using the simulation, try disabling any browser extensions. If you are running the simulation with an Android device, use the latest version of Google Chrome.

ADDITIONAL GUIDANCE	This is a short exploration that is intended to help students visualize the relationship between the velocity of an orbiting object and the force of gravity acting on it. During day 2, students will have the opportunity in small groups to continue investigating the motion of space objects.

ALTERNATE ACTIVITY	You can provide each pair of students with a computer with access to https://www.openscied.org/simulation/gravity-orbits. This will take a significant amount of time, but it will allow the students to experience the changes in the motion of the satellite firsthand.

Discuss the types of motion observed. Present **slide E**. Ask students to share their observations through a Turn and Talk about the prompts:

- *What types of motion exhibited by the satellite did we observe?*
- *How could our results help explain why an object can remain in a stable orbit?*

KEY IDEAS

Purpose of this discussion: Capture students' observations and ideas about the motion of the satellite around Earth in terms of the changes in velocity and the magnitude and direction of the forces acting on it.

For the first prompt, look for students to say the following:

- The satellite moved around Earth.
- The satellite moved away from Earth.
- The satellite collided with Earth.

For the second prompt, listen for the following ideas:

- Changing the velocity of the satellite and the distance between the satellite and Earth resulted in different types of motion.
- When the velocity was too large compared to the gravitational force, the satellite moved away from Earth.
- When the velocity was too small compared to the gravitational force, the satellite collided with Earth.

3 · MAKE PREDICTIONS ABOUT CHANGES IN VELOCITY

2 min

MATERIALS: None

Make predictions. Present **slide F**. Say, *I think we are in a much better position to predict how changing some of these variables might affect how space objects interact.* Ask students to turn and talk with the prompt:

- *What changes do you expect to observe in the velocity of the orbiting object (satellite) when*
  - *the distance is halved?*
  - *the distance is doubled?*

After about a minute, ask a few volunteers to share their ideas. Accept all answers. Say, *I have some materials for us to test these ideas.*

4 · USE A PHYSICAL MODEL TO INVESTIGATE THE ROLE OF DISTANCE IN ORBITAL MOTION

18 min

MATERIALS: Circular Motion Investigation, Scissors, Circular motion set up (see *Circular Motion Setup*)

Demonstrate the experimental setup. Before assigning set up stations, demonstrate to the class how to use the materials using one of the experimental setups. Present **slide G**. Begin by spinning the orbiting object, with just a couple washers on the bottom of the string. Keep the object spinning at a constant velocity for some time, then use the first prompt:

- *What prevents the orbiting object from flying away?*

Look for students to say that the carabiner with the washers keeps it spinning. If students do not seem convinced about this, invite a volunteer to cut the fishing line right above the carabiner.

Draw parallels between the manipulative and the real world. Then ask the next two questions on the slide:

- *Which parts of this physical system represent space objects in the real world?*
- *Which ones do not?*

Listen for the following ideas:

- The spinning object represents a planet or a satellite orbiting another object.

- The carabiner with washers causes a force that keeps the spinning object from flying away. That force represents the gravitational force acting on a planet or satellite.
- The string represents the orbital radius, but in the real world there is not a physical connection between both objects.
- The hand spinning the stopper does not represent a part of the system, but it is necessary to keep the radius and speed constant.

Brainstorm ideas about how to use the experimental setup. Present **slide H**. Use the slide prompts to remind students about the purpose of using this physical model and the variables we need to measure to answer our research question. Using the slide prompts, this discussion might play out like this:

Suggested prompt	Sample student response
What is the question we are trying to answer?	We want to know what happens to the velocity of the orbiting object if we change the distance.
How can we use these materials to answer this question?	We can increase and decrease the fishing line length above the tube.
What variables do we measure?	We can measure the distance of the fishing line from the tube to the orbiting object. We can measure the velocity of the orbiting object.
How do we measure them?	(Accept all answers.)

If students struggle coming up with ideas about measuring the velocity of the object, ask them:

- *How have we measured the velocity of moving objects in the past? For example, how do we measure the velocity of a car?*

Look for students to say that we measure the distance it travels over a period of time.

Introduce the period of revolution. Present **slide I**. Say, *Scientists define the time it takes an object to go around another one as the period of revolution. For example, Earth's period of revolution is 365.25 days.*

- *What does the time for one revolution tell us about*
  - *objects in our model?*
  - *objects in space?*
- *Why is this quantity useful for describing the orbits of space objects?*

Look for students to mention the following ideas:

- The period of revolution is the time it takes the spinning object to complete a full circle.
- The period of revolution tells us how fast space objects move.
- This quantity tells us how big the orbit is and how long it takes space objects to orbit.

Carry out initial exploration with materials. Present **slide J**. Organize the class into small groups of 3-4 students. Distribute the materials to each group to carry out their investigation. Distribute *Investigating Circular Motion* to every student. Read the slide instructions aloud to describe the overview of this investigation:

1. *Experiment with the equipment to keep the radius constant (the string marker remains at the same height, near the bottom of the tube).*
2. *Measure the time it takes the orbiting object to complete 20 revolutions.*
3. *Then change the radius and observe any changes in the velocity of the orbiting object. Record your observations.*

Before students begin their data collection, display **slide K** and review the general safety protocols for the activity.

Give students 8 minutes for this activity. Walk around the classroom and make sure students are recording their findings in their handout individually. They will need these results recorded to make sense of the results.

5 · DEVELOP AN EXPLANATION ABOUT THE STABILITY AND CHANGE OR ORBITS

6 min

MATERIALS: *Investigating Circular Motion*

Develop an explanation. Present **slide L**. Give students about 6 minutes to write their answers to the questions in the "Data analysis" section of *Investigating Circular Motion*. If time allows it, invite a couple of volunteers to share their answers.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- Use evidence about velocity, distance, and gravitational force obtained from the physical and computer simulations to support their explanations. (SEP: 2.6; DCI: ESS1.B.1)
- Account for the stability and change of orbits by describing the relationship between gravitational force and velocity. (CCC: 7.1; DCI: ESS1.B.1)
- Use evidence to describe how the distance of an orbiting object influences the relationship between gravitational force and velocity. (SEP: 2.6; CCC: 7.1; DCI: ESS1.B.1)

What to do

For students who are absent this day, provide them with a computer with access to https://www.openscied.org/simulation/gravity-orbits. Encourage them to describe the changes in motion of the satellite as they manipulate the velocity and distance of the satellite. This strategy can also help students who are struggling to describe how gravitational force, velocity, and distance help explain the stability and change of orbits.

English language learner students might benefit from sentence stems that can help them organize their ideas. Provide them with the following sentence stems:

- The relationship between gravitational force and velocity is a key factor in determining _____.
- When _____ of an orbiting object is balanced with _____, it results in _____.
- Changes in _____ of an orbiting object can impact the orbit stability by _____.
- When the distance of the orbiting object increases, its _____ has to _____ in order to remain in a stable orbit.

A student response might look like this:
The relationship between gravitational force and velocity is a key factor in determining the stability and change of orbits. When the velocity of an orbiting object is balanced with the gravitational force, it results in a stable orbit. Changes in the velocity of an orbiting object can impact the stability of the orbit by either causing it to shift into a more-distant orbit if the velocity increases or descend into a closer orbit if the velocity decreases. When the distance of the orbiting object increases, its velocity has to decrease in order to remain in a stable orbit.

Building toward 3.A Use different models, including a physical manipulative and a computer simulation, to generate data supporting an explanation for how space objects can remain in stable orbits and how their orbits can change. (SEP: 2.6; CCC: 7.1; DCI: ESS1.B.1)

6 · NAVIGATE

5 min

MATERIALS: None

Discuss information needed to predict the orbital period of space objects. Present **slide M**. As a class, discuss the slide prompt to elicit 1-2 student ideas:

- *What information would we need about any space object to predict how long it will take to go around the Sun?*

Listen for the following ideas:

- the distance of the object from the Sun
- the period of revolution

Motivate the need to continue investigating orbital motion. Present **slide N**. Use the slide prompt to motivate investigating orbital motion further:

- *Chelyabinsk was a meteor that orbited the Sun. Could knowing how long it will take similar objects to go around their orbits help us predict their potential for a collision with Earth? Why or why not?*

Accept all answers, but look for students to suggest that this information might not help us because the orbits from these space objects do not overlap with Earth's.

End of day 1

7 · NAVIGATE

3 min

MATERIALS: None

Reflect on the prior day's learning. Present **slide O**. Say, *Last time, we used a physical model to investigate the period of revolution.* Use the prompts on the slide to motivate the need to extend our investigation to objects in our solar system.

Suggested prompt	Sample student response
Why is the period of revolution useful in helping us predict future collisions of space objects with Earth?	It tells how long it will take an object to go around the Sun. We know how long it will take it to return to a given position in space.
How can we determine the period of revolution for objects in our solar system?	We need to know the distance. It is related to the size or radius of the orbit.

Say, *We know that there is a relationship between the radius of a circular orbit and its period of revolution.*
We are going to use a simulator to investigate this mathematical relationship for the planets in our solar system.

8 · MODEL PLANETARY ORBITS

12 min

MATERIALS: *Kepler's Third Law*, device with access to https://www.openscied.org/simulation/keplers-laws/, headphones (optional), https://www.openscied.org/simulation/keplers-laws/

Use a simulator to model solar system orbits. Display **slide P**. Distribute devices and *Kepler's Third Law* to students. Organize students in pairs, and encourage them to work together. Depending on time constraints and your access to technology, you may choose to have students share devices in pairs.

Give students about ten minutes to complete part 1 of the handout, looking at the default orbit. As they work, circulate the room to check for understanding of the following ideas:

- The period of an orbit is how long it takes for the orbiting object to go around completely one time. The period is not dependent on the object's starting place in its orbit. The period is measured in Earth years.

✱ ATTENDING TO EQUITY

This PhET simulation includes sound and sonification features. These are nonspeech sounds, such as musical tones, that correspond to changing values in the simulation. This feature is intended to create a more immersive simulation environment

- Distances in the solar system are measured in AU, astronomical units. We use AU because the distances in the solar system are so large that using units such as kilometers would result in very big numbers. (Note: One AU is approximately the average distance between Earth and the Sun and is equivalent to about 150 million km. It is not necessary for students to know this value.)

For the purpose of this lesson, we are restricting the orbital shapes in the simulation to perfect circles. This will make it easier for students to manipulate the size of the orbit without disrupting its stability and to focus on the relationship between orbital size and period of revolution. Since this relationship is constant for objects in stable orbits around the Sun, investigating circular orbits first will help scaffold the development of students' understanding of Kepler's laws. The relationships they identify hold true for objects whose orbits are not circles as well. Visually check students' screens to ensure they have the "Always Circular" option checked in the right-side toolbar.
Reinforce the idea of "period of revolution." As students complete part 1 of *Kepler's Third Law*, briefly check in on their understanding of the quantities and units we are using when measuring orbits in our solar system. You may choose to do this with the whole class or in small groups, depending on the needs of your class. Take this opportunity to reinforce the idea of "period" as the time for one orbit, that is, an object's "year." Note that astronomers prefer "period" as a unit to measure planets' motions because we can quickly compare it to Earth's orbital period, or year.

Follow up by saying, *We already know that the size of an orbit can affect its period of revolution. Now let's see how this works mathematically for planets in our solar system.*

and can help reinforce concepts such as the relationship(s) between distance, gravitational force, and velocity of the moving object. The sounds can increase accessibility for students with visual impairments. To avoid the sonification feature creating a distracting or cacophonous environment, consider having students minimize the volume on the devices or provide students who benefit from the sonification with headphones while having others turn off the sound feature using the controls on the bottom of the simulation.

9 · EXAMINE THE MATHEMATICAL RELATIONSHIP BETWEEN THE PERIOD OF REVOLUTION AND THE SIZE OF THE ORBIT

15 min

MATERIALS: *Kepler's Third Law*, device with access to https://www.openscied.org/simulation/keplers-laws/, https://www.openscied.org/simulation/keplers-laws/

Collect data comparing orbits of planets in our solar system. Display **slide Q**. Show students the relevant simulation controls by navigating to https://www.openscied.org/simulation/keplers-laws/. Demonstrate how you can change the "target orbit" using the dropdown menu in the top right. Say, *We are going to use the orbits of two different planets in our solar system to gather data. The distances and times in the simulation are accurate for our solar system.*

Give students about ten minutes to work with a partner to complete parts 2 and 3 of *Kepler's Third Law*.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: As students work with the simulation tools to generate and record data, look for the following indications that they are making accurate measurements and calculations:

- The values of both period (T) and radius (a) for Earth are 1. (SEP:2.6; CCC: 3.5; DCI: ESSB.1)
- For orbits larger than Earth's, T/a is greater than 1. (SEP:2.6; CCC: 3.5; DCI: ESSB.1)
- For orbits smaller than Earth's, T/a is less than 1. (SEP:2.6; CCC: 3.5; DCI: ESSB.1)
- Changes in a cause exponential growth in T. (CCC: 3.5)
- Students describe the meaning of Kepler's third law in terms of the distance between the planet and the Sun and its period of revolution. (DCI: ESSB.1)
- An object 3.5 AU from the Sun would take about 6.5 Earth years to complete one orbit. (CCC: 3.5)

See *Kepler's 3rdLaw Key* for sample responses to all questions on *Kepler's Third Law*. During the mid-unit transfer task, in Lesson 7, students will use similar sensemaking to explain the changes in the orbit of a space object based on data about its period of revolution and semimajor axis (radius). If students are struggling with this last question, consider having them practice using additional examples with varying periods of revolution and radii.

Building toward 3.B Use algebraic thinking to examine scientific data generated with a computer model to predict the effect of changes in the radius (a) on the period of revolution of an object in orbit around the Sun. (SEP:2.6; CCC: 3.5; DCI: ESSB.1)

Describe the mathematical relationship. Present **slide R**. Use the prompts from the slide to guide discussion.

Suggested prompt	Sample student response
What did you notice about the relationship between an orbit's radius and its period of revolution?	• When the radius increases, the period also increases. • When the radius increases, the planet moves slower, so the period or revolution gets longer.
Does that match what we saw in the circular motion lab last time?	• Yes. Bigger orbits went slower because they had less gravity. • This is consistent with what we observed in the circular motion lab. When the radius increased, the velocity got slower. That would make the time longer.
What did we learn about the way this relationship works by looking at data from planets in our solar system?	• For planets in our solar system, an increase in the radius results in a larger increase in the period. • The period goes up faster than the radius. If the radius doubles, the period gets more than twice as big. • You need exponents to make the relationship consistent.
Does this relationship make sense?	• Yes, because it would make sense that something going around the Sun would take longer if it is farther away.

Reflect on the meaning of the equation. Display **slide S**. Tell students that this relationship is considered a law of orbital motion. Say, *A law is a true statement that describes a phenomenon and allows us to make predictions.* Highlight that the constant we have identified changes only if the object at the center of the orbit, the Sun, changes. Use the slide prompts on **slide S** and **slide T** to help students think about what this means.

Suggested prompt	Sample student response
What do the different parts of this equation mean? What units do they have?	T is the period of revolution, it's the amount of time it takes the object to orbit once. T is measured in years. a is the radius of the circular orbit. It's the distance between the Sun and the object in orbit. a is measured in astronomical units.
What does this relationship mean in words?	As the radius increases, the period of revolution increases proportionally. An object close to the Sun will have a shorter year than one farther away. The farther away an object is from the Sun, the longer its year is.

Suggested prompt	Sample student response
What would happen to this relationship if the mass of the Sun changed.	The proportions in the relationship would stay the same. The constant would change.
Why can we consider this relationship a "law"?	It is the same for all objects in orbit. For everything orbiting the Sun, the relationship is $T^2 = a^3$. That means if you know the size of an orbit, you can figure out what its period of revolution is. It will work the same for any planetary system. The only thing that would change is the constant, based on the mass of the star in the middle.

Establish Kepler's third law. Present **slide U**. Mention that the relationship we just established between the period of revolution and the radius of the orbit is also known as Kepler's third law.
Use the slide prompt to elicit 1-2 ideas about how to use this constant to predict the motion of space objects:

- *Based on this constant, what information do we need to determine the period of revolution of any object in our solar system?*

Look for students to mention that we need to know the distance of the object from the Sun (its orbital radius).

10 · UPDATE PERSONAL GLOSSARIES AND INTRODUCE PROGRESS TRACKER

10 min

MATERIALS: *Progress Tracker*, three colored pencils of different colors

Update Personal Glossaries. Display **slide V**. Say, *Let's take a moment to add a definition for the term "period of revolution."*

Give students a couple minutes to update their Personal Glossary. Encourage students to use words and symbols to describe this term. If time permits, allow a few students to share their definitions.

Introduce this unit's Progress Tracker. Remind students that we use a Progress Tracker to make a record of our sensemaking and ideas throughout each unit. Distribute *Progress Tracker* and colored pencils. Display **slide W**. Introduce the format for this unit's Progress Tracker and its focus on our ideas and questions.

This unit's Progress Tracker has three columns:

1. What did you figure out?
2. Which lenses did you use to figure this out?
3. How did using these lenses help you figure this out?

Students should add their *Progress Tracker* in their science notebook. If students need more space in later lessons, have available additional copies of the second page of *Progress Tracker*. See the *Progress Tracker KEY* for a sample entry.

Have students establish their own color and symbol coding system. They should have colors and/or symbols designated for tracking each of the M-E-F perspectives as well as things such as new questions, changes, or other annotations throughout the unit. Allow flexibility here. Some students may want to sort things differently. Have students fill in the key at the top of *Progress Tracker* to keep track of the meaning as

✱ ATTENDING TO EQUITY

Universal Design for Learning: Use *representations* like color and/or symbol coding to organize the Progress Tracker over time. Have students create a key to track what colors and/or symbols represent in their Progress Tracker. While color coding is a useful way to quickly reference themes across the Progress Tracker, symbol coding provides an alternative for students and helps ensure accessibility for any student who may be color blind. If color coding is used, be sure that students have access to a variety of colors and can select colors that work for them.

they add to this handout throughout the unit.✱

Students may choose to include ideas from this lesson as well as the previous lessons. Collect pencils at the end of class so other classes can use them.

SCIENCE NOTEBOOK



As students set up their Progress Tracker, this is a good opportunity to have them check in on the organization of their science notebook binder. Have students make sure that they have their Personal Glossary easily accessible and have a section in the notebook set up for this unit with flags, sticky notes, etc. to separate parts of the unit. This will allow them to easily access their Personal Glossary and Progress Tracker throughout the unit.

ALTERNATE ACTIVITY

This Progress Tracker has the option of being used at the end of every lesson. This *Teacher Guide* only has students adding to it in certain lessons. However, if it is beneficial for your students to provide them an opportunity to distill their thinking before going public, it might be strategic to add a moment to use it at the start, middle, or end of a lesson. This also could assist with makeup for students who have missed class or for review. One option is to have students record the key ideas on a public version of the tracker that is always available to students.

Encourage students' *action* and *expression* in using different representation systems and categories. Allowing students to *express* their ideas using multiple modalities supports student ownership of their learning by giving students choice, access, and control in navigating their own understanding around the science ideas.

11 · NAVIGATE

5 min

MATERIALS: science notebook, 8.5"x11" copy paper

Motivate where we are going next with an exit ticket. Present **slide X**. Say, *We saw that some space objects, like planets, orbit in **stable** circular paths around the Sun.*

- *Do you think that all objects in the solar system have orbits that look like this?*
- *What evidence or experiences do you have that could support your claim?*

Distribute a piece of paper to every student and give students a few minutes to answer the slide prompts as an exit ticket. Then say, *Let's explore these questions next time*. You do not need to collect the exit ticket. Rather, students will use their ideas to discuss with a partner at the beginning of the next class.

ADDITIONAL GUIDANCE

Students may conflate an orbit, or its shape, with the object and its shape. For example, when drawing a circular orbit, students may also assume that the object in orbit is spherical or round (or vice versa). Drawing the object on the orbital path can help distinguish these two ideas. If students are struggling, remind them that the orbit is a pathway in space, not a physical object. The "shape" of an orbit is describing the path of motion. If students are not sure that the object must be placed somewhere along the orbital path, that is another indication that they need support distinguishing these two concepts.

Additional Lesson 3 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH	**Number and Quantity** **CCSS.MATH.CONTENT.HS.N-VM.1** Vector and Matrix Quantities: Recognize vector quantities as having both magnitude and direction. Students consider the changes in the magnitude and direction of force and velocity to establish the relationship between these variables in stable orbits.

LESSON 4: Why do objects sometimes collide in space?

PREVIOUS LESSON

We used a simulation to figure out what conditions are necessary for orbit. We conducted an investigation to quantify how speed and force, among other variables, are related in circular motion. We analyzed how planets move. We connected the circular motion and universal gravitation equations and identified the relationship between period and orbital radius.

THIS LESSON

INVESTIGATION

2 days





NASA/Goddard/University Of Arizona

We decide to look at the orbits of objects that are not planets because planets do not seem to be at risk of colliding with each other. We explore elliptical orbits in the solar system and determine that the Sun is always located at one of the foci of the ellipse. We read about and model objects in space that could collide with Earth. We develop a model based on data to explain how the Peekskill meteor and Earth collided. We wonder how we would know if two objects whose orbits cross will actually collide.

NEXT LESSON

We will look at a simulation of orbits to notice that the speed of objects in elliptical orbits changes along the path. We will construct energy transfer diagrams to model this change.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2



WHAT STUDENTS WILL DO

4.A Develop and revise a model based on evidence of the orbital features of space objects to explain why space objects can collide with Earth, highlighting the limitations of the model in predicting future collisions. (SEP: 2.3; CCC: 4.4; DCI: ESS1.B.1)

WHAT STUDENTS WILL FIGURE OUT

- Orbits are elliptical in shape with the Sun located at one of the foci.
- Objects in space are at risk of colliding if their orbit paths cross.
- Asteroids, comets, and meteor showers are different types of objects in space that have the potential to collide with Earth.

Lesson 4 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	3 min		**NAVIGATE** Have students make inferences about the likelihood of a collision of objects moving in circular objects.	A-B	completed exit tickets from Lesson 3
2	5 min		**CONSIDER THE IMPORTANCE OF DESCRIBING THE SHAPE OF ORBITS** Use the shape of Comet Halley's orbit to consider the importance of describing the shape of orbits.	C-E	*Orbital Shapes*
3	5 min		**INTRODUCE MAIN PARTS OF AN ORBIT** Give students some time to read about the parts of an orbit described in *Orbital Shapes*.	F-G	*Orbital Shapes*
4	20 min		**MODEL PLANET AND COMET ORBITS** Distribute materials to every pair of students to model circular and elliptical orbits. Use their observations to discuss how the parts of the orbit change as the eccentricity of the orbit increases.	H-L	*Orbital Shapes*, 18" x 15" corrugated sheet, butcher paper, 2 pushpins, pencil, eraser, 12" ruler, calculator, 21 cm loop of twisted nylon string., 10 cm loop of twisted nylon string, 15 cm loop of twisted nylon string
5	5 min		**COMPARE ORBITAL MODEL SHAPES** Facilitate a whole class discussion about comparing the orbit shapes of planets and comets.	M	*Orbital Shapes*, model of planet's orbit (low eccentricity, model of comet's orbit (high eccentricity)
6	7 min		**USE MODEL TO PREDICT THE POTENTIAL OF A COLLISION BETWEEN EARTH AND A COMET** Orient students to the questions in part 4 of *Orbital Shapes*, guiding them to apply their new ideas about the elements of orbits in order to predict the potential for a collision between Earth and a comet.	N	*Orbital Shapes*
					End of day 1
7	3 min		**NAVIGATE: REVISIT ORBITAL SHAPES** As a class, review some of the orbital shapes we explored last time that can help explain the likelihood of a collision between Earth and other space objects.	O-P	
8	12 min		**USE ORBIT PATHS TO CONSIDER RISK TO EARTH** Distribute *Objects in Space* for students to read about objects in the solar system that might be at risk for colliding with Earth.	Q-R	*Objects in Space*

Part	Duration		Summary	Slide	Materials
9	20 min		**CONSTRUCT A MODEL BASED ON EVIDENCE** Distribute materials to small groups for them to recreate the orbital shape of the Peekskill meteor using data.	S-W	18" x 15" corrugated sheet, butcher paper, 2 pushpins, pencil, colored pencils, eraser, 12" ruler, calculator, 21 cm loop of twisted nylon string (for the Peekskill meteor orbit), 10 cm loop of twisted nylon string (for Earth's orbit), 50 cm piece of twisted nylon string (optional)
10	8 min		**UPDATE PERSONAL GLOSSARY AND PROGRESS TRACKER** Discuss the meanings of new terms and add them to Personal Glossaries. Distribute colored pencils so students can update their Progress Tracker.	X-Y	colored pencils, *Progress Tracker*
11	2 min		**NAVIGATE** As a class, consider what additional information is needed about the motion of orbiting objects to know if they are at risk for colliding with Earth.	Z	

End of day 2

Lesson 4 • Materials List

	per student	per group	per class
Lesson materials	• *Orbital Shapes* • 18" x 15" corrugated sheet • butcher paper • 2 pushpins • pencil • eraser • 12" ruler • calculator • 21 cm loop of twisted nylon string. • model of planet's orbit (low eccentricity • model of comet's orbit (high eccentricity) • *Objects in Space* • science notebook • colored pencils • *Progress Tracker*	• 10 cm loop of twisted nylon string • 15 cm loop of twisted nylon string • 18" x 15" corrugated sheet • butcher paper • 2 pushpins • pencil • colored pencils • eraser • 12" ruler • calculator • 21 cm loop of twisted nylon string (for the Peekskill meteor orbit) • 10 cm loop of twisted nylon string (for Earth's orbit) • 50 cm piece of twisted nylon string (optional)	• completed exit tickets from Lesson 3

Materials preparation (40 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch all the handouts so they can be added to students' notebooks.

Before day 1

- Each group of three students will need three string loops, each 21 cm long, made of twisted nylon string, along with one string loop 10 cm long and one string loop 15 cm long. The 10 cm and 21 cm long loops will be reused on day 3 to create the orbits of Earth and the Peekskill meteor.
- Cut segments of string to achieve the desired length, and tie each string into a loop with a knot. You might want to add a tag with a piece of tape to easily identify the length of each loop. Collect these loops at the end of each day.
- For each student, stack a 18" x 15" corrugated sheet under a sheet of butcher paper.
- If possible, prepare sets of push pins for each group. It is useful to have one yellow or orange push pin and one clear or dark-colored push pin so that students can easily keep track of which one represents the Sun.

Before day 2

- Have colored pencils ready to distribute to students for use on the model and Progress Tracker.

Lesson 4 • Where We Are Going and NOT Going

Where We Are Going

The focus of this lesson is to develop an understanding of orbits as elliptical in shape and to connect this to identifying objects that have orbits that intersect with Earth's orbit, creating the potential for a collision.

This lesson is designed to continue to target **SEP 2.3**, Develop, ~~revise, and/or use~~ a model based on evidence to illustrate and/or predict the relationships ~~between systems or~~ between components of a system. Students evaluate the impact of new data on developing the overarching models of objects colliding with Earth. This is supported in this lesson through the use of the Progress Tracker as well as within the modeling task. In the next lesson, students will continue using this practice through the use of shape models and the addition of speed. Both lessons connect specifically to the system of Earth, the Sun, and other objects in space that have the potential to collide with Earth. This is a direct tie to the anchoring phenomenon and DQB.

This lesson continues to develop student understanding of Kepler's laws covered in this DCI element:

- **DCI ESS1.B.1** Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun (HS-ESS1-4).

The previous lesson establishes the relationship between orbit period and orbital radius. In this lesson we explore elliptical shapes and motivate the need to explore the motion of objects along their orbit.

This lesson is designed to support understanding of the following crosscutting concept:

- **Systems and System Models:** Models can be used to predict the behavior of a system, but these predictions have limited precision and reliability due to the assumptions and approximations inherent in models.

Students will develop models that explain why Earth and the Peekskill meteor collided. The lesson is designed to help students identify how descriptive data about the shapes of orbits can be used to predict the behavior of space objects and, consequently, anticipate future collision events. They will also consider the limitations of their models, which will motivate further exploration of the motion of space objects in the next lesson.

Students will encounter or co-develop definitions for the following words in this lesson: *ellipse, foci, semimajor axis, eccentricity, asteroid, comet*. **Do not** post any words or ask students to add them to their Personal Glossary until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

This lesson does not cover systems that are too small to be studied directly. This is covered in other units such as in the wires simulation from *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*.

LEARNING PLAN for LESSON 4

1 · NAVIGATE

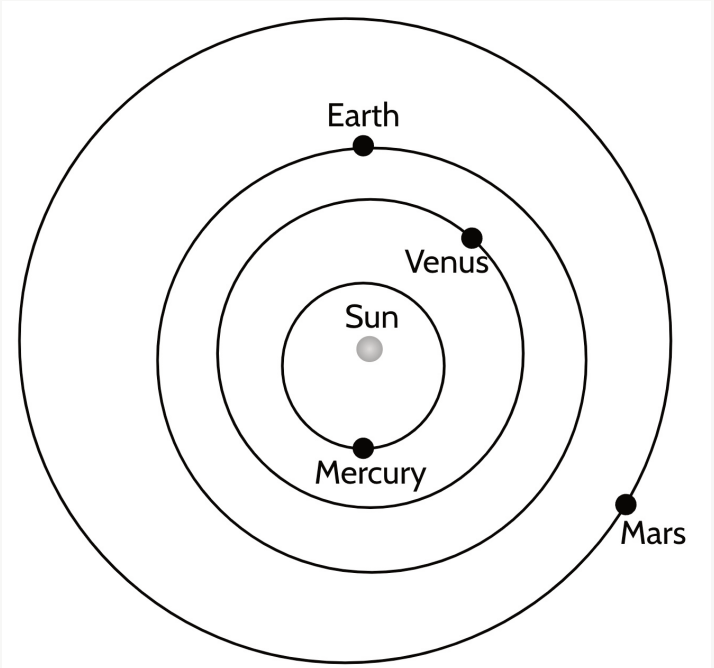
3 min

MATERIALS: completed exit tickets from Lesson 3

Review evidence about the motion of space objects. Present **slide A**. Give students a chance to pull out and review their exit ticket from last class. If students were absent or do not have their exit ticket, ask them to simply consider the prompts again:

- *Do you think that all objects in the solar system have orbits that look like this?*
- *What evidence or experiences do you have that could support your claim?*

Present **slide B**. Ask students to turn and talk about the prompts on the slide, and then use the prompts to elicit 1-2 student ideas:



Suggested prompt	Sample student response
Do we have evidence that all objects in the solar system have orbits that look like this?	We saw some objects moving in a circular orbit and other objects moving in oval-shaped orbits.
Do you think these planets are likely to collide? Why or why not?	Those planets are not likely to collide because their orbits are circular and fit into one another just right.

Say, *If all objects in the solar system moved in a circular orbit like this, they would be less likely to collide. However, we also know that space objects have collided with Earth, like the Chelyabinsk meteor. Do you think the shape of an object's orbit could help predict if it will collide with us?*

Accept all answers. Say, *Let's take a look at some other objects that are not planets and see if they can give us some clues as to what their orbits look like and if there are overlaps.*

2 · CONSIDER THE IMPORTANCE OF DESCRIBING THE SHAPE OF ORBITS

5 min

MATERIALS: *Orbital Shapes*

Lead an Initial Ideas Discussion about the orbit of Halley's Comet. Display **slide C**. Say, *This image shows the orbits of our planets, with the addition of the orbit of Halley's comet.* Elicit some ideas using the prompts:

- *What do you notice?*
- *What do you wonder?*

Say, *Clearly this orbit is really different from what we have seen so far. It has a different shape, and it moves differently than what we've seen before.*

Consider the importance of predicting the shape of orbits. Display **slide D**. Elicit some ideas using the prompt:

- *How could understanding different orbit shapes help us explain and predict space collisions?*

Use this discussion to motivate toward the importance of investigating different orbit shapes. Look for the following ideas:

- If we know the shape of the orbits, we could see if they intersect.
- The shape of the orbit tells us where space objects will be at some point in the future, so we can make predictions about potential collisions.

Say, *Since the shape of the orbit can help us predict the motion of space objects, let's explore what exactly is different about the shape of orbits.*

Elicit noticings about circular and elliptical orbits. Present **slide E**. Distribute *Orbital Shapes* to every student and give them a moment to write their noticings about circular and elliptical orbits in part 1 of the handout using the prompts:

- *What specific things do you notice are different about these orbits?*
- *If you had to describe what was different about these orbits using quantities, what would you need to measure?*

After a minute, invite some volunteers to share their ideas with the class. Look for the following ideas:

- The Sun is at the center of the circular orbit.
- The Sun is closer to one side of the elliptical orbit.
- The distance between the planet and the Sun is the same along the circular orbit.
- The distance between the planet and the Sun changes along the elliptical orbit.
- We would need to be able to measure the distance between the planet and the Sun.

Say, *OK, these two orbits are clearly different. Let's try to describe the differences in their shapes more accurately.*

✱ STRATEGIES FOR THIS INITIAL IDEAS DISCUSSION

Purpose of this discussion: The goal of this discussion is to problematize the importance of learning about elliptical (noncircular)orbital shapes. Through the prompts and student responses, we intend to foster curiosity and critical thinking about the unique characteristics of Halley's comet's orbit. The goal is to lead students to question why the orbit is not a circle, why it varies in speed, and what implications these non-circular features may have. Emphasis will be placed on the significance of understanding diverse orbital shapes and movements.

Look for these noticings:

- The orbit shape is not a circle, it is egg shaped.
- It looks like it goes fast at some points and slow at some points.
- It gets really close to the center.

Look for these wonderings:

- Why is it not a circle?
- Why does it speed up and slow down?
- Why hasn't it crashed with other objects?
- Why do some objects move in circular orbits while others move in egg-shaped orbits?

Place particular emphasis on responses related to the elliptical orbit shape. Make sure that when students describe the orbits of space objects, they are referring to the shape of the actual orbit, not the shape of the object itself.

3 · INTRODUCE MAIN PARTS OF AN ORBIT

5 min

MATERIALS: *Orbital Shapes*

Identify parts of an orbit. Present **slide F**. Say, *We cannot see the orbits that space objects follow, but we can observe these space objects over time to describe and predict their motion. Scientists have identified different parts of the orbit shape that can help them describe and predict the motion of space objects. Let's read more about these parts.*

Orient students to read part 2 of *Orbital Shapes* with a partner. Give them a few minutes to read the descriptions of the semimajor axis, empty foci, center of the orbit, and eccentricity. Prompt them to try to make connections between the descriptions and what we have already seen.

After this time, say, *Now that we are more familiar with some of the terms used by scientists to describe orbits, let's see if we can use these terms to describe more accurately the differences between circular and elliptical orbits.*

Motivate using a physical model to explore circular and elliptical orbits. Present **slide G**. Use the slide prompts to elicit 1-2 student ideas:

- *How do you think the shape of the orbit will change if we double*
    - *the length of the semimajor axis?*
    - *the distance between the foci?*

Accept all ideas. Say, *I have a physical model that will help us test some of our ideas.*

4 · MODEL PLANET AND COMET ORBITS

20 min

MATERIALS: *Orbital Shapes*, 18" x 15" corrugated sheet, butcher paper, 2 pushpins, pencil, eraser, 12" ruler, calculator, 21 cm loop of twisted nylon string., 10 cm loop of twisted nylon string, 15 cm loop of twisted nylon string

Develop a model of a planet's orbit (low eccentricity). Present **slide H**. Organize the class in groups of 3 students. Distribute materials and assign each student a different length of string loop. In each group, one student will model a circular orbit with a radius of 21 cm, another with a radius of 15 cm, and the third with a radius of 10 cm.

Tell students they are going to use these materials to make a shape that looks like a circular orbit of a planet.

Make a connection back to the Circular Motion lab from Lesson 3 by saying, *A circle has a constant radius. In the Circular Motion lab we had the string on the spinning object that we swung around that stayed at the same length. Here we have a loop of string.* Use the slide's animated image to show students how to use the materials you provided to create a circle.

Model a planet's orbit. Give students a couple of minutes to construct a model of the circular orbit assigned to them and label the important parts, in accordance with the prompts on their handout and the slide. Towards the end of the time limit, remind students to use the steps in the handout to calculate the eccentricity of the orbit they created.

ADDITIONAL GUIDANCE

The goal of this activity is to help students conceptualize all orbits as ellipses and to understand that the orbital behavior of an object is dependent upon—or can be mathematically described by—the properties of the ellipse. It is not the case that all planetary orbits are nearly circular, but for comparison purposes they can be treated that way. Earth's orbit has a very low eccentricity, near to zero, so a circular model is a good approximation at this scale.

Debrief planet ellipse models. Have students compare their models with the other members of their group using the prompt at the bottom of **slide H**. After a minute or two, present **slide I**, then invite a few volunteers to share some of their findings using the prompts:

Suggested prompt	Sample student response
What did your orbits have in common?	They are all circles.
What was different?	Some are bigger than others.
What is the semimajor axis?	The semimajor axis is the length from the center to the edge.
What other name do we have for that length when the shape is a circle?	For our circles, the semimajor axis is the radius of the circle.
What happened to the shape of the orbit when the semimajor axis increased?	The longer the semimajor axis, the bigger the size of the orbit.
What are the values of the eccentricities we calculated?	The eccentricities are zero or near zero.

Make predictions about changes in the shape of an orbit. Present **slide J**. Suggest that now that we can describe the parts of a circular orbit and its eccentricity, we will develop a model of a comet's orbit. Use the first slide prompt to remind students about the shape of comet orbits:

- *How do you think the shape of the orbit will change as the distance between the foci grows larger?*

Encourage students to show their ideas with their hands. Look for them to show a "squished" orbit with their hands.

Model a comet's orbit (high eccentricity). Present **slide K**. In the same groups, ask students to use the 21 cm string loop to construct a model of an elliptical orbit, but with a different distance between the foci from the other group members.

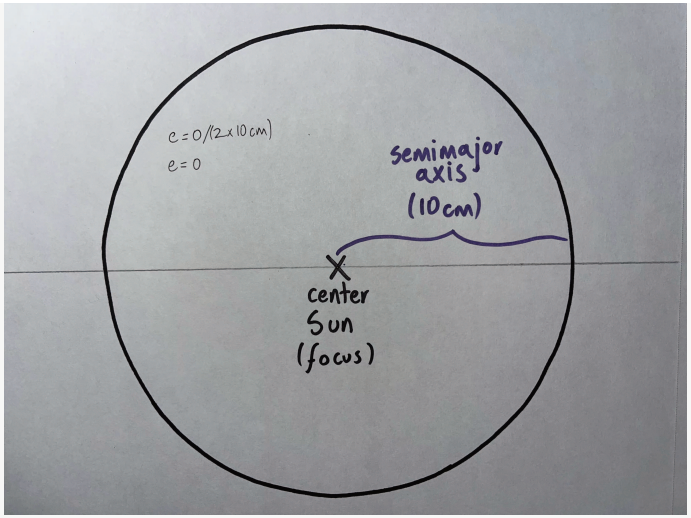
Encourage students to use their pushpins and string to emulate the animated image presented on the slide. Suggest that they use their finger or the back of the marker while testing things out.

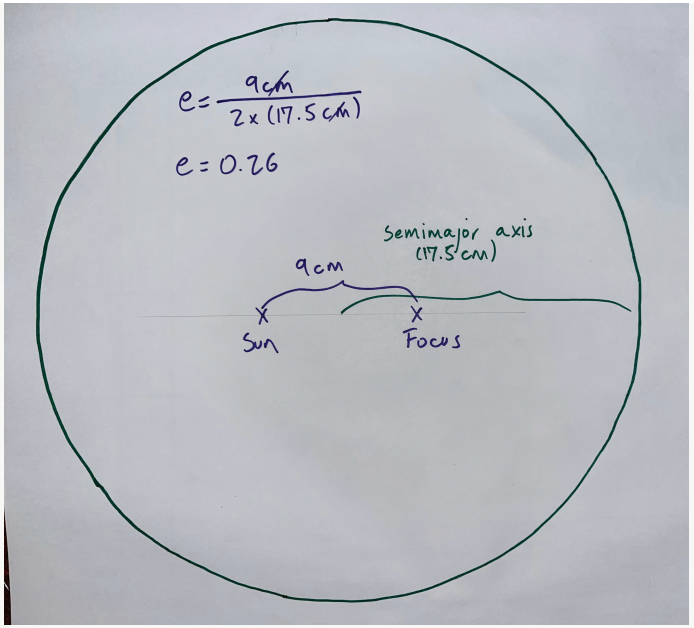
Give students a couple of minutes to construct a model of the elliptical orbit assigned to them and label the important parts, in accordance with the prompts on their handout and the slide. Remind students to use the steps in the handout to calculate the eccentricity of the orbit they created.

Debrief comet ellipse orbit models. Present **slide L**. As before, have students compare their model with those of the other members of their group. Then use the slide prompts to invite a few volunteers to share some of their findings:

Suggested prompt	Sample student response
What did your orbits have in common? What was different?	The length of the string used is the same. The eccentricity is different. The distance between the foci is different.
What patterns do you see between the shapes of the orbits and their eccentricities?	The higher the eccentricity, the more egg-like is the shape of the orbit.

These images show examples of how the ellipses and their labels might look.





ADDITIONAL GUIDANCE

The second push pin in this model represents the second focus of the ellipse, which is located at an empty point in space. It is a mathematical point, not a physical object. Students commonly try to assign an object to this focus, such as the Moon or the orbiting object itself. Check students' labels to make sure they understand there is no physical object at the second focus.

The semimajor axis should extend from the center of the ellipse, located in between and equidistant from the foci, to the edge where the line is drawn.

When using the same string, increasing the distance between foci will result in a smaller orbit. In the real solar system, the smallest orbits are not the most eccentric ones. Using a longer string allows for the construction of an orbit with high eccentricity and a semimajor axis similar to or larger than that of the circular orbit.

5 · COMPARE ORBITAL MODEL SHAPES

5 min

MATERIALS: *Orbital Shapes*, model of planet's orbit (low eccentricity, model of comet's orbit (high eccentricity)

Compare orbital properties. Present **slide M**. As a class, discuss the differences between the orbits of planets and comets using the prompts:

✱ STRATEGIES FOR THIS BUILDING UNDERSTANDINGS DISCUSSION

Purpose of this discussion: Build a conceptual understanding of the relationships between orbital eccentricity, shape of the ellipse representing the orbital

Suggested prompt	Sample student response
How do the orbit shapes and the locations of the Sun and foci compare?	The planet's orbit is circular, and the comet's orbit is squished. The foci of the planet's orbit are both on the Sun in the middle of the orbit. The foci of the comet's orbit are far apart, near the ends of the orbit path, and the Sun is at one of them.
How do the eccentricities compare?	The planet's orbit has an eccentricity of zero, and the comet's orbit has an eccentricity between zero and one.

path, and behavior of objects in orbit. In this discussion we don't focus on the potential for collisions, but the understanding that the mathematical properties of an orbit determines the object's behavior is foundational for future lessons.

Listen for the following ideas:

- The planet's orbit is circular, and the comet's orbit is squished.
- The foci of the planet's orbit are both on the Sun in the middle of the orbit.
- The foci of the comet's orbit are far apart, near the ends of the orbit path, and the Sun is at one of them.
- The planet's orbit has an eccentricity of zero, and the comet's orbit has an eccentricity between zero and one.

6 · USE MODEL TO PREDICT THE POTENTIAL OF A COLLISION BETWEEN EARTH AND A COMET

7 min

MATERIALS: *Orbital Shapes*

Make a connection between eccentricity and collisions. Present **slide N**. Orient students to the questions in part 4 of *Orbital Shapes*, guiding them to apply their new ideas about the parts of orbits in order to predict the potential for a collision between Earth and a comet:

- How do you think the shape or eccentricity of the orbits of objects in our solar system influences the likelihood of colliding with Earth, which has a nearly circular orbit?
- What additional information would you need to create a model that predicts the potential of a collision between a comet and Earth with high accuracy?

Give them a few minutes to complete their answers. Collect these models in part 4 of the handout to assess students' thinking about this phenomenon.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- Develop a model that shows the orbits of Earth (low eccentricity) and a comet (high eccentricity). (SEP: 2.3; DCI: ESS1.B.1)
- Include the Sun, Earth, and the comet in their model. (SEP: 2.3)
- Use the model to describe how the shape of the orbit can influence the potential for a collision between Earth and a comet. (SEP: 2.3; DCI: ESS1.B.1)
- Mention parts of the orbits, such as the semimajor axis, the eccentricity, or the location of Earth and the comet at different times, as information needed to make more-accurate predictions of a potential collision. (SEP: 2.3; CCC: 4.4; DCI: ESS1.B.1)

What to do

If students are struggling to create a predictive model, suggest that they create two simple models—one with a space object moving along a low eccentric orbit and one with a space object moving along a high eccentric orbit, including Earth's orbit in each. Ask them to explain how the potential for a collision might increase or decrease based on the shape of the object's orbit.

See *Orbital Shapes Key* for sample responses.

Building toward 4.A.1. Develop and revise a model based on evidence of the orbital features of space objects to explain why space objects can collide with Earth, highlighting the limitations of the model in predicting future collisions. (SEP: 2.3; CCC: 4.4; DCI: ESS1.B.1)

End of day 1

7 · NAVIGATE: REVISIT ORBITAL SHAPES

3 min

MATERIALS: None

Remind students where we left off. Present **slide O**. Say, *Last time, we got to investigate objects moving in orbits with different shapes*. Review these orbital shapes by asking students to turn and talk with the prompts. After a minute or less, ask students to share with the class:

Suggested prompt	Sample student response
What new orbit shapes did we see last time?	We saw orbits with high and low eccentricity.
How does knowing the shapes of orbits help us consider the risk of Earth colliding with another space object?	Different orbit shapes may bring objects closer or farther from Earth, impacting collision risk. Certain orbit shapes might increase the chances of collisions. Some orbits intersect, so that can help predict a potential collision.

Motivate the need to read about different space objects. Present **slide P**. As a class, continue the discussion with the prompts:

Suggested prompt	Sample student response
Should we be worried about collisions with other planets? Why or why not?	No, the orbit paths do not cross because they are all near circles around the Sun with different radii.
What things in space might hit Earth?	Comets, asteroids, or space debris might hit Earth.

Say, *So we think the orbit shape does matter because it helps us understand whether a space object is likely to overlap with another orbit and collide. That makes me want to know what kinds of objects are out there with this kind of orbit and how much of a risk they pose!*

8 · USE ORBIT PATHS TO CONSIDER RISK TO EARTH

12 min

MATERIALS: *Objects in Space*

Read about the motion of objects in our solar system. Distribute *Objects in Space*. Present **slide Q**. Remind students that our goal of the reading is to know about how these objects move in space and if they have the potential to collide with Earth and cause damage. Give them about 10 minutes to complete this reading.

Turn and talk about the potential to collide with Earth. Present **slide R**. Ask students to turn and talk with the prompt:

- *What in the reading helps us consider whether these things have the potential to collide with Earth and cause damage?*

Allow students a couple of minutes to discuss before inviting them to share their ideas with the class.

Listen for the following ideas:

- how large the objects are
- the shape of their orbits
- changes in the orbit
- The meteor showers are mostly really small stuff, but comets and asteroids can be much bigger.
- if the orbit of the object crosses Earth's orbit
- if the space object's orbit is outside the orbital plane

Say, *OK, so we have some kind of idea as to why something might collide with Earth. Why don't we try to model the orbits of some of these objects to see what they would look like.*

9 · CONSTRUCT A MODEL BASED ON EVIDENCE

20 min

MATERIALS: science notebook, 18" x 15" corrugated sheet, butcher paper, 2 pushpins, pencil, colored pencils, eraser, 12" ruler, calculator, 21 cm loop of twisted nylon string (for the Peekskill meteor orbit), 10 cm loop of twisted nylon string (for Earth's orbit), 50 cm piece of twisted nylon string (optional)

Brainstorm information needed to construct a predictive model of a collision. Present **slide S**. Suggest we model a specific scenario of one of these space objects to help explain why a space object might collide with Earth.

Say, *Another object that we saw collided with Earth was the Peekskill meteor. Now that we have some ideas about how to describe the orbital shape of a space object with higher accuracy, what information do we need to reconstruct the orbit of the Peekskill meteor?*

As you discuss this prompt with the class, look for mentions of orbit components, such as eccentricity, semimajor axis, or period of revolution.

Continue this discussion with the prompts:

✱ SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

Encourage students to use a pencil during this activity. Since they will share their model with their peers and revise it, using a pencil will allow them to erase elements of the

- *What objects need to be included?*
- *What norms for representation should we establish?*

Listen for the following ideas:
- Sun, Earth, and the Peekskill meteor
- the orbits of Earth and Peekskill meteor
- Use a consistent view or angle.

Suggest we use a 2-D representation, as it will be easier to use some of the tools we have previously used to reconstruct the orbits of these objects.

Say, *I have some of this information, based on calculations scientists have previously made.*

Construct a model based on evidence. Present **slide T**. Distribute materials to every pair of students. Ask them to use the information and conversion factor between centimeters (cm) and astronomical units (AU) described in the slide table in order to reconstruct the orbits of Earth and of the Peekskill meteor.✱

	Earth	Peekskill meteor
Eccentricity	≅0	0.4
Semimajor axis	1.0 AU	1.5 AU
Distance between foci	0	1.2 AU
*Use the following conversion factor: **1.0 AU = 5 cm***		

ADDITIONAL GUIDANCE

Some students might create the Peekskill meteor orbit by placing the Sun at the center, which will result in two concentric orbits (one for the meteor and one for Earth). Remind them that elliptical orbits have the Sun at one of their foci.

The 5 cm string loop will allow students to create Earth's orbit, while the 11 cm string loop will allow students to create the Peekskill meteor orbit.

ALTERNATE ACTIVITY

Give students a 50 cm piece of string and allow them to create their own string loops to create each orbit. This will increase the technical difficulty of the task, but it will push students to think more deeply about how to translate technical information about the shape of orbits to a physical model.

Give them about 6 minutes for this task.

Prepare for a gallery walk. Present **slide U**. Let students know that they will be interacting with some of their peers' models through a gallery walk. Ask them to prepare a T-chart in their science notebook to record similarities and differences between models.

Facilitate a gallery walk. Students should stay with their partner, rotating to see models from three other pairs for 1 minute each. During that time, they should discuss and write down similarities and differences between models in their science notebook.

model they feel need to be changed. Using a pen might discourage students from revising their model later on during the activity.

Return to small groups to reflect on initial models. Present **slide V**. Ask students to return to their initial model with their partner and discuss what revisions they might want to make. Give them a few more minutes to revise their model.

Consider the limitations of the model. Present **slide W**. Ask students to answer the following questions in their notebook:

- *Is the shape of orbits enough to predict a future collision between Earth and a space object? Why or why not?*
- *What additional information would you need to predict where and/or when a collision could occur?*

Collect student notebooks and models for assessment at the end of the day.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

Look for students' work to

- include evidence of the eccentricity of the orbits of Earth and the Peekskill meteor in a model of the orbits of each space object. (SEP: 2.3; DCI: ESS1.B.1)
- include different elements in the model, including the Sun, Earth, and the Peekskill meteor. (SEP: 2.3)
- use the model to show how the orbits of Earth and the Peekskill meteor help explain why these objects collided. (SEP: 2.3; DCI: ESS1.B.1)
- describe the limitations of this type of model to predict a potential collision between Earth and a space object with more accuracy, including lack of information about the actual position at different points in time, the velocity of the objects, or the plane of the orbits. (CCC: 4.4)

What to do: Sometimes students can struggle with developing ideas about the limitations of their model being able to make predictions. If they do, ask them to think about how many dimensions we are accounting for in our models. See *Example Collision Model* for an example of how this model looks when using the materials suggested for this activity and the data for developing the orbit.

Building toward 4.A.2 Develop and revise a model based on evidence of the orbital features of space objects to explain why space objects can collide with Earth, highlighting the limitations of the model in predicting future collisions. (SEP: 2.3; CCC: 4.4; DCI: ESS1.B.1)

10 · UPDATE PERSONAL GLOSSARY AND PROGRESS TRACKER

8 min

MATERIALS: colored pencils, *Progress Tracker*

Add words to Personal Glossaries. Present **slide X**. Say, *Having shared language for things can help us communicate about what we are seeing within data.* Ask students what new terms we started using in this lesson to describe the phenomenon. Look for students to suggest words like *ellipse*, *foci, semimajor axis,* and *eccentricity*. Discuss these words as a class to make sure everyone has a shared definition and then give students a minute to record their definitions in their Personal Glossary.

Example student definitions

- Ellipse: a round shape formed by tracing with a string around two foci, also includes circles
- Foci: the points where the pushpins go to make an ellipse with a string
- Semimajor axis: the distance from the center of an ellipse out to the farthest point, equal to the radius for a circle.
- Eccentricity: how squished or stretched out an ellipse is from being a circle. Higher eccentricity means more stretched, with foci farther apart.

Update Progress Trackers. Present **slide Y**. Ask students to get out their *Progress Tracker* and review what they have recorded so far. Then, using the slide, ask them to think about what they have to add to their Progress Tracker and take a couple minutes to discuss with a partner near them. See the *Progress Tracker KEY* for a sample entry.

Distribute or have students collect colored pencils to continue their Progress Tracker. Have students individually add to their Progress Tracker considering the prompt:

- *Use words and representations that have helped you make sense of the motion and interactions of space objects.*

11 · NAVIGATE

2 min

MATERIALS: None

Consider other factors for colliding versus missing space objects. Present **slide Z**. Ask students to share some of their ideas about the prompt:

- *Is the shape of orbits enough to predict a future collision between Earth and a space object? Why or why not?*
- *What additional information would you need to predict where and/or when a collision could occur?*

Accept all answers.

ADDITIONAL GUIDANCE

The goal of this discussion is to highlight the stringent conditions required for a space collision to occur. By addressing questions about intersecting orbits and the orbit path of an object, the focus is on clarifying that intersecting orbits alone do not guarantee collisions. The aim is to create awareness that perfect conditions, beyond mere intersection, must align for space collisions to occur. Reinforce the idea that seeing the lines cross in a 2-D model does not necessarily mean that the orbits cross in 3-D space. This discussion will serve as a motivation for the need to learn about speed in orbits as a crucial factor in collision predictions.

Motivate a closer look at the motion of objects in their orbits by summarizing our ideas. Say, *An intersection between two orbits is more likely when one or both of the orbits are elliptical.* Cross your arms to show that when you say "intersection", you mean a place where two lines cross.

Then say, *Just like how we see more accidents at an intersection in a city because we have cars going in different directions, we think that will be where we will see a collision in space. But just because there is an intersection, doesn't mean the objects will be there at the same time. Next time, let's see if we can predict when the objects will be at this intersection so we can know if there will be a collision.*

Additional Lesson 4 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

These are the ELA-related ideas that students are using in this lesson:
CSS.ELA-ELA/Literacy -RST.11-12.1 Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.

Students will use *Objects in Space* to distinguish between comets, asteroids, and meteor showers, clarifying gaps in their understanding from Lesson 1 that are connected to related phenomena they analyzed in that lesson.

CCSS.ELA-LITERACY.RST.9-10.7 Translate quantitative or technical information expressed in words in a text into visual form (e.g., a table or chart) and translate information expressed visually or mathematically (e.g., in an equation) into words.

Students represent two of the types of space objects and their orbital paths on paper, translating technical information about the eccentricities and semimajor axes of Earth's and the Peekskill meteor's orbits to create their models. The representation they create serves the purpose of predicting why or whether something collides with Earth and others don't, addressing questions that emerged in Lesson 1.

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH	**Number and Quantity** CCSS.MATH.CONTENT.HS.N-Q.2 **Quantities:** Reason quantitatively and use units to solve problems. Define appropriate quantities for the purpose of descriptive modeling. Students define the parts of the orbit, including the semimajor axis and the distance between foci, to calculate the eccentricity of orbits.

LESSON 5: How do objects travel within their orbit paths?

PREVIOUS LESSON

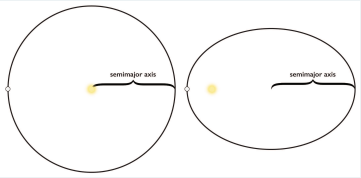
We explored elliptical orbits and their properties. We read about objects in space that may have the potential to collide with Earth and modeled the orbits of Earth and the Peekskill meteor to explain their collision. We wondered how we would know if objects whose orbits cross will actually meet at the crossing point and collide.

THIS LESSON

INVESTIGATION

2 days





We want to know more about how to predict the motion of orbiting objects and decide to investigate the speed of objects in elliptical orbits. We look at a simulation of orbits and notice that the speed of objects in elliptical orbits changes along the path. We use energy thinking to make sense of this and construct energy transfer diagrams to model this change. We make predictions about the orbit of the Chelyabinsk meteor based on what we have figured out that we can test against scientists' predictions next time.

NEXT LESSON

We will wonder if gravitational forces can change orbital paths and will consider the limitations of our two-object models. We will look at an image of our solar system with the asteroid belt and will make predictions as to what could lead to the redirection of the Chelyabinsk meteor from the asteroid belt towards Earth. We will develop models for the two possibilities: gravitational forces from other objects or a collision with another asteroid.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2



WHAT STUDENTS WILL DO

5.A Develop and use an energy transfer model that illustrates how energy flows and is conserved within an elliptical orbital system between the orbiting object and the gravitational field. (SEP: 2.3, 5.2; CCC: 5.1, 5.3; DCI: ESS1.B.1, PS2.B.1, PS3.A.2, PS3.B.2)

WHAT STUDENTS WILL FIGURE OUT

- Orbiting objects move faster when closer to the Sun and slower when farther away.
- Speed changes of orbiting objects are related to the distance between the orbiting object and the Sun and are due to energy transfer between the object and the Sun and the gravitational field between them.

Lesson 5 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	5 min		**NAVIGATE** Facilitate discussion of factors that determine whether orbiting objects collide and factors that can change the severity of the collision.	A-C	
2	9 min		**EXPLORE ORBITS AND SPEED** Compare the speed of objects for high- and low-eccentricity orbits.	D-G	chart paper, chart paper markers, https://astro.unl.edu/classaction/animations/renaissance/kepler.html
3	21 min	☑	**USE M-E-F FRAMING TO MODEL ORBITAL SPEED** Guide students to consider M-E-F framing and structure investigations on energy and force in orbits.	H-L	*Orbital Energy Transfer*, color pencils, https://astro.unl.edu/classaction/animations/renaissance/kepler.html
4	7 min		**BUILD A CONSENSUS MODEL** Pull students together for a Scientists Circle to develop an initial consensus model for M-E-F perspectives of orbital motion.	M	*Orbital Energy Transfer*, chart paper, chart paper markers
5	3 min		**NAVIGATE** Discuss the need for further investigations to understand the flow of energy in elliptical orbital motion.	N	Ideas for Investigations and Data We Need poster, chart paper markers
					End of day 1
6	3 min		**NAVIGATE** Discuss the energy of orbital motion and qualities of an orbit that explain changes in velocity.	O	
7	21 min		**CONCEPTUALIZE FLOW OF ENERGY** Use a pendulum model to draw connections to the flow of energy in an elliptical orbital system.	P-T	*Energy Transfer Investigation*, chart paper, chart paper markers, impactor with weight of 20-80 g (see *Making Impactors*), fish line string with length of 50 cm
8	15 min	☑	**USE MATHEMATICAL THINKING** Identify the variables in stored energy and kinetic energy equations and use them to make predictions for stages of pendulum and orbital motion.	U-V	*Energy Transfer Investigation*, calculator
9	6 min		**NAVIGATE BY MAKING PREDICTIONS** Use our energy transfer model to make predictions about the severity of the Chelyabinsk meteor collision and changes in orbital paths.	W-X	
					End of day 2

Lesson 5 • Materials List

	per student	per group	per class
Lesson materials	• science notebook • *Orbital Energy Transfer* • color pencils • *Energy Transfer Investigation* • calculator		• chart paper • chart paper markers • https://astro.unl.edu/classaction/animations/renaissance/kepler.html • Ideas for Investigations and Data We Need poster • impactor with weight of 20-80 g (see *Making Impactors*) • fish line string with length of 50 cm

Materials preparation (30 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch all the images and handouts so they can be added to students' notebooks.

Lesson 5 • Where We Are Going and NOT Going

Where We Are Going

The goal of this lesson is to develop understanding about and model how objects move around their orbital paths. Focus is given to velocity and how it changes as objects move around elliptical (noncircular) orbits (Kepler's second law). To illustrate the mechanism behind this change in velocity, students model the energy transfer between the objects and the gravitational field in an orbital system. Students will use these ideas about energy transfer through gravitational fields during the mid-unit transfer task (Lesson 7).

This lesson is designed to coherently build new ideas related to the following disciplinary core idea:

- **ESS1.B.1** Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. ~~Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system.~~ (HS-ESS1-4)

This lesson asks students to apply disciplinary core ideas that they have been developing over several units, which are key to the sensemaking in the lesson. These include the following:

- **PS2.B.1 Definitions of Energy.** Newton's law of universal gravitation ~~and Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic~~ forces between distant objects. (HS-PS2-4) (HS-PS3-1),(HS-PS3-2)
- **PS3.A.2 Definitions of Energy.** At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, ~~sound, light, and thermal energy~~. (HS-PS3-2) ~~(HS-PS3-3)~~
- **PS3.B.2 Conservation of Energy and Energy Transfer.** Energy cannot be created or destroyed, but it can be transported from one place to another ~~and transferred between systems~~. (HS-PS3-1),~~(HS-PS3-4)~~

This lesson is designed to continue to target **SEP 2.3**:

- Develop, ~~revise,~~ and/or use a model based on evidence to illustrate and/or predict the relationships ~~between systems or~~ between components of a system.

This lesson is designed to support target **SEP 5.2**:

- Use mathematical, ~~computational, and/or algorithmic~~ representations of phenomena ~~or design solutions~~ to describe and/or support claims and/or explanations.

This lesson coherently connects to CCCs related to energy:

- **5.1** The total amount of energy ~~and matter~~ in closed systems is conserved.
- **5.3** Energy cannot be created or destroyed—only moves ~~between one place and another place,~~ between objects and/or fields, ~~or between systems~~.

While students will not develop the idea in this unit that the total amount of matter in closed systems is conserved, they will investigate the flows of matter within the system to explain the changes in the amount of matter of the meteor as it moves through Earth's atmosphere (Lesson 11), when it hits the surface (Lesson 10), and after the collision (Lesson 14).

Students will not co-develop definitions for new vocabulary in this lesson.

Where We Are NOT Going

The speed of objects around elliptical orbits is not quantitatively addressed. This would go beyond the scope of the math appropriate for this course.

The area-sweeping model of Kepler's second law is also not addressed because it does not coherently enrich students' sensemaking about the anchoring phenomenon.

In some instructional materials, energy transfer is discussed in terms of energy transformations from one form of energy (i.e., potential energy) into another form (e.g., kinetic energy). This approach assumes that potential energy is a property of an object rather than of systems. We adopt an approach that integrates energy transfer, systems, and fields rather than introducing forms of energy beyond kinetic energy and energy stored in fields. Defining systems as the unit of investigation where energy is transferred in and out will allow students to see fields as a key part or component of the system where energy can be stored based on the relative position of two interacting objects.

LEARNING PLAN for LESSON 5

1 · NAVIGATE

5 min

MATERIALS: None

Review findings about space collisions. Present **slide A**. Remind students that we decided that the shape of an orbit can help us predict a future collision with Earth. Use the slide prompts to elicit some ideas about needed additional information:

- *How could the shape of an orbit help us predict whether an object will collide with Earth?*
- *What additional information about the Earth-object system did we want to collect to help us predict?*

Look for the following ideas:

- If the orbit intersects with Earth's orbit, there is a possibility of a collision.
- We need to know the object's speed, where it is, and when it will be at the intersection.

Motivate measuring speeds in a simulation. Present **slide B**. Say, *The speed of space objects seems to be an important factor to consider. Because of the enormous scale of the solar system, we won't be able to observe the motion of objects in space unless we wait for months, and it requires equipment that we don't have. What have we used in the past to investigate systems at scales that are too big or too small to manipulate directly in the classroom?*

Look for students to suggest using a simulation.

Develop ideas about the use of the simulation. Present **slide C**. Remind students about when we looked at atoms in a wire in *Wire Simulation Investigation*, or when we looked at tectonic plate motion in *Particle Investigations* we used those simulations to investigate something specific that we could not do ourselves. Use the slide prompt to develop ideas about what we would want to be able to do with the simulation:

- *What would we want to be able to change in a simulation to investigate the speeds of various orbiting objects?*

In addition to speed, look for ideas about changing the shape of the orbit or some of the factors that affect the shape, such as distance.

If students do not have any ideas, ask, *What do we need to be able to change to see how objects with really elliptical orbits move?*

Then say, *I have a simulation where we can change the shape of the orbits, and then we can measure its speed. Let's see what we can figure out.*

2 · EXPLORE ORBITS AND SPEED

9 min

MATERIALS: science notebook, chart paper, chart paper markers, https://astro.unl.edu/classaction/animations/renaissance/kepler.html

Set up a data table to record orbital speeds. Say, *Let's set up a data table to keep track of what we notice about objects with various eccentricities. Take a moment to go into your Personal Glossary and turn and talk with a partner about what eccentricity describes and how it is related to the shape of an orbit.*

After a minute, present **slide D** and use the slide prompt to have students set up a data table in their science notebook for our observations in speed:

Eccentricity of orbit	Speed observations
0.70	
0.50	
0.30	
0.00	

Observe the speed of orbiting objects. The notes below outline different parts of discussion and a demonstration of the simulation that you work through with your students. We recommend using **slide E** as teacher guidance only. In other words, we suggest that you project the simulation in front of the classroom so all your students can have a good visual access to it; the slide will guide you through the main discussion points for while you are projecting the simulation.

Guidance from **slide E**

1. Display the simulation: https://astro.unl.edu/classaction/animations/renaissance/kepler.html
2. Decrease the eccentricity to 0.00 and start animation.
3. Select the "Newtonian Features" tab in the bottom left and check the box to show the velocity vector.
4. Orient students to the blue line and axis that shows velocity on the graph.
5. Increase the eccentricity to the maximum (0.70) and allow time for students to take and record observations.
6. Decrease the eccentricity to 0.50 and give time for taking and recording observations.
7. Decrease the eccentricity to 0.30 and give time for taking and recording observations.
8. Decrease the eccentricity to 0.00 and give time for taking and recording observations.

Elicit findings from speed investigation. Present **slide F**. Use the slide prompts to invite some volunteers to share their observations.

Suggested prompt	Sample student response
What did you observe about the velocity when the orbit had a high eccentricity--0.70?	The speed changed as the object went around. The graph became curvy. The object went faster when it was near the Sun. When the object was farther away from the Sun it moved slower.

Suggested prompt	Sample student response
What did you observe happened to the velocity when the eccentricity of the orbit decreased?	The speed was becoming more constant. The graph was closer to being a horizontal line. The velocity vector stayed the same length more often.

Make a prediction. Present **slide G**. Tell students that scientists know that the Chelyabinsk meteor had an elliptical orbit with an eccentricity of 0.60. For extra support you may draw an orbit with eccentricity of 0.60 on a poster or whiteboard. Use the prompts on the slide to get students to turn and talk about the motion of the Chelyabinsk meteor:

- *What can we predict about the motion of the meteor along its orbit?*
- *Would it matter where along its orbit the collision occurred with Earth? Why or why not?*

Listen for the following ideas:

- It is like the elliptical orbit motion.
- Collision would be worse if it was during a fast section.
- Collision would not be so bad if it was during a slow section.

Accept all answers.

Say, *It sounds like we have some ideas regarding the motion of the Chelyabinsk meteor. The severity of space collisions is something we can actually figure out if we understand the motion of space objects in orbits.*

3 · USE M-E-F FRAMING TO MODEL ORBITAL SPEED

21 min

MATERIALS: *Orbital Energy Transfer*, color pencils, https://astro.unl.edu/classaction/animations/renaissance/kepler.html

Consider possible models to help with sensemaking. Present **slide H** and use the prompt to ask students what models or perspectives we have that might help us make sense of our observations of the speed of objects in orbits.

Suggested prompt	Sample student response
What M-E-F perspectives do we have that might help us explain why the velocity of objects changes as they go around elliptical orbits?	Gravity force equation. Matter-Energy-Forces Perspective triangle. Kinetic energy, since it has to do with velocity.

Say, *It seems like an energy perspective is going to be an important perspective to use for sensemaking here since many of the other models or perspectives you mentioned have energy as the central focus or as a component, like in the gravity force equation. So let's use this perspective of energy to model orbital speed. A force perspective might also help us with sensemaking. Let's also use this perspective in our models.*



Develop a model. Present **slide I**. Distribute *Orbital Energy Transfer* and colored pencils to each student. Display the simulation with an orbiting object with an eccentricity of .700 with the animation playing and the velocity vectors displayed. Direct students to use their findings and the https://astro.unl.edu/classaction/animations/renaissance/kepler.html to create a model for an object orbiting the Sun with a high eccentricity. Emphasize that students should first model what is happening with matter and then explain where the energy of the orbiting objects transfers to and from as its speed changes. See assessment guidance in this *Teacher Guide* for what to look for and how to support students in the moment.

Give students 10 minutes to complete part A of the *Orbital Energy Transfer* handout.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment

- Students mention where energy is transferred to when the orbiting object slows down. (CCC: 5.3; PS3.B.2)
- Students mention where energy is transferred from when the orbiting object speeds up. (CCC: 5.3; PS3.B.2)
- Students consider the forces acting on the orbiting object at different points and how the magnitude of the forces changes with distance. (PS2.B.1)
- Describe how these forces can cause energy transfer in or out of the object according to the direction of the motion of the object. (PS2.B.1, PS3.B.2)

What to do: This is not a moment to judge the accuracy of students' ideas about energy transfer. Instead, keep track of them as you walk around the classroom. If a majority of students don't really know where energy transfers to and from the orbiting object, highlight that as a question we need to continue exploring, because energy is neither created nor destroyed. You will explore these ideas during the discussion related to **slide R**.

Use the *Orbital Energy Key* to assess students. If students are struggling, use the guidance provided in the included rubric.

- If students are struggling to answer questions 2 and 3, revisit these ideas during the pendulum demonstration related to **slide R** when developing the energy transfer model.
- For question 3, if students struggle to think about what transferred energy into the object, ask students, *What sped the object up?*

Building toward 5.A.1 Develop and use an energy transfer model that illustrates how energy flows and is conserved within an elliptical orbital system between the orbiting object and the gravitational field. (SEP: 2.3, 5.2; CCC: 5.1, 5.3; DCI: ESS1.B.1, PS2.B.1, PS3.A.2, PS3.B.2)

ALTERNATE ACTIVITY

Extension Opportunity: The motion of an orbiting object can also be explained using a forces perspective by looking at both the changing strength of the force based on distance and the angle between the gravitational force on the object and its velocity. This is an opportunity to discuss the three types of acceleration and how they result from forces:

- speeding up: force and acceleration in the same direction as velocity
- slowing down: force and acceleration in the opposite direction as velocity
- turning: force and acceleration perpendicular to velocity

A perfectly circular orbit is a great example of turning at a constant speed. More-eccentric orbits provide a complex example of how speeding up and slowing down can combine with turning at nonright angles. Using https://astro.unl.edu/classaction/animations/renaissance/kepler.html with both velocity and acceleration vectors shown (under "Newtonian Features" tab), pause the animation at various points along the orbit. Have students look at the relationship and angle between the directions of velocity and acceleration arrows and discuss the changes in motion.

If there is time, students could also use the simulation themselves to explore this and draw out the forces and velocity on various points along the orbital path to model the types of acceleration and how they explain the changes in speed of the orbiting object.

This additional modeling could be inserted before or after students model the energy perspective. It can be motivated by coming back to students' suggestion of using a forces perspective to understand the motion of the orbiting object.

Develop energy thinking. Present **slide J**. Use the slide prompts to get students to develop ideas about the energy of the space object using their findings:

- *Where do we expect the space object to be increasing in kinetic energy as the object goes around its orbit?*
- *Where do you expect it to be decreasing in kinetic energy?*

Look for the following ideas:

- Kinetic energy increases when it speeds up.
- Kinetic energy decreases as it slows down.

Direct students to label these parts on their model in part A of the handout.

Elicit prior learning about energy conservation. Present **slide K**. Use the slide prompts to elicit prior learning about energy:

- *Where in prior units have we used either of these ideas to explain a phenomenon?*
- *When energy increases in one part of a system, it has to come from somewhere.*
- *When energy decreases in one part of a system, it has to go somewhere.*

Look for the following ideas:

- Efficiency of a system in Texas grid
- When we measured loss of energy transferred as heat to surroundings when wiring increased in distance
- When we transferred energy in compression and stretched matter in *Earth's Interior Unit*

Develop a model. Present **slide L**. Direct students to use their findings and the https://astro.unl.edu/classaction/animations/renaissance/kepler.html to create a model for an object orbiting the Sun with a high eccentricity in part B of *Orbital Energy Transfer*. Give students 7 minutes to answer the prompts in part B of *Orbital Energy Transfer*.

4 · BUILD A CONSENSUS MODEL

7 min

MATERIALS: *Orbital Energy Transfer*, chart paper, chart paper markers

Develop a consensus model. Present **slide M**. Ask students to bring their science notebook and gather in a Scientists Circle. Sketch on chart paper and label the Sun and an elliptical orbit (eccentricity ~0.65). Decide with the class whether they want to start by modeling high or low velocity points on the orbit. Use student ideas to identify those high and lose velocity points on your model. Use the following prompts to gather as many ideas as possible:

Suggested prompt	Sample student response
What are the forces like at those points?	• At the low velocity points, the object is far away from the Sun, so the gravitational force is weak but still points towards the Sun. • At the high velocity points, the object is very close to the Sun, so the gravitational force is strong and points towards the Sun.
Once it slows down, where does its energy go?	• Into space • Back to the Sun (Accept all answers here and identify moments of confusion.)
Where does the energy come from to speed it up?	• From the Sun • From space (Accept all answers here and identify moments of confusion.)

As the class shares ideas, use the slide prompts to highlight areas of agreement or disagreement:

- *What do we all seem to agree on?*
- *What do we disagree on?*
- *What are some new ideas we may want to consider?*

Once all three perspectives of M-E-F have been discussed, identify any moments of confusion and motivate the need to learn about those confusing ideas, particularly about the unbalanced forces on the orbiting object and how those forces are the mechanism that transfers energy.

5 · NAVIGATE

3 min

MATERIALS: Ideas for Investigations and Data We Need poster, chart paper markers

Develop ideas for investigations and data. Present **slide N**. Say, *In our model, we have some ideas we disagreed on or had some confusion about.* Use the slide prompt to elicit some ideas:

- *What further investigations or data do we need to support our thinking?*

Point out some of the questions that students had related to the energy of a space object as it goes around its orbit. As students share these ideas with the class, make a public record of them on the Ideas for Investigations and Data We Need poster to refer to across later lessons. Suggest we start next time by trying to make progress on that series of questions.

End of day 1

6 · NAVIGATE

3 min

MATERIALS: None

Consider investigation difficulty. Present **slide O**. Remind students that in the previous class we had tried to model the energy of orbital motion but struggled to do so. Say, *Last time, we wanted to investigate the flow of energy to better understand how we can predict the motion of orbiting objects.* Use the prompt on the slide to get students to think about why energy investigation for space objects is difficult to do:

Suggested prompt	Sample student response
What makes it difficult to directly investigate where energy is stored and transferred to space objects?	It would be hard for us to observe the motion of actual space objects. We don't have the tools to do so. The objects are far away.
What tools and resources do we have to investigate the energy of an object along its orbit?	Simulations. Physical models.

Say, *Last time, you all had a lot of ideas about how the energy of an object changes as it gets closer to and further from a large mass. An orbit is way too big a scale to recreate in a classroom. But I did think of another way that we could investigate over and over how energy changes when something is closer to Earth versus farther from Earth. Have any of you ever seen or gotten to use a pendulum before?*

7 · CONCEPTUALIZE FLOW OF ENERGY

21 min

MATERIALS: *Energy Transfer Investigation*, chart paper, chart paper markers, impactor with weight of 20-80 g (see *Making Impactors*), fish line string with length of 50 cm

Introduce the pendulum model. Present **slide P**. Demonstrate the pendulum using the instructions in the *Pendulum Demonstration Protocol* document. Use the protocol for students to make connections between the motion and energy of a pendulum and orbital motion and energy. The purpose of the pendulum model is to investigate the transfer of energy between a gravitational field and the pendulum and then draw connections to the transfer of energy of a space object in orbital motion. Distribute *Energy Transfer Investigation* to each student.

ADDITIONAL GUIDANCE	There are many ways to engage the students in the pendulum model using the instructions in *Pendulum Demonstration Protocol*. It is best to have both a physical pendulum and Slide Q playing in the background. If it is not possible to have a physical pendulum, you can still use the instructions in *Pendulum Demonstration Protocol* to guide students. However, we highly recommend doing the demonstration with a physical model as you are able to manipulate the pendulum in ways you can't with the gif. Doing the physical pendulum might give you more control over the variables you are highlighting at different steps, but it might take more time and it might be more difficult to observe changes as the pendulum sometimes moves too fast.

Observe the speed of orbiting objects. Slide Q can be used concurrently with a physical pendulum or as a replacement. You can still follow the instructions in the *Pendulum Demonstration Protocol* to guide students in understanding the flow of energy.

Connect the speed of the pendulum to orbits. Present **slide R**. Use the slow-motion gif of the pendulum swinging. Say, *Let's think about the speed and kinetic energy of the pendulum and connect it to orbits. What do you notice about its kinetic energy?*

See the prompts in *Pendulum Demonstration Protocol* for more support.

Develop an energy transfer model. Present **slide S**. Say, *Because the connections are pretty strong between the pendulum and orbital motion, our energy understanding of the pendulum will be able to be applied to orbital motion. Let's set the basis for our energy transfer model.*

See the prompts in *Pendulum Demonstration Protocol* for more support.

Introduce stored energy equation. Present **slide T**. Say, *The amount of energy stored in the gravitational field relative to Earth's surface can be calculated by simply multiplying the height of the object times the force of gravity on it. For Earth, the force of gravity is just mass times our Earth's gravity of 9.81 m/s^2 because the change in distance is not significant, but for asteroids it is a bit more complicated because the force of gravity changes as its distance from the Sun changes.*

Save this poster you made if this is your last class period for this lesson. If it is not, remember to remove the Energy transfer poster additions at the end of this period so you can add these again on the co-constructed poster you make for the next class.

8 · USE MATHEMATICAL THINKING

15 min

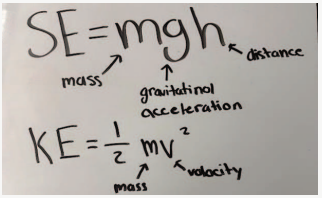
MATERIALS: *Energy Transfer Investigation*, science notebook, calculator

Analyze our models through an energy perspective. Present **slide U**. Suggest that we can use the equations we developed earlier to calculate the very, very, very small amount of velocity change Earth would also undergo as the swinging pendulum and Earth moved back together due to this energy transfer out of the field. Emphasize that for now, though, we will focus only on the amount of energy transferred into or out of the gravitational field between Earth and object 1 as the object falls back to and rises away from Earth from any given height to cause changes in its kinetic energy.

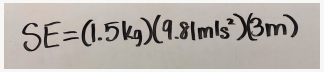
With your class. Distribute calculators to each student and guide students into calculating the kinetic energy and stored energy for both the pendulum and an asteroid for stage 1:

On a poster, whiteboard, or projector draw or show stage 1 of the pendulum and the orbit. Ask students: Where along the orbit did you place your asteroid for stage 1? Students should say that it is farthest from the Sun. Dot and label an asteroid point on the orbit farthest from the Sun as shown in the image. Remind students that even though the pendulum is motionless at this point, the asteroid is still moving but in its slowest motion. Ask students: What do we expect the energy to be like for the asteroid at this point in the orbit? They should say that there should be a lot of stored energy and a small amount of kinetic energy.

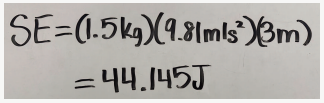
Say, OK, let's go ahead and calculate the energy amounts for both the pendulum and the asteroid. On the poster, whiteboard, or projector write or show the equations for kinetic energy and stored energy in gravitational fields. Label what each variable represents in the equations. Remind students that these equations are also found in their handout and that it might be worthwhile to label their equations as shown.



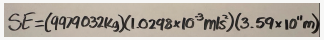
Say, Let's start with the stored energy for our pendulum. According to the data, what are the mass and the height of the pendulum in stage 1? Students should say 1.5 kg and 3 m. Set up the equation using those values and 9.81 m/s2 for g. Point out that we can use that value for gravitational acceleration because the pendulum is on Earth. Ask a student to use a calculator to calculate the stored energy and verify that another student calculated the same value.



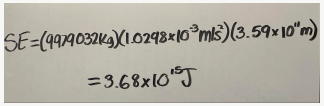
Now write the value next to the equation (44.145 J). Say, OK, let's try to calculate the stored energy for the asteroid in stage 1. Ask students, What are the mass and the height of the asteroid in stage 1?



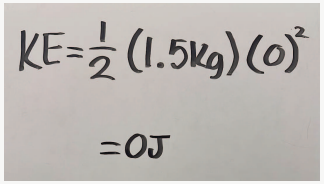
Students should say 9,979,032 kg and 3.59 x 1011 m. Now ask students if we can use the same value for gravitational acceleration. Students might be conflicted here. If students say, yes, we can use the same value, remind them that the gravity changes with height, and with our asteroid, we are dealing with a significant height change that will change the value in a significant manner. Tell them that the gravitational acceleration value is already calculated for them and to look at the table again and find the value for stage 1. They should say 1.03 x 10-3 m/s2. Set up the equation using those values from the table.



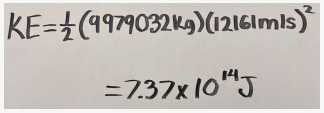
Then ask students to use a calculator and calculate the value of the stored energy (3.68 X 1015 J).



Prompt students that we now have to do the calculations for the kinetic energy for both the pendulum and the asteroid. Say, OK, let's calculate the kinetic energy for each. Let's start with the pendulum. Remember, at that point the pendulum is still for a split second. How much kinetic energy do we expect the pendulum to have at this point? Students should say that the kinetic energy is zero. Go ahead and write out the kinetic energy equation with the 1.5kg as the mass and then 0 for the velocity and then "KE = 0 J" next to the pendulum.



Move on to the calculation for the asteroid. Ask students what the mass and velocity values are for the asteroid at stage 1. They should say the values are 9,979,032 kg and 12,161 m/s. Set up the equation with the values plugged in and ask students to do the calculation on a calculator. Verify that multiple students got the same result and then write it next to the equation with the values (7.37 x 1014 J). Say, Do our energy values make sense with our previous predictions? Students should say yes. Now prompt students to calculate the energy amounts for stages 2 and 3 of the pendulum-Earth system and the asteroid-Sun system. Remind students that we can keep using the same respective masses for each system because the mass is conserved due to the fact that the masses are not changing.



With a partner. Prompt students to work with a partner and use the jigsaw strategy for the calculations for stages 2 and 3 so that each pair of students calculates the energy for only one more stage and then they can share their findings with another pair. Remind them to label the location of the asteroid along its orbit for their stage. Prompt them to also complete the questions at the end of the handout.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: See *Energy Transfer Investigation KEY* for guidance.

- Students develop a mathematical energy transfer model that shows an equal amount of energy transfer between the field and the object. (SEP: 2.3, DCI: PS3.B.2)
- Students use their mathematical energy transfer model as evidence to show that the asteroid-Sun system is closed because there is an equal amount of energy transfer between the field and the asteroid. (SEP: 2.3, 5.2, CCC: 5.1, DCI: PS3.B.2, PS3.A.2)
- Students use their mathematical energy transfer model as evidence to show that Kepler's law is valid because the object experiences high and low kinetic energy points along its path. (SEP: 2.3, 5.2, DCI: ESS1.B.1, PS3.A.2)
- Students identify that they can use their mathematical energy transfer models to predict where and how fast an orbiting object will be along its path. (SEP: 2.3, DCI: ESS1.B.1, PS3.B.2)

What to do: Use the *Energy Transfer Investigation KEY* to assess students. If students are struggling, use the guidance provided in the included rubric.

- Sometimes, students will incorrectly use the values for each stage for the orbital motion. Encourage students to revisit the data for each stage and verify that they used the correct data for the calculations.
- Sometimes, students can struggle with calculating the changes in energy between stages. Encourage students to think about how we refer to changes in energy as an after-minus-before process.
- When students are asked to provide evidence that the Sun-asteroid system is a closed system, students can potentially struggle with thinking about energy transferring in or out of the Sun-asteroid system. Encourage students to think about whether there are any other forces, besides the gravitational force between the two objects, interacting with the system that might be transferring energy in or out of it.
- During the mid-unit transfer task, students will use the kinetic energy equation to calculate the amount of energy of an object at the moment of collision with another object. Consider providing additional practice questions at the end of this lesson where students need to calculate the kinetic energy of orbiting objects with varying velocities and masses.
- During the mid-unit transfer task, students will consider how a gravity tractor can transfer energy to an asteroid to change its orbit. See how students describe energy transfer between the object and the gravitational field. If students only mention the values of kinetic energy and energy stored in fields, provide feedback that prompts them to describe whether and how energy is transferred in the system.

Building toward 5.A.2 Develop and use an energy transfer model that illustrates how energy flows and is conserved within an elliptical orbital system between the orbiting object and the gravitational field. (SEP: 2.3, 5.2; CCC: 5.1, 5.3; DCI: ESS1.B.1, PS2.B.1, PS3.A.2, PS3.B.2)

Share findings. Present **slide V**. Invite some volunteers to share their findings about the energy of the pendulum and the asteroid's orbit. Use the slide prompts to elicit findings:

Suggested prompt	Sample student response
What patterns do you notice about the changes in energy?	Whenever kinetic energy decreases, stored energy increases in equal amounts.

Suggested prompt	Sample student response
What do your patterns tell us about the energy transfer of the object?	Whenever stored energy decreases, kinetic energy increases in equal amounts.

Say, *Right, we can clearly see how our changes in energy are consistent throughout the stages. That means we can say the energy is conserved. We just proved that energy does flow in and out of the system and is not being created or destroyed as our kinetic energy levels change.*

9 · NAVIGATE BY MAKING PREDICTIONS

6 min

MATERIALS: None

Apply our models. Present **slide W**. Once students finish their models, use the slide prompt to get students to think about the application of their models:

- *How can we use these models and patterns to predict where an object will be along its orbital path and predict a future collision?*

Look for the following idea:

- We can use them to predict where an object will be and how fast it is going through the calculations.

Navigate with an exit ticket. Present **slide X**. Say, *We have figured out a lot about the motion of space objects, their energy as they move, and how gravitational force from massive objects can cause orbital motion.* Pose the following prompt as an exit ticket:

- *Using what we have figured out, sketch a quick model of what you think the orbit of the Chelyabinsk meteor might have looked like in the solar system before it collided with Earth. Make it clear where in the orbit you think the collision happened.*
- *Use your model to explain: What was the kinetic energy of the Chelyabinsk meteor like at the point in its orbit where it collided with Earth?*

Collect the exit tickets. Say, *Let's come back to these next time and see if we are right.*

Additional Lesson 5 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

Number and Quantity
CCSS.MATH.CONTENT.HS.N-Q.2 **Quantities:** Reason quantitatively and use units to solve problems. Define appropriate quantities for the purpose of descriptive modeling.

Students define the parts of a Sun-asteroid system and a pendulum-Earth system. They define different quantities to calculate energy conservation in these systems.

Algebra
CCSS.MATH.CONTENT.HS.A-SSE.1a **Seeing Structure in Expressions:** Interpret the structure of expressions: Interpret parts of an expression, such as terms, factors, and coefficients.

Students interpret what the parts of the equations of kinetic energy and energy stored in fields mean in the real world.

LESSON 6: How can force interactions in space change the orbital path of a space object?

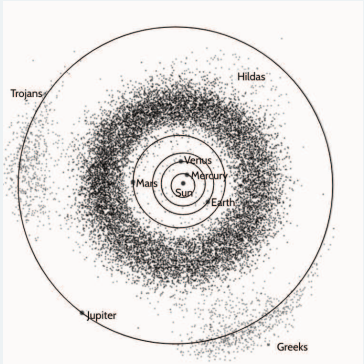
PREVIOUS LESSON

We wanted to know more about how to predict the motion of orbiting objects and decided to investigate the speed of objects in elliptical orbits. We looked at a simulation of orbits and noticed that the speed of objects in elliptical orbits changes along the path. We used energy thinking to make sense of this and constructed energy transfer diagrams to model this change. We made predictions about the orbit of the Chelyabinsk meteor based on what we have figured out that we can test against scientists' predictions next time.

THIS LESSON

INVESTIGATION

1 day



Adapted from: Mdf at English Wikipedia

We are wondering if gravitational forces can change orbital paths and consider the limitations of our two-object models. We look at an image of our solar system with the asteroid belt and make predictions as to what could have led to the redirection of the Chelyabinsk meteor from the asteroid belt towards Earth. We develop models for the two possibilities: gravitational forces from other objects or a collision with another asteroid.

NEXT LESSON

We will read about two strategies designed to deflect hazardous impactors on a collision course with Earth. We will use data collected by scientists and some of the mathematical models we have developed in this unit to explain how these strategies work.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

11.A Develop models of the forces due to gravitational interactions from Jupiter and forces from collisions with other space objects and use these models to predict how the orbit of the Chelyabinsk meteor can be changed by different types of force interactions in space to evaluate our working model of space collisions. (SEP: 2.3, 4.5; CCC: 4.4; DCI: ESS1.B.1, PS2.B.1)

WHAT STUDENTS WILL FIGURE OUT

- Scientists believe that the Chelyabinsk meteor was likely redirected by a combination of collisions and gravitational forces from nearby objects.
- Many meteors that collide with Earth come from the asteroid belt where they could have been redirected by collisions with other asteroids or by the gravitational forces from nearby objects.

Lesson 6 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	5 min		**NAVIGATE** Make predictions about what could have led to the redirection of the Chelyabinsk meteor from the asteroid belt towards Earth.	A-B	
2	10 min		**DEVELOP MODELS OF CHELYABINSK REDIRECTION FROM ITS ORBIT** Direct students to develop models that show how contact forces and forces at a distance could have caused the redirection of the Chelyabinsk meteor.	C	*Redirection of Asteroids*
3	15 min		**COMING TO CONSENSUS** Send students on a gallery walk to compare models to find similarities and differences about how the Chelyabinsk meteor could have been redirected.	D-E	*Redirection of Asteroids*, prepared Possibilities poster, chart paper markers, painter's tape
4	13 min		**READ SCIENTISTS' PREDICTIONS AND NAVIGATE** Read about what scientists predict caused the redirection of the Chelyabinsk meteor and make predictions as to how often this type of redirection happens.	F-G	*Chelyabinsk Meteor's Origin*, highlighter
5	2 min		**HOME LEARNING: SELF REFLECTION** Return the models students developed in Lesson 1 to explain why some objects remain in Earth's orbit while others hit Earth.	H	student models from Lesson 1 (motion of space objects)

End of day 1

Lesson 6 • Materials List

	per student	per group	per class
Lesson materials	• *Redirection of Asteroids* • science notebook • *Chelyabinsk Meteor's Origin* • highlighter • student models from Lesson 1 (motion of space objects)		• prepared Possibilities poster • chart paper markers • painter's tape

Materials preparation (45 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch the handout so it can be added to students' notebooks.

Prepare chart paper for a poster. Title the poster "Possibilities."

Prepare *Redirection of Asteroids* printed single sided.

Lesson 6 • Where We Are Going and NOT Going

This lesson is designed to coherently build on ideas related to the following disciplinary core ideas in a new context:

- **ESS1.B.1 Earth and the Solar System.** Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system.
- **PS2.B.1 Types of Interactions.** Newton's law of universal gravitation and ~~Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic~~ forces between distant objects. (HS-PS2-4)

Students have developed ideas about orbits, and how they are determined by gravitational interactions between two objects. In this lesson they will add the understanding that gravitational effects from a third body can change the orbit of a planet. In the next lesson they will learn and analyze two strategies designed to deflect hazardous asteroids on a collision course with Earth.

Students will rely on a force frame to consider gravitational interactions in this lesson. They will apply ideas from Newton's Universal Law of Gravitation throughout this lesson.

Students will encounter or co-develop definitions for the following word in this lesson: *perturbation.* **Do not** post any words or ask students to add them to their Personal Glossaries until after the class has developed a shared understanding of their meaning.

LEARNING PLAN for LESSON 6

1 · NAVIGATE

5 min

MATERIALS: None

Make predictions about the limitations of our models. Present **slide A**. Say, *Last time, you made predictions about what the orbit of the Chelyabinsk meteor might have looked like before its collision with Earth. I looked up what scientists have predicted, and the leading theory is that the Chelyabinsk meteor had a close to circular orbit and was in the asteroid belt. Turn and talk with a partner about how this theory compares to your prediction. Does it surprise you?*

After a minute, ask students to share with the class. Look for students to say that they had expected the Chelyabinsk meteor to be in a much more elliptical orbit.

Then ask the second and third questions on the slide*:*

- *What are the limitations of our model?*
- *What are we not including that could explain why it failed to predict where the Chelyabinsk meteor was?*

Look for the following idea:

- Our model only really had 2 or 3 objects in it.

Make predictions about the redirection of the Chelyabinsk meteor. Present **slide B**. Ask the questions on the slide to generate ideas about the redirection of the meteor*:*

- *Is it possible that the orbit of an object like the Chelyabinsk meteor could be changed by something?*
- *What types of force interactions could lead to a change in the orbit of a space object?*

Look for the following ideas:

- a collision with another meteor
- the gravitational pull from a planet like Jupiter or Mars

2 · DEVELOP MODELS OF CHELYABINSK REDIRECTION FROM ITS ORBIT

10 min

MATERIALS: *Redirection of Asteroids*



Model redirection of meteor. Present **slide C**. Direct students to show their thinking about what the two possibilities for the redirection of the Chelyabinsk meteor might look like. Distribute *Redirection of Asteroids*. Give students 10 minutes to use the instructions in the handout to develop their models. Have students tape their models to the wall.

ASSESSMENT OPPORTUNITY

What to look/listen for

- Students model a 2 body system with the Chelyabinsk meteor and Jupiter that can result in a redirection of the Chelyabinsk meteor (SEP 2.3,DCI: PS2.B.1)
- Students are using an arrow facing toward Jupiter to model the gravitational force on the Chelyabinsk meteor from Jupiter. (SEP: 2.3; DCI: PS2.B.1)
- Students label the force on the Chelyabinsk meteor from Jupiter as the force of gravity. (SEP: 2.3, DCI: PS2.B.1)
- Students predict that the force they modeled will result in the Chelyabinsk meteor speeding up or slowing down and moving slightly more in the direction of Jupiter (a wider orbit than expected). (SEP: 2.3, DCI: ESS1.B.1, PS2.B.1)
- Students predict that the force they modeled will result in minimal changes in the speed and direction of Jupiter. (SEP: 2.3 DCI: ESS1.B.1, PS2.B.1)
- Students model a collision with an asteroid that will result in a change of the orbit of the Chelyabinsk meteor to be in the direction towards Earth. (SEP: 2.3; DCI: ESS1.B.1)
- Students identify the force that results in the change in orbit to be a collision or impact force. (DCI: ESS1.B.1)
- Students identify that our models inherently cannot be entirely accurate due to the limitations of our understanding in scale, our inconsideration of other space objects, and/or the precision in the changes in motion for the Chelyabinsk meteor. (CCC: 4.4)

What to do

- Point students to their Progress Tracker to help remind them of our modeling conventions for forces.
- Use probing questions such as the following to help students see that our scenario is just another 2-body problem:
    - *What are the objects we need to consider?*
    - *What objects are creating the gravitational field?*
    - *Do we have to consider the gravitational force from nearby asteroids? Why or why not?*
- Ask students to look back in their notebook at Newton's law of gravitation to think about how the distance between the two objects might affect the force.
- Ask students to look back in their notebook at how collisions between two objects can affect the motion of the objects.
- Ask students to consider how accurate our predictions are based on our models and what might be affecting that accuracy,
- During the mid-unit transfer task, students will consider how a gravity tractor can alter the orbit of an asteroid without touching it. To ensure that all students can explain how forces at a distance can affect the orbit of a space object, walk around the classroom looking at the representations they use to explain how the forces of Jupiter acting on the Chelyabinsk meteor could affect its orbit. Use questions such as these:
    - *In which direction would the Chelyabinsk meteor move due to the force of Jupiter acting on it?*
    - *Why could Jupiter exert a significant force on the Chelyabinsk meteor?*

Building toward: 11.A.1 Develop models of the forces due to gravitational interactions from Jupiter and forces from collisions with other space objects and use these models to predict how the orbit of the Chelyabinsk meteor can be changed by different types of force interactions in space to evaluate our working model of space collisions. (SEP: 2.3, 4.5; CCC: 4.4; DCI: ESS1.B.1, PS2.B.1)

3 · COMING TO CONSENSUS

15 min

MATERIALS: science notebook, *Redirection of Asteroids*, prepared Possibilities poster, chart paper markers, painter's tape

Prepare students for a gallery walk. Present **slide D**. Let students know that they will be interacting with some of their peers' models through a gallery walk. Ask them to prepare a T-chart in their science notebook to record similarities and differences between models.
Facilitate a gallery walk. Students should get up and rotate to see models from three other students for 1 minute each. During that time, they should discuss and write down in the T-chart in their science notebook any similarities and differences between models.

Come to consensus around the different possibilities. Present **slide E**. Bring the class together in a Scientists Circle. Use the Possibilities poster you prepared before class. You can also use a copy of the handout under a document camera. Then ask three students to volunteer to show their models to the class.

Ask the students in the circle to look for places of agreement or disagreement with their own models, such as these:

- use of arrows
- direction of arrows
- labeling of forces

Ask students to justify their ideas if they disagree with a representation. Encourage students to respond to one another as you come to consensus.

After you have come to a consensus, facilitate a discussion using the slide prompts:

- *How do we know which possibility would have a bigger impact on the path of the meteor?*
- *How do we know which possibility is more likely?*
- *What changes in our initial models do we need to make to reflect this new information about what could have caused the Chelyabinsk meteor to crash into Earth?*

Accept all answers and give students a moment to make changes to their initial models with their new ideas.

4 · READ SCIENTISTS' PREDICTIONS AND NAVIGATE

13 min

MATERIALS: *Chelyabinsk Meteor's Origin*, highlighter

Read about the scientists' predictions. Present **slide F**. Distribute *Chelyabinsk Meteor's Origin* and a highlighter to each student. Explain that we will read about what scientists think caused the redirection of the Chelyabinsk meteor from the asteroid belt so they can find out which possibility is predicted to be the most probable. Instruct them to highlight the evidence that scientists used to determine what mechanisms may have redirected the Chelyabinsk meteor from the asteroid belt towards Earth. Give them 10 minutes to read and highlight the *Chelyabinsk Meteor's Origin*.

With your class. Use the slide prompt to generate ideas about what evidence scientists used to make their predictions:

- *What evidence did scientists argue with to determine what redirected the meteor?*

Listen for the following ideas:

- The observed trajectory and speed support the idea of gravitational perturbation.
- Fragmentation of the meteor supports the idea of a collision-based redirection.

Complete an exit ticket about effects on our planet. Present **slide G**. Read the text at the top of the slide: *We figured out that there are many different interactions between objects in our solar system.* Then use the prompts on the slide as an exit ticket:

- *How do you think these many different interactions have affected Earth over time?*
- *How likely do you think it is for these interactions to cause another meteor to hit Earth again?*

Give students a few minutes to think and prompt students to share their ideas. Look for 1-2 ideas about changing Earth's orbit (which might change its climate), cratering, biological extinctions, likelihood for more collisions, etc.

Say, *Let's think about these questions more next time. Maybe we can look at some data or information about how interactions have affected Earth over its history.*

5 · HOME LEARNING: SELF REFLECTION

2 min

MATERIALS: student models from Lesson 1 (motion of space objects)

Describe home learning. Present **slide H**. Say, *I think we have made a lot of progress since we started this unit. I will give you back the models that you developed in the first lesson to explain why some objects remain in Earth's orbit while others hit Earth.*

Ask students that as a home learning, they will reflect on how their ideas have changed since the start of the unit. Use the prompts to describe the focus of their self-reflection:

- *How have your ideas changed since then?*
- *What activities, discussions, or investigations have helped you change the way you understand this phenomenon now?*

This is an important self-reflection opportunity before the summative assessment in Lesson 7.

Additional Lesson 6 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA	CCSS.ELA-LITERACY.RST.11-12.1: Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account. Students will read and analyze what scientists predict caused the redirection of the Chelyabinsk meteor. They are to highlight specific evidence scientists used to develop their argument and will cite that evidence verbally when they share with the class their ideas about what evidence scientists used.

LESSON 7: What can we do if an orbiting object poses a significant risk for Earth?

PREVIOUS LESSON

We wondered if gravitational forces could change orbital paths and considered the limitations of our two-object models. We looked at an image of our solar system with the asteroid belt and made predictions as to what could have led to the redirection of the Chelyabinsk meteor from the asteroid belt towards Earth. We developed models for the two possibilities: gravitational forces from other objects or a collision with another asteroid.

THIS LESSON

PUTTING PIECES TOGETHER

1 day





NASA/Johns Hopkins Applied Physics Lab

We read about two strategies designed to deflect hazardous impactors on a collision course with Earth. We use data collected by scientists and some of the mathematical models we have developed in this unit to explain how these strategies work.

NEXT LESSON

We will discuss how often we might need to deflect incoming objects. We will analyze a graph of the frequency of different-sized objects that have entered Earth's atmosphere over a 28-year period. We will construct a line of best fit and use it to predict the frequency of larger-mass objects reaching Earth's atmosphere. We will calculate the related kinetic energy and estimate the potential damage these could inflict.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2



WHAT STUDENTS WILL DO

Transfer Task PE: HS-PS2-4 Use mathematical representations of Newton's Law of Gravitation ~~and Coulomb's Law~~ to describe and predict the gravitational ~~and electrostatic~~ forces between objects. (SEP: 2.3, 5.2; DCI:PS2.B.1, PS2.B.2, PS3.B.2, ESS1.B.1; CCC:1.1, 3.5)

WHAT STUDENTS WILL FIGURE OUT

- Scientists are developing and testing strategies intended to deflect hazardous impactors on a collision course with Earth.
- A small spacecraft traveling at high speed can have enough kinetic energy to change the orbit of an impactor.
- A gravity tractor can slowly move an impactor into a different orbit by using the force of gravity acting between the spacecraft and the impactor.

Lesson 7 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	4 min		**BRAINSTORM STRATEGIES TO DEFLECT IMPACTORS** Ask students to brainstorm about possible strategies to change the orbit of a space object and discuss the reasons for investing in such strategies.	A	
2	6 min		**PRESENT DEFLECTION STRATEGIES** Project videos demonstrating how the gravity tractor and DART strategies work.	C–D	https://youtu.be/hpx0NeO6LYM, https://youtu.be/jtPib1wMFOE
3	35 min		**COMPLETE ASSESSMENT TRANSFER TASK** Complete an assessment about the identification of exoplanets.	E	*Changing Asteroid Orbits*, calculator, computer with access to https://youtu.be/czB61D6qwoc?si=-_iv-yVanrHupGeO (optional), computer with access to https://www.openscied.org/simulation/keplers-laws/ (optional)

End of day 1

Lesson 7 • Materials List

	per student	per group	per class
Lesson materials	• science notebook • *Changing Asteroid Orbits* • calculator		• https://youtu.be/hpx0NeO6LYM • https://youtu.be/jtPib1wMFOE • computer with access to https://youtu.be/czB61D6qwoc?si=-_iv-yVanrHupGeO (optional) • computer with access to https://www.openscied.org/simulation/keplers-laws/ (optional)

Materials preparation (15 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch all the images and handouts so they can be added to students' notebooks.

Lesson 7 • Where We Are Going and NOT Going

In this lesson we are targeting the following disciplinary core ideas related to the performance expectation we are targeting in the assessment opportunity:

- **PS2.B.1** Newton's law of universal gravitation ~~and Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic~~ forces between distant objects. (HS-PS2-4)
- **PS2.B.2** Forces at a distance are explained by fields (gravitational, ~~electric, and magnetic~~) permeating space that can transfer energy through space. ~~Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields.~~ (HS-PS2-4),(HS-PS2-5)

We are also targeting these two additional DCIs:

- **ESS1.B.1** Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. (HS-ESS1-4)
- **PS3.B.2** Energy ~~cannot be created or destroyed, but it~~ can be transported from one place to another and transferred between systems. (HS-PS3-1),(HS-PS3-4)

Students also use mathematical representations of orbital motion to support explanations about the changes in a two-object system due to a collision with a third object (SEP5). This will require students looking ahead for productive manipulations and anticipating the nature of the solution based on the units of the variables of interest being solved for.

Students will not encounter or co-develop any new definitions in this lesson.

LEARNING PLAN for LESSON 7

1 · BRAINSTORM STRATEGIES TO DEFLECT IMPACTORS

4 min

MATERIALS: science notebook

Navigate with the Exit Ticket, and connections to pop culture. Present **slide A**. Use the first slide prompt, which was the last prompt on the Exit Ticket, to elicit student responses:

- *How likely do you think it is for these interactions to cause another impactor to hit Earth again?*

Look for students to have a range of responses. Ask the second prompt on the slide: *How many of you have seen science fiction movies or TV shows, or read a book where something like this happens?* Open up the space for a minute or two for students to share connections to movies and books from pop culture that they enjoy or have connected with. Then say, *Usually they come up with a solution though, right? Let's think for a moment about what those could look like.*

Brainstorm strategies to prevent a hazardous impactor from hitting Earth. Present **slide B**. Use the slide prompts to elicit student responses:

- *What are some strategies that we could use to change the orbital path of a large space object that is likely to collide with Earth?*

Accept all ideas, from bombs to tractors. Say, *Preventing a collision with Earth isn't just a topic from pop culture. Scientists have also been exploring strategies to change the orbit of an impactor.*

2 · PRESENT DEFLECTION STRATEGIES

6 min

MATERIALS: https://youtu.be/hpx0NeO6LYM, https://youtu.be/jtPib1wMFOE

Set up the assessment. Present **slide C**. Explain to students that you have heard about two interesting strategies that scientists are considering for changing the orbit of impactors. Project the slide video that briefly shows how a spacecraft is used in this strategy. This video can be found in the following link: https://youtu.be/hpx0NeO6LYM. Present **slide D**. Project the slide video that briefly describes this strategy. This video can be found in the following link: https://youtu.be/jtPib1wMFOE. ✱
Discuss any doubts students have about these strategies before continuing.

✱ ATTENDING TO EQUITY

Universal Design for Learning. These videos are intended to provide additional *representations* for students to understand the strategies and prompts in the transfer task.

3 · COMPLETE ASSESSMENT TRANSFER TASK

35 min

MATERIALS: *Changing Asteroid Orbits*, calculator, science notebook, computer with access to https://youtu.be/czB61D6qwoc?si=-_iv-yVanrHupGeO (optional), computer with access to https://www.openscied.org/simulation/keplers-laws/ (optional)

Administer the assessment individually to students. Present **slide E**. Say, *We are going to use some of the ideas we have developed about matter, energy, and gravitational forces to explain how and why these strategies for changing the orbit of space objects could work.*

Have students prepare for the assessment. Distribute to each student one copy of *Changing Asteroid Orbits* and a calculator. Tell students they will be allowed to use the notes they recorded in their science notebook throughout the unit. ✱✱

✱ SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

Students might come with different strategies to rearrange formulas to highlight a quantity of interest. Some students might

This assessment will take students the remainder of the class period to complete. Once completed, students should turn in their assessment to you for feedback.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: See *Key: Changing Asteroid Orbits* for sample responses.

What to do: Review *Key: Changing Asteroid Orbits* for ways to modify instruction and provide feedback.

Transfer task HS-PS2-4 Use mathematical representations **of** Newton's Law of Gravitation ~~**and Coulomb's Law**~~ to describe and predict the gravitational ~~**and electrostatic**~~ forces between objects**.** (SEP: 5.2; CCC: 1.1; DCI:PS2.B.1, PS2.B.2)

Additional Lesson 7 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

Number and Quantity
CCSS.MATH.CONTENT.HS.N-RN.2 **The Real Number System:** Rewrite expressions involving radicals and rational exponents using the properties of exponents.

CCSS.MATH.CONTENT.HS.N-Q.1 **Quantities:** Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays.

In the *Changing Asteroid Orbits* transfer task, students will use expressions involving radicals and rational exponents to solve for an unknown variable.
Algebra
CCSS.MATH.CONTENT.HS.A-SSE.2 **Seeing Structure in Expressions:** Use the structure of an expression to identify ways to rewrite it.

CCSS.MATH.CONTENT.HS.A-CED.4 **Creating Equations:** Rearrange formulas to highlight a quantity of interest, using the same reasoning as in solving equations.

Students will calculate the kinetic energy of an object due to its mass and velocity. They will also use the T^2/a^3 relationship to find the semimajor axis of an orbit. Students might come with different strategies to rearrange these formulas to highlight a quantity of interest. Some students might be tempted to skip steps for rearranging the formulas, which can lead to algebraic errors. Encourage students to write every step they follow to solve an equation. You can ask students to compare their solutions with an elbow partner in order to expose them to additional ways to rearrange an equation.

be tempted to skip steps for rearranging the formulas, which can lead to algebraic errors. Encourage students to write every step they follow to solve an equation. You can ask students to compare their solutions with an elbow partner in order to expose them to additional ways to rearrange an equation.

✱ SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

You can have a couple of computers in a designated area that students can use. One computer can have access to https://www.openscied.org/simulation/gravity-orbits, while the second computer can have access to https://www.openscied.org/simulation/keplers-laws/. Let students decide which simulation can help them clarify their ideas. These models might help students explore the relationships among distance, velocity, mass, and gravity, which can help them include these variables during this assessment moment.

LESSON 8: What is the probability of a future or past meteor event impacting Earth?

PREVIOUS LESSON *We read about two strategies designed to deflect hazardous impactors on a collision course with Earth. We used data collected by scientists and some of the mathematical models we developed in this unit to explain how these strategies worked.*

THIS LESSON

INVESTIGATION

1 day



Meteor size (kg)	Frequency per year	Frequency of a single event	Kinetic energy (in J)
10,000,000	0.01	1 per 100 years	2×10^{17} J
100,000,000	0.001	1 per 1,000 years	2×10^{18} J
1,000,000,000	0.0001	1 per 10,000 years	2×10^{19} J
1×10^{10}	0.00001	1 per 1×10^{5} years	2×10^{20} J
1×10^{11}	0.000001	1 per 1×10^{6} years	2×10^{21} J
1×10^{12}	0.0000001	1 per 1×10^{7} years	2×10^{22} J
1×10^{13}	0.00000001	1 per 1×10^{8} years	2×10^{23} J
1×10^{14}	0.000000001	1 per 1×10^{9} years	2×10^{24} J
1×10^{15}	0.0000000001	1 per 1×10^{10} years	2×10^{25} J

We discuss how often we might need to deflect incoming objects and identify what types of data we need to figure this out. We analyze a graph of different-sized objects that have entered Earth's atmosphere over a 28-year period, construct a line that best fits it, and use it to predict the frequency of larger-mass objects reaching Earth's atmosphere. We calculate the related kinetic energy and estimate the potential damage these could inflict. We argue for why we should continue to invest in DART-like technologies and what this also might imply about Earth's past.

NEXT LESSON *We will share initial explanations for what might have happened to all the objects of different sizes that reached Earth from space over its 4.5-billion-year history. We will brainstorm factors besides mass that might affect what happens to these objects when they reach Earth. We will record new questions we have and sources of data and investigations that could help us answer these questions.*

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2



WHAT STUDENTS WILL DO

8.A Develop and use a mathematical model based on a function fit to data to predict the number, frequencies (proportions), kinetic energy, and scale of potential destruction from meteors of different sizes reaching Earth in the near future and the rate of such events in the past (SEP: 5.2; DCI: ESS3.B.1, PS3.B.3; CCC: 3.1).

WHAT STUDENTS WILL FIGURE OUT

- There is a linear correlation between the size and frequency of meteors reaching Earth during a 28-year data collection period.
- Although exceptionally large meteors are rare and unlikely to reach us in our lifetime, their potential impact could extend beyond city destruction, potentially altering human history.
- The mathematical relationship we've established should guide our future plans, especially regarding investments in DART-like technologies.
- While these relationships offer insights into Earth's 4.5-billion-year history, more data are needed to confirm or refute their historical predictions

Lesson 8 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	3 min		**NAVIGATE** Discuss how often we might need to deflect incoming objects and identify what types of data we need to figure this out.	A	
2	6 min		**ANALYZE DATA** Orient students to the data and axes used in a graph of the frequency of different-sized objects that have entered Earth's atmosphere per year over a 28-year period.	B-E	*Frequency vs. Mass*, *Canadian Camera Network* (optional), *Identify-Interpret Strategy (I2)* (optional), whiteboard markers, sticky notes, 1-kg (2-lb) and 10-kg (22-lb) physical weights (optional)
3	14 min		**USE MATHEMATICAL THINKING TO PREDICT FREQUENCY OF EVENTS** Discuss the patterns in the data, draw a line of best fit, determine its slope, and use it to predict the frequency of larger-mass objects reaching Earth's atmosphere.	F-K	12" ruler, *Frequency vs. Mass*, *Impactor Prediction Table*
4	9 min		**QUANTIFY DANGER** Motivate choosing a real-life equivalent that will help us quantify danger. Have students work in partners to finish the related kinetic energy and destruction calculations.	L-N	calculator, *Impactor Prediction Table*, The Chelyabinsk meteor card only from *Phenomena Cards* from lesson 1.
5	9 min		**BUILDING UNDERSTANDINGS DISCUSSION ABOUT THE SCALE OF DANGER** Build understanding of the scale of danger these events pose to us in the future and what our mathematical model predicts about what happened in the past.	O-P	
6	4 min		**NAVIGATE** Have students stop and jot their initial ideas about what happened to all the meteors predicted by our mathematical model that reached Earth over its entire history.	Q	8.5" x 11" copy paper

End of day 1

Lesson 8 • Materials List

	per student	per group	per class
Lesson materials	• *Frequency vs. Mass* • *Canadian Camera Network* (optional) • *Identify-Interpret Strategy (I2)* (optional) • 12" ruler • *Impactor Prediction Table* • calculator • 8.5" x 11" copy paper	• The Chelyabinsk meteor card only from *Phenomena Cards* from lesson 1.	• whiteboard markers • sticky notes • 1-kg (2-lb) and 10-kg (22-lb) physical weights (optional)

Materials preparation (45 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch all the images and handouts so they can be added to students' notebooks.

An optional, out-of-class reading is provided, *Canadian Camera Network*, to help answer questions that may arise related to how the mass of a meteor can be derived from a photograph. You may want to prepare some copies of this resource for any potentially interested students.

Display the scale chart from *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*, which you have previously referred to in Lesson 1 of this unit.

Slide B provides an image of a 1-kg (2-lb) mass as a reference for students. If available, you could also bring to class 1-kg and 10-kg (22-lb) physical weights used for exercise to show students--either from home or borrowed from the weight room at your school.

Lesson 8 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently build on ideas related to the following disciplinary core ideas in a new context:

- **ESS1.C.2: The History of Planet Earth**. ~~Although active geologic processes, such as plate tectonics and erosion, have destroyed or altered most of the very early rock record on Earth,~~ ~~other~~ objects in the solar system~~, such as lunar rocks,~~ asteroids, and meteorites~~, have changed little over billions of years. Studying these objects~~ can provide information about Earth's ~~formation and~~ early history.
- **PS3.B: Conservation of Energy and Energy Transfer.** Mathematical expressions, which quantify ~~how the stored energy in a system depends on its configuration (e.g. relative positions of charged particles, compression of a spring) and~~ how kinetic energy depends on mass and speed, allow~~ the concept of conservation of energy~~ to be used to predict and describe system behavior.

Students extrapolate in this lesson a mathematical model of current rates of meteor impacts to predict the rates of impacts over Earth's history, many millions of years into the past. In later lessons they will look at some of the other aspects in the crossed-out parts of the DCI listed above.

Students will rely in this lesson on an energy frame to calculate the kinetic energy of such meteors and use it to define a scale destruction and thus quantify danger from impactors. This idea will support students' sensemaking throughout the second lesson set. Since kinetic energy is dependent on the mass and velocity of the object, students will investigate in Lesson 10 which of these two variables better explains the damage a meteor can cause. They will develop the idea that the amount of kinetic energy of the meteor helps explain the changes in matter and energy in the system and the impact it can have on the planet. In Lessons 14 and 15, they will use these ideas to explain how giant meteors can alter Earth's systems.

Students will encounter the following term in this lesson: *logarithmic scale.* **Do not** post any words or ask students to add them to their Personal Glossaries until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

Students will not engage with the idea of energy conservation in this lesson. This idea was previously explored in Lesson 5.

LEARNING PLAN for LESSON 8

1 · NAVIGATE

3 min

MATERIALS: None

Discuss DART technology. Present **slide A**. Say, *Last time, we explored some technology that could prevent Earth from a future impact from a space object.* Give students a half minute to read the two questions on the slide on their own and then discuss them as a class.

Suggested prompt	Sample student response
We have technology under development to deflect potential incoming objects, such as DART, but how often do we think something like this will be needed?	Impacts from small objects are more common than impacts from larger objects. Impacts from large objects are rare. We might need it far in the future.
What kind of data could help us figure this out?	We need to know how many objects are actually out there, how many actually hit Earth, and their size.

2 · ANALYZE DATA

6 min

MATERIALS: *Frequency vs. Mass*, *Canadian Camera Network* (optional), *Identify-Interpret Strategy (I2)* (optional), whiteboard markers, sticky notes, 1-kg (2-lb) and 10-kg (22-lb) physical weights (optional)

Describe patterns in the data. Display **slide B**. Distribute *Frequency vs. Mass*. Give the class half a minute to study the data shown on the slide and handout. Then discuss as a class what patterns students notice in the data.

Sample student responses

- There are thousands of meteors that reach our atmosphere each year.
- Most are relatively small (1.0 kg).
- As the mass of the meteor increases, the number of them that reach our atmosphere each year decreases.

ALTERNATE ACTIVITY

Slide B provides an image of a 1-kg mass as a reference for students. If available, you could also bring to class 1-kg (2-lb) and 10-kg (22-lb) physical weights to show students--either from home or borrowed from the weight room at your school.

ADDITIONAL GUIDANCE

Extension Opportunity
If students ask how the mass of a meteor can be derived from a photograph, you could offer them an opportunity to explore the data collection method a bit further outside of class. Provide access to or a copy of *Canadian Camera Network* to interested students who want to investigate this further. It will describe the methodology behind the derivation of estimated mass from the photographs taken.

Orient to axes used on the graph. Display **slide C**. Explain that the graph shown on the slide is of the data we just looked at, but the way the graph axes intervals are set up may look different than most of the coordinate graphs they have previously encountered. Ask students what they notice about the increments used on the *y*-axis or the *x*-axis.

Sample student responses

- The increments for the major intervals on each axis increase or decrease by a factor of 10.
- The spacing between each minor interval changes.

ADDITIONAL GUIDANCE

Scaffolding "analyzing and interpreting data" SEP: During the second lesson set of this unit, students will analyze graphs displaying data at different scales. The prompts on **slide C** are intended as scaffolding to guide students' analysis of graphs. The goal of this scaffolding is to prompt students to pay attention to the scale shown on the *x*-axis and *y*-axis of a graph. Remove this scaffolding in subsequent by not asking these prompts explicitly to give students more responsibility in the way they engage with this practice.

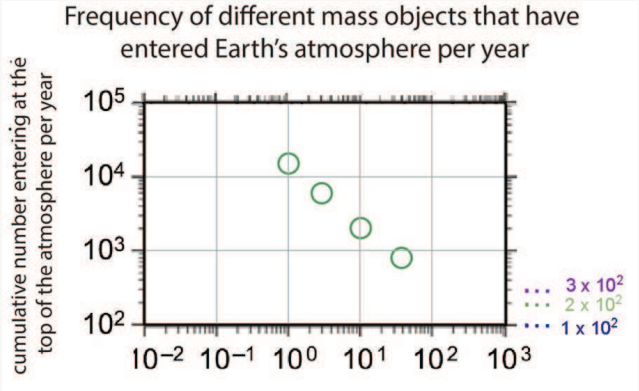
If you feel some students could benefit from additional scaffolding and support to engage in this practice, consider providing them with the *Identify-Interpret Strategy (I2)*.

Explain that this way of setting up an axis of a graph so that it uses factors of 10 at major intervals is called a *logarithmic scale* and that scientists and engineers find a logarithmic scale sometimes helps them see clearer trends in the data.

Use whiteboard markers or sticky notes to annotate a few of the minor intervals on the projected image of the graph on **slide C t**o show what each minor interval represents. Do this on the right side of the graph where there is more room to write.

Then to check understanding ask students what the value of the next minor interval would be (e.g., the next interval above $3 * 10^2$ would be $4 * 10^2$).

Make a prediction. Display **slide D**. Discuss the question on the slide as a class and follow up with the questions shown below to help students articulate the idea of using a line of best fit through the data to make this prediction.



Data source: Halliday, I. (2001)

Suggested prompt	Sample student response
How many 100-kg objects would you predict reach our atmosphere each year?	2 x 10^2 300 Between 200 and 300

Suggested prompt	Sample student response
How do the patterns from the graph help us make this prediction?	If you draw a straight line through the data points, you can see where it goes. You can visualize where the trend in the points reaches 100 kg.
What do we need as scientists in order to determine whether our prediction is correct?	We will need more data.

Orient to the sources of four additional data sets. Display **slide E**. Give students half a minute to orient to the additional types of data that scientists collected.

ADDITIONAL GUIDANCE

There is no need to discuss the data sources further at this point. If, however, students raise questions about the data (e.g., What is an infrasound measurement?), it may be helpful to provide this additional information:

- The first data set, the one we have looked at already, is represented by a green circle on the graphs.
- The second data set was from 60 different detection stations around the world. Meteors produce a very low frequency sound, below 16 Hz, which is below the range of human hearing, if they explode in the atmosphere, and that sound can be detected up to a few thousand kilometers away.
- The fourth data set is from ground-based telescopes.
- The third and fifth data sets are additional observations from satellites.

3 · USE MATHEMATICAL THINKING TO PREDICT FREQUENCY OF EVENTS

14 min

MATERIALS: 12" ruler, *Frequency vs. Mass*, *Impactor Prediction Table*

Predict frequency of an event. Present **slide F**. Distribute a ruler to each student. Ask students to look at *Frequency vs. Mass* and describe what patterns they notice in all these data. Students will say that the data appear to fall along (or very close to) a straight line (or linear relationship).

Draw a line of best fit. Suggest that we develop a line of best fit to represent the trend we think the data are showing us in order to help us make predictions for areas of the graph where we don't have data. Remind students that in the past we have used CODAP to estimate a line of best fit. Ask students what we could do to create this line ourselves. Listen for ideas about using a ruler to try to follow the trend of the data points. Have students draw a line of best fit with their ruler.

Predict frequency. Display **slide G**. Then ask students to work with a partner to consider the prompt on the slide: *Use your best-fit line to predict how often other meteors the size of the Chelyabinsk meteor will reach Earth.* Move around the room to support students as they work. Give about four minutes for this. Look for students to find an intersection between their best-fit line and ~10^{7} on the *x*-axis. This should correspond to a *y* value of approximately 10^{-2}. Note pairs that have figured this out before coming back together and asking them to share.

Discuss the meaning of (# events/year) as a class and develop a way to convert to (one event/# years). Ask, *How often does this model predict an event the size of the Chelyabinsk meteor occurs?*
Look for students to say 10^{-2} or 0.01 per year. Ask, *But what does that mean? How is one hundredth of an event happening per year?* Look for students to suggest that some years nothing happens at all. Some may suggest that it represents a 1% chance of occurrence. Suggest turning the decimal into a fraction (1/100) and then ask, *How can we interpret this fraction?* Give students a moment to process this question with a partner before calling on someone. Look for students to say that this could mean one event every hundred years. Write out this calculation clearly at the front of the room for reference.

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING SCALE, PROPORTION, AND QUANTITY

The focus of this lesson is primarily on helping students use this element of the crosscutting concept:

- The significance of a phenomenon is dependent on the scale, proportion, and quantity at which it occurs.

But taking a moment here to connect to prior work with scale gives you an opportunity to explicitly foreground how these additional *elements* of these crosscutting concepts appear to be particularly relevant to explaining and predicting the phenomena in this lesson. You may want to ask students for examples of

Develop a mathematical model. Say, *That is a much easier way to think about these events—in terms of how many years it would take for one of these to hit rather than some tiny percentage per year. For any y values that are less than 1 we should probably turn the data point we are interested in into an equivalent fraction so that we can better understand the probability that one will hit us during our lifetimes. Anything bigger than the Chelyabinsk meteor is probably going to pose a not-insignificant threat or risk, but let's figure out the predicted frequency for impactors even larger than the Chelyabinsk meteor.* Distribute *Impactor Prediction Table* to each student. Present **slide H** to guide the class in setting up the first three columns of the table on the handout and entering the values in the first row.

Mass (kg)	Frequency per year	Frequency of a single event		
10,000,000 (10^7)	0.01	1 per 100 years		
100,000,000 (10^8)				
1,000,000,000 (10^9)				

Determine an estimated slope. Suggest we look at the graph again to get an estimate of the slope of our best-fit line to help us in continuing to fill out this table. Display **slide I**. Give the class half a minute to consider the poll question on the slide and the three possible responses and then poll the class. Establish consensus around answer b (When mass increases by a factor of ten, there are about 1/10th as many of those meteors per year).

ADDITIONAL GUIDANCE

If students argue that when the mass increases by a factor of ten, that 1/10 th as many meteors is a bit off from the slope predicted, encourage them to derive a different fraction to use (e.g. there are about 1/9th as many of those meteors per year, or 10).

Use the approximate slope to continue the table. Do the next two rows together as a class, converting scientific notation to standard notation for each entry:

Mass (kg)	Frequency per year	Frequency of a single event		
10,000,000 (10^7)	0.01	1 per 100 years		
100,000,000 (10^8)	0.001	1 per 1,000 years		
1,000,000,000 (10^9)	0.0001	1 per 10,000 years		

Consider the potential limits of the mathematical model. Emphasize that the mathematical model includes only those data collected over the 28 years time period. Display **slide J**. Give students a half a minute to individually think about the question on the slide and then discuss as a class. Anticipate some uncertainty or controversy around whether the mathematical model holds beyond the range of data over which it was collected.

Connect to prior work with testing model limitations across different scales. Emphasize that a recurring practice in science is to test to see if the models that we or scientists build based on data collected at one scale hold over a much larger or a much smaller scale. ✱ Refer to the scale chart developed in *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)* and ask where we have used ideas like this in our prior two units– *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)* and *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*:

- Related to the pattern of decreasing frequency of larger-mass meteors but only having a limited amount of data we have directly observed so far: *Some systems can only be studied indirectly as they are too small, too large, too fast, or **too slow** to observe directly.*
- Related to whether the mathematical model holds over much larger scales (beyond the extents of the data collected so far): *Patterns observable at one scale may not be observable or exist at other scales.*

students to recall an example of similar thinking and wonderings we had from this unit. Listen for students to recall one or more of these examples from this current unit:

- From Lesson 2: Whether the trend in gravitational force vs. height at a smaller scale (seemingly constant at the scale of the dimensions of our room) holds over a larger scale (thousands of miles away from Earth's surface)
- From Lesson 5: Whether the trend in energy stored in a gravitational field vs. height from Earth' surface at a smaller scale (a seemingly linear relationship near Earth's surface) holds over a larger scale (ends up being nonlinear when viewed thousands of miles away from Earth's surface)

Suggest that we try to extend the mathematical model to see what it predicts for larger mass and over longer timescales to evaluate whether the predictions seem reasonable, and then determine what additional data we could gather to try to support or refute those predictions.

Use mathematical models to make predictions. Display **slide K**. Give students three minutes to work with a partner to fill in the predictions for 6 additional rows on *Impactor Prediction Table*. Move around the room to support students as they work.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment

- Students accurately determining the frequency of larger-mass meteors reaching Earth in the past. (SEP: 5.2; ESS3.B.1; CCC: 3.1) The last two rows of *Impactor Prediction Table* should have the following values:

Mass (kg)	Frequency per year	Frequency of a single event
1×10^{14}	0.000000001	1 per 1,000,000,000 years
1×10^{15}	0.0000000001	1 per 10,000,000,000 years

What to do: Encourage students to identify a scale factor that the value in each row changes by to help them identify that as size increases by a factor of 10, frequency decreases by a factor of 10. Remind students to convert frequency per year to a fraction in order to figure out the value for the last column.

Building toward 8.A.1 Develop and use a mathematical model based on a function fit to data to predict the number, frequencies (proportions), kinetic energy, and scale of potential destruction from meteors of different sizes reaching Earth in the near future and the rate of such events in the past (SEP: 5.2; DCI: ESS3.B.1, PS3.B.3; CCC: 3.1).

4 · QUANTIFY DANGER

9 min

MATERIALS: calculator, *Impactor Prediction Table*, The Chelyabinsk meteor card only from *Phenomena Cards* from lesson 1.

Motivate choosing a real-life equivalent that will help us quantify danger. Present **slide L**. Ask students the prompts on the slide:

- *How can we quantify how dangerous each of these meteors might be?*
- *What Earth-bound events can we use as a comparison to understand the effects they might have on a city, for example?*

You can help students understand these questions by pointing to *Impactor Prediction Table* and asking, *Where is the line where the size of these meteors becomes very dangerous? Like the level of destroying an entire city? What have we used before to quantify the danger of a collision?* Students may suggest forces or maximum force. Validate these ideas and ask, *What is something you have heard of on Earth that can wipe out an entire city?* Look for students to suggest a bomb. Be aware that students in your class may have a personal connection or may have lost an ancestor related to the bombings in Hiroshima and Nagasaki. Make space for students to share personal connections to these events if they have them, but do not prompt them to do so if they don't bring it up themselves, and seem eager to share. ✱

The examples that follow use the energy of a nuclear bomb, like the one that destroyed an entire city in Japan in 1945 during World War II (1.5×10^{13} joules). If students choose another type of bomb or a type of natural hazard, you can search the internet to look up the energy of that event and use that as a comparison instead. We have used the example of a WWII nuclear bomb in all the examples in this lesson.
Add two columns to the *Impactor Prediction Table* for kinetic energy (KE) and destruction and calculate the first row together. Present **slide M**. Ask students what velocity we should assume for impactors. Students may not know, but they may have some ideas of where we could look. Suggest that we go with a worst-case velocity--the speed of the Chelyabinsk meteor. Distribute the Chelyabinsk meteor card *Phenomena Cards* from lesson 1. Ask students to look back to the data on this card. They should settle on about 20 km/s. Make sure we convert this to 20,000 m/s before calculating KE. Walk through the calculation for the first row together as a class.

Work with a partner to finish the kinetic energy and destruction calculations. Present **slide N** and distribute a calculator to each student. Break students into pairs or trios to complete the kinetic energy and destruction calculations. There are eight additional rows (lettered A-H on the slide). In a class of thirty, you will need to have two partner teams calculate each value. Frame this as a double check to make sure we have the values correct. If there is disagreement, repeat the calculations as a class to determine the accurate number.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment

- Students accurately applying the equation for kinetic energy and then converting these numbers into the equivalency decided on by the class to quantify the scale of destruction. In the example we use a WWII-era nuclear bomb as a real-life unit representing something powerful enough to destroy a city and wreak havoc on human life. (SEP: 5.2; DCI: PS3.B.3; CCC: 3.1)

What to do: Move around the classroom to support students in setting up their equations and completing the conversion. Look for disagreement between the partners working on the last column. If one pair of partners is struggling, consider having the partners form a group of four to find the source of their disagreement before recording their number.

Building toward: 8.A.2 Develop and use a mathematical model based on a function fit to data to predict the number, frequencies (proportions), kinetic energy, and scale of potential destruction from meteors of different sizes reaching Earth in the near future and the rate of such events in the past (SEP: 5.2; DCI: ESS3.B.1, PS3.B.3; CCC: 3.1).

✱ ATTENDING TO EQUITY

If you choose to use a nuclear bomb, make sure to be clear with students that there are two real events, each of which destroyed a different city, killed hundreds of thousands of people, and wreaked havoc on human life. This is not meant to frighten students but to impress the danger of nuclear weaponry, and we do not choose this example lightly, without awareness of context, power, and historicity. Be aware that students in your class may have a personal connection or may have lost an ancestor related to the bombings in Hiroshima and Nagasaki and consider steering the class away from these examples if you think a student may feel singled out. Alternatively, if students feel comfortable sharing, this could be an opportunity for students to tell their family stories related to nuclear weaponry. If that is the case, invite students to share., forming a bridge between what is happening in class, and their personal histories.

5 · BUILDING UNDERSTANDINGS DISCUSSION ABOUT THE SCALE OF DANGER

9 min

MATERIALS: None

Build understanding of the scale of danger these events pose to us. Present **slide O**. Use the prompts on the slide to lead a conversation about relative danger in the future:

- *Which size of meteor is the most dangerous to people?*
- *How likely is one that could drastically affect the history of humanity in our near future?*
- *How does our work inform whether we should continue to invest in developing DART-like technologies?*

Use the key ideas callout below to identify and highlight important ideas.

Build understanding of the assumptions and associated limitations of our model. Present **slide P**. Use the prompts on the slide to lead a discussion about the assumptions of our model and how that might affect its predictive power into the past:

- *Does the mathematical model we used to make these predictions hold for the 4.5-billion-year history of Earth?*
- *What kind of data would we need to support or refute our predictions?*

Use the key ideas callout below to identify and highlight important ideas.

KEY IDEAS

Purpose of this discussion: The purpose of this discussion is threefold:

- Though meteors reaching Earth that are many times larger than the Chelyabinsk meteor are rare and have a little likelihood of reaching us in our lifetime, such meteors would have enough kinetic energy to destroy more than just a city and could change the course of human history.
- The mathematical relationship we developed should inform our plans for the future (related to investment in DART-like technologies).
- These relationships may tell us something about what has happened over the history of Earth, but we need more data to support or refute whether those relationships hold over these longer time scales.

Key Ideas to look/listen for

- Chelyabinsk meteor-sized impactors could still be very dangerous and happen on average once a century.
- Meteors that reach Earth that are 10 times bigger are predicted to reach Earth 1/10th as often.
- Meteors that are 1,000s of time larger than the size of the Chelyabinsk meteor haven't reached Earth over the window of time we have been collecting more-direct observations (e.g., 28 years), but the model predicts they will over a longer timescale.
- Probability and frequency decrease as the size of the meteor increases, but the predicted energy levels of them increase; this suggests that over the long term we are going to need a DART-like technology to prevent getting hit by a much bigger meteor at some point in the future.
- The model predicts that many really large meteors will have reached Earth's atmosphere over its history.

6 · NAVIGATE

4 min

MATERIALS: 8.5" x 11" copy paper

Navigate with an exit ticket. Suggest that we consider a bit further the sort of data we might need to support or refute our predictions for what has happened in the past. Display **slide Q**. Read the text at the top of the slide, *Our planet is over 4.5 billion years old.* Give students 3 minutes to respond to the two prompts on the slide using a piece of blank paper to collect as an exit ticket:

- *So what happened to all the meteors that reached Earth over that time that were much smaller than the Chelyabinsk meteor?*
- *What about the ones that were many factors of 10 bigger?*

Suggest that we think about these two questions further next time we are together. Collect these exit tickets.

Additional Lesson 8 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

Functions
CCSS.MATH.CONTENT.HS.F-IF.4 **Interpreting Functions:** For a function that models a relationship between two quantities, interpret key features of graphs and tables in terms of the quantities, and sketch graphs showing key features given a verbal description of the relationship.

The function that students fit to the graph is a linear one. They interpret the logarithmic scale of the graph, and they interpret the values they calculate for frequencies as probabilities, as #per year and 1 per # of years.

LESSON 9: What happened to all the meteors that reached Earth over its history?

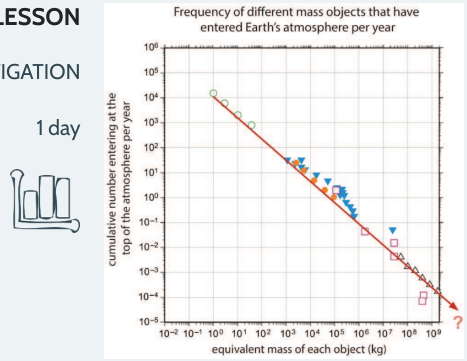
PREVIOUS LESSON

We discussed how often we might need to deflect incoming objects. We analyzed a graph of the frequency of different-sized objects that have entered Earth's atmosphere over a 28-year period. We constructed a line of best fit and used it to predict the frequency of larger-mass objects reaching Earth's atmosphere. We calculated the related kinetic energy and estimated the potential damage these could inflict.

THIS LESSON

INVESTIGATION

1 day



We share initial explanations for what might have happened to all the objects of different sizes that reached Earth from space over its 4.5-billion-year history. We brainstorm factors besides mass that might affect what happens to these objects when they reach Earth. We record new questions we have and sources of data and investigations that could help us answer these questions.

NEXT LESSON

We will investigate whether a meteor's velocity or mass better predicts its crater size. We will analyze our results using the coefficient of correlation to establish that the velocity of an impactor better predicts the crater's size. We will learn that meteors with sufficient kinetic energy can vaporize upon surface impact. We will explain the changes in matter and energy within the meteor-Earth system.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

9.A: Ask questions that arise from using a mathematical model to predict the relative frequency, scale, and significance of impact or collisions from large meteors on the history of our planet and identify sources of evidence needed to answer these questions. (SEP: 1.2; CCC: 3.1; DCI: ESS1.C.2)

WHAT STUDENTS WILL FIGURE OUT

- The mass of a meteor (or space object) probably affects whether anything impacts Earth's surface or whether it all burns up in the atmosphere.
- There are additional factors besides mass (e.g., speed, angle, or trajectory, material of the meteor, and where it hits) that may also affect the outcome.
- We are not certain that our mathematical model from the last lesson holds for earlier in Earth's history or for moons and other planets.

Lesson 9 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	11 min		**NAVIGATE** Discuss and record initial explanations for what might have happened to all the objects that reached Earth over its history.	A	chart paper, chart paper markers
2	12 min		**DEVELOP NEW QUESTIONS** Have students record new questions they have on sticky notes. Discuss and record additional factors that might affect what happens to objects when they reach Earth.	B-D	4 3x3 sticky notes (different colors--pink/yellow/green/blue), fine-tip colored marker, What happened (effects) to all the objects that reached Earth over the last 4.5 billion years? poster
3	10 min		**BRAINSTORM DATA AND INVESTIGATIONS NEEDED** Have students record on sticky notes ideas for data and investigations needed to answer our questions.	E-G	4 3x3 sticky notes (different colors--pink/yellow/green/blue), fine-tip colored markers
4	12 min		**ADD TO THE DRIVING QUESTION BOARD** Have students share questions and add them to the Driving Question Board. Collect students' ideas for data and investigations needed and add them to related poster from Lesson 1.	H	4 3x3 sticky notes (different colors--pink/yellow/green/blue), fine-tip colored markers, Investigation Ideas and Data We Need poster from Lesson 1, chart paper markers, chart paper

End of day 1

Lesson 9 • Materials List

	per student	per group	per class
Lesson materials	• 4 3x3 sticky notes (different colors--pink/yellow/green/blue) • fine-tip colored marker • fine-tip colored markers		• chart paper • chart paper markers • What happened (effects) to all the objects that reached Earth over the last 4.5 billion years? poster • Investigation Ideas and Data We Need poster from Lesson 1

Materials preparation (20 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Post in the room the Investigation Ideas and Data We Need poster from Lesson 1.

Four different-colored sticky notes are used in this lesson. If you use different colors than those suggested (pink, yellow, green, and blue), update the corresponding directions and graphics in the slides.

Lesson 9 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently build ideas related to the following disciplinary core idea, which students used in the prior lesson:

- **ESS1.C.2** Although active geologic processes, such as plate tectonics and erosion, have destroyed or altered most of the very early rock record on Earth, other objects in the solar system, ~~such as lunar rocks,~~ asteroids, and meteorites, ~~have changed little over billions of years. Studying these objects~~ can provide information about Earth's formation and early history. (HS-ESS1-6)

This lesson extends students' use of the crosscutting concept from the previous lesson that the significance of a phenomenon is dependent on the scale, proportion, and quantity at which it occurs, considering different-size scales of meteors again and different timescales (a single year) versus the entire history of Earth. This crosscutting concept will be used again in the next lesson.

The mathematical model from the prior lesson *Frequency vs. Mass*, now becomes the phenomena that reanchors the rest of the unit in this lesson. A major goal of this lesson, then is to expand the scope of the Driving Question Board. It uses two rounds of question formation and two rounds of brainstorming ideas for data and investigations needed to answer those questions that are derived from mathematical model developed in the last lesson (*Frequency vs. Mass*) to ensure that the scope of questions are well aligned to lessons in the second half of this unit.

Where We Are NOT Going

In this lesson, students will not engage with the idea that objects in the solar system have changed little in billions of years. This idea will be explored in more depth in Lessons 12 and 13.

LEARNING PLAN for LESSON 9

1 · NAVIGATE

11 min

MATERIALS: chart paper, chart paper markers

Compare initial explanations. Present **slide A**. Say, *We started considering these questions last time. Let's revisit them again to develop our initial ideas further. Our planet is over 4.5 billion years old. So what has happened to all the objects that were much smaller than the Chelyabinsk meteor that reached Earth over that time? What about all the objects that were many factors of 10 bigger?* Give students 3 minutes to discuss with a partner.

Share and record initial explanations. Write the following question at the top of a piece of chart paper: "What happened (effects) to all the objects that reached Earth over the last 4.5 billion years?" Under this write "Effects at different scales:" Divide the rest of the chart paper into 3 columns. Say, *Let's come together and brainstorm the potential effects of different-sized impactors. Let's start by thinking about what we know happened with the Chelyabinsk meteor.* Ask students to share what they remember happened as a result of the Chelyabinsk meteor impact. As students share, record their ideas in the middle column of the chart paper under the heading "Chelyabinsk-sized."

Suggested prompts

- *What were the impacts of the Chelyabinsk meteor?*
- *What are some other potential effects of any Chelyabinsk-sized meteor?*

Sample student responses

- It hit the surface.
- Some of it caught on fire.
- Could make a crater
- Bright light and flash across the sky
- Created shockwaves.
- Blew out windows.
- Break into pieces

Now say, *So what happened to all the meteors that reached Earth over that time that were much smaller than the Chelyabinsk meteor?* As students share, record their ideas in the left column of the chart paper under the heading "Smaller than the Chelyabinsk meteor"

Sample student responses

- Burn up
- Meteor showers
- Shooting stars
- Small craters
- No damage
- Won't get through atmosphere

Then ask, *What about the ones that were many factors of 10 bigger than the Chelyabinsk meteor?* As students share, record their ideas in the right column of the chart paper under the heading "Many factors of 10 larger than the Chelyabinsk meteor".

Sample student responses

- Significantly more damage
- Destroy cities
- Caused the dinosaur extinction

- Make a huge hole or crater
- Make the sky cloudy and cause climate change
- Melted Earth and made the Moon
- Went to the bottom of the ocean

Follow up by asking why we don't see any direct evidence of a lot of craters from the larger-scale impacts that students described. Accept all responses. This question is designed to prime students to start considering the role of active geologic processes, such as plate tectonics and erosion, in destroying or altered most of the earlier rock record on Earth.

2 · DEVELOP NEW QUESTIONS

12 min

MATERIALS: 4 3x3 sticky notes (different colors--pink/yellow/green/blue), fine-tip colored marker, What happened (effects) to all the objects that reached Earth over the last 4.5 billion years? poster

Ask questions about meteor impacts. Present **slide B**. Say, *It seems like we still have a lot of questions about the history of these impacts. Let's spend some time today recording new questions to add to our DQB and brainstorming additional sources of data and investigations that could help us make progress on those questions.* Give each student four different-colored sticky notes and a fine-tip colored marker. Ask students to arrange the sticky notes on their desk as shown on the slide. Read the text on the slide and cue students to use the pink sticky note to record a question they now have about historical impacts.

ADDITIONAL GUIDANCE

If you change the color of sticky notes used or are limited in the colors available, change the directions on the related slides to indicate a way to label and refer to different stickies (e.g. A, B, C, D).

ASSESSMENT OPPORTUNITY

What to look/listen for: A question that arises from using a mathematical model on how the size or mass of meteors affects the frequency, scale, and significance of impacts or collisions. (SEP: 1.2; DCI: ESS1.C.2; CCC: 3.1)

Sample student questions

- How big is a meteor that is 1,012 kg compared to the size of a city?
- Do all the pebble-sized meteors burn up?
- Are there thousands of shooting stars every night?
- Where are the huge meteors if they hit the planet?
- 4.5 billion years seems like a lot of time. How many huge meteors have hit the planet?
- What organisms survived when the meteor that killed the dinosaurs hit Earth?
- Did other organisms get wiped out besides the dinosaurs when really big meteors hit Earth in its past?
- Why don't we invest more in DART-like technologies, based on the trends in the data we have seen?

What to do: If students don't have any questions, encourage them to review the What happened (effects) to all the objects that reached Earth over the last 4.5 billion years? poster and think of a question one could ask about what happens when different-sized meteors hit Earth over its history.

Building toward 9.A.1: Ask questions that arise from using a mathematical model to predict the relative frequency, scale, and significance of impact or collisions from large meteors on the history of our planet and identify sources of evidence needed to answer these questions. (SEP: 1.2; DCI: ESS1.C.2; CCC: 3.1)

Brainstorm additional factors. Present **slide C**. Say, *Our predictions of different effects of these objects were all based on differences in the mass of the objects that reach Earth. So what other factors, besides mass, might affect what happens to these objects when they reach Earth?* Ask students to discuss this question with a partner for two minutes.

Ask additional questions. Present **slide D**. Say, *Using the yellow sticky note, record a new question you now have about what other factors, besides mass, might affect what happens to these objects when they reach Earth.*

ASSESSMENT OPPORTUNITY

What to look/listen for: A question that arises from using a mathematical model on how the scale (such as speed and density) or type of meteor material or impact location on Earth could affect the significance or outcomes of impacts or collisions. (SEP: 1.2; DCI: ESS1.C.2; CCC: 3.1)

Sample student questions

- How much does the type of material a meteor is made of (ice, rock, metal) affect what happens to it?
- Does the way it hits (straight vs angle) Earth's atmosphere affects the outcome?
- Does the speed of a meteor slow down the entire way through the atmosphere?
- Do all meteors that reach a lake or Ocean, make it to the bottom of it intact>

What to do: If students don't have any questions, encourage them to think of a question one could ask about what about a meteor besides its mass could affect the severity of the outcome when it reaches Earth.

Building toward 9.A.2: Ask questions that arise from using a mathematical model to predict the relative frequency, scale, and significance of impact or collisions from large meteors on the history of our planet and identify sources of evidence needed to answer these questions. (SEP: 1.2; DCI: ESS1.C.2; CCC: 3.1)

3 · BRAINSTORM DATA AND INVESTIGATIONS NEEDED

10 min

MATERIALS: 4 3x3 sticky notes (different colors--pink/yellow/green/blue), fine-tip colored markers

Develop ideas for investigations and data. Present **slide E**. Say, *Using the green sticky note, brainstorm an idea for an investigation we could conduct or data we could use to answer either one of your two questions.*

✱ STRATEGIES FOR THIS INITIAL IDEAS DISCUSSION

Purpose of this discussion: The purpose of this discussion is to question the generalizability of our mathematical model from the last lesson based on what we know (or are assuming) about the history of our solar system and the differences in the masses and atmospheres of the moons and planets that make it up.

Key Ideas to look/listen for

- In the past the solar system may have had more stuff in it, which would have been busier and led to more collisions.
- Other planets that have a bigger mass (e.g., Jupiter) might get hit by

ASSESSMENT OPPORTUNITY

What to look/listen for: Identifying investigation ideas that could provide evidence needed to answer questions about how the characteristics of meteors affect the frequency, scale, and significance of impact or collisions. (SEP: 1.2; DCI: ESS1.C.2; CCC: 3.1)

Sample student ideas

- Drop a rock into water/earth materials and change the size and material of it.
- Look at radar data from submarines to see if there are meteors at the bottom of the ocean.
- Throw some impactors into earth materials at different speeds and directions and see the effects on the size of the crater.
- Investigate the materials of the meteors that have hit Earth.
- Test to see how different materials act when they hit earth materials or an earth-like material.

What to do: If students are struggling, point to one of their questions or a question from another student and ask them to consider how we could answer that question.

Building toward 9.A.3: Ask questions that arise from using a mathematical model to predict the relative frequency, scale, and significance of impact or collisions from large meteors on the history of our planet and identify sources of evidence needed to answer these questions. (SEP: 1.2; DCI: ESS1.C.2; CCC: 3.1)

Have an Initial Ideas Discussion. Project **slide F**. Give students 2 minutes to discuss the prompts on the slide with their partner. Then lead a brief discussion to help students articulate any assumptions of our model (*Frequency vs. Mass*) from lesson 8.

- *Does the mathematical model we used to make these predictions hold for the 4.5-billion-year history of Earth? Why or why not?*
- *Do you think our model holds for our Moon or other planets?*

Develop ideas for investigations and data. Present **slide G**. Say, *Using the blue sticky note, brainstorm an idea for the kinds of data that could help us answer these two new questions we are considering about our mathematical model from the last lesson.*

ASSESSMENT OPPORTUNITY

What to look/listen for: Identifying sources of data that could provide evidence needed to answer questions about the impact or significance of meteor collisions across the history of our planet. (SEP: 1.2;DCI: ESS1.C.2; CCC: 3.1)

Sample student ideas

- Find observational data of stuff flying close to other planets and moons and compare it to Earth's data.
- Compare craters on Earth to craters on other solar system objects.
- Search for data about meteors that have hit Earth--their size, material, etc.
- Study fossils and rock layers to see if they have meteor material in them.

What to do: If students are struggling, ask them how we would know if our current observations of meteors and their impacts is the same today as it was in the past and what data could help us figure that out.

Building toward 9.A.4: Ask questions that arise from using a mathematical model to predict the relative frequency, scale, and significance of impact or collisions from large meteors on the history of our planet and identify sources of evidence needed to answer these questions. (SEP: 1.2; DCI: ESS1.C.2; CCC: 3.1)

more meteors since they produce stronger gravitational force interactions.

- Moons or planets that are smaller than Earth might pull in fewer meteors because of their weaker gravity.
- Moons or planets that have no (or little) atmosphere might have more meteors that reach their surface intact and/or impact their surface.

4 · ADD TO THE DRIVING QUESTION BOARD

12 min

MATERIALS: 4 3x3 sticky notes (different colors--pink/yellow/green/blue), fine-tip colored markers, Investigation Ideas and Data We Need poster from Lesson 1, chart paper markers, chart paper

Share questions and add to the DQB. Display **slide H**. Ask students to recall the protocol they used for sharing, calling on, linking in, and clustering questions on the Driving Question Board from lesson 1. Use an additional piece of chart paper that expands the space of the Driving Question Board (DQB) and begin the process. Continue until everyone has shared at least one question. If students still have additional questions, shift to giving them an additional minute to add them silently to the DQB, sorting into clusters if they know where they go or simply putting them on the edge for now, which the class can work on clustering later. Use chart markers to label any new DQB categories that come up.

Navigate. Say, *Wow, we have a lot of new questions and a lot of ideas for investigations to help answer them. The next step seems to be to get started with one of these lines of investigation. Let's plan on starting class next time with pursuing some of the questions and data and investigation ideas we have related to different meteor sizes and their interactions with our atmosphere.* Collect all green and blue sticky notes with investigation and data ideas and add them to the Investigation Ideas and Data We Need poster from Lesson 1.

LESSON 10: What determines the size of the crater made on impact?

PREVIOUS LESSON

We shared initial explanations for what might have happened to all the objects of different sizes that reached Earth from space over its 4.5-billion-year history. We brainstormed factors besides mass that might affect what happens to these objects when they reach Earth. We recorded new questions we have and sources of data and investigations that could help us answer these questions.

THIS LESSON

INVESTIGATION

2 days



We consider whether the velocity or the mass of a meteor better predicts the size of the crater it forms. We plan and carry out an investigation to generate data for testing our predictions. Using the coefficient of correlation, we analyze our results and determine that the velocity of an impactor better predicts the size of the crater. We learn that meteors with enough kinetic energy can vaporize upon impact with the surface, and we use these ideas to refine our explanation of the changes in matter and energy within the meteor-Earth system. We wonder how the planet was affected by a meteor that struck 65 million years ago.

NEXT LESSON

We will analyze data from a video of a satellite being tested in a high-speed wind tunnel. We will develop an explanation for why only a relatively small amount of the Chelyabinsk meteor's matter was in solid pieces when it reached the surface. We will argue that only a small fraction of the matter that most frequently enters Earth's atmosphere actually ends up leaving an impact on its surface.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

10.A Plan an investigation in groups and as a class to produce data to serve as the basis for evidence regarding the relationship between the kinetic energy of the impactor and the size of the crater it produces and how changes in the mass and velocity of the impactor do not have equal effects on its kinetic energy. (SEP: 3.1; DCI: PS3.B.4; CCC: 1.5)

10.B. Apply the correlation coefficient to analyze the relationship between changes in the mass and velocity of an impactor and the size of the crater it produces and use these ideas to refine an explanation about the changes in matter and energy within the meteor-Earth system. (SEP: 4.2, 4.5; DCI: PS3.B.4; CCC: 1.5, 5.2)

WHAT STUDENTS WILL FIGURE OUT

- Craters are not imprints of the objects but are larger than the object was.
- Craters are surrounded by areas of ejecta.
- The kinetic energy of an impactor is a good predictor of the size of a crater.
- In comparison to mass, the velocity of an impactor has a stronger relationship with the size of the crater it creates.
- Increasing the mass also increases the size of the crater.
- Impactors with enough kinetic energy can vaporize upon surface impact.

Lesson 10 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	4 min		**NAVIGATE** Recall ideas we had about the amount of damage meteors can cause.	A-B	Driving Question Board
2	5 min		**DETERMINING DAMAGE CAUSED BY METEOR** Remind students about the use of the kinetic energy equation to measure the damage caused by a meteor. Use this equation to discuss how the mass and the velocity of an impactor affect its kinetic energy.	C-D	
3	20 min		**PLAN CRATER INVESTIGATION** Introduce the materials for the investigation. Instruct groups to design protocols for changing the mass and the velocity of the impactor and to reach consensus on which method will enable the class to collect more-accurate data. Have all groups carry out one trial and use crater measurements to identify sources of error in the investigation and strategies to reduce them.	E-I	
4	16 min		**CARRY OUT INVESTIGATION** Give students the rest of the class to collect their data first in the handout and then in the copy of https://docs.google.com/spreadsheets/d/1DnA5xImtGnQJVHRq60N4XQEUWa2MLSc8QNDR9v7JnTs/copy you shared with the class.	J-K	2 laptops, Crater Size Investigation
					End of day 1
5	4 min		**NAVIGATE** Remind students about the purpose of the Crater Size Investigation.	L	
6	20 min		**ANALYZE AND INTERPRET DATA** Distribute a computer to every student to analyze the data collected by the class during the Crater Size Investigation. Use the correlation coefficient to identify which meteor variable (velocity or mass) has a stronger relationship with crater size.	M-O	computer, copy of https://docs.google.com/spreadsheets/d/1DnA5xImtGnQJVHRq60N4XQEUWa2MLSc8QNDR9v7JnTs/copy you shared with the class
7	6 min		**CONSIDER CHANGES IN MATTER OF METEOR** Consider changes in the matter of an impactor during a collision with Earth's surface.	P-S	
8	10 min		**REVISE EXPLANATION** Ask students to use their new ideas to write in their science notebook a revised explanation of how the energy of the meteor transfers to the Earth-meteor system and the changes in matter that take place.	T-U	8.5" x 11" copy paper, M-E-F poster
9	5 min		**NAVIGATE** Motivate the need to look at larger craters. Distribute a piece of paper to every student to complete an exit ticket about the consequences on Earth 65 million years ago of a meteor that left a crater with a diameter of 112 miles.	V-W	8.5" x 11" copy paper, Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster
					End of day 2

Lesson 10 • Materials List

	per student	per group	per class
Crater Size Investigation materials		• *Lab Data Sheet* • copy of https://docs.google.com/spreadsheets/d/1DnA5xImtGnQJVHRq60N4XQEUWa2MLSc8QNDR9v7JnTs/copy you shared with the class • 15.7-cup storage container • flour • crater measuring tool • wooden skewer • measuring tape • 6" ruler • 12" ruler • 2 impactors (one with a mass of 30 g • the second one with a mass of 15 g • 45 g • or 60 g • depending on the mass you assign each group) • butcher paper • shaker with cocoa powder • dry erase marker (ultra fine tip)	
Lesson materials	• computer • 8.5" x 11" copy paper		• Driving Question Board • 2 laptops • copy of https://docs.google.com/spreadsheets/d/1DnA5xImtGnQJVHRq60N4XQEUWa2MLSc8QNDR9v7JnTs/copy you shared with the class • M-E-F poster • Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster

Materials preparation (120 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole-punch all handouts so they can be added to students' notebooks.

When you access https://docs.google.com/spreadsheets/d/1DnA5xImtGnQJVHRq60N4XQEUWa2MLSc8QNDR9v7JnTs/copy, it will spin off a copy of the data collection spreadsheet automatically. Duplicate this spreadsheet for each class period you have. Subsequently, title each duplicated spreadsheet "Crater Data Collection" and include in each copy's file name some text for easy identification corresponding to its respective class.

In each class, students will record their results in this master copy.

Make sure to have the Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster (from Lesson 1) displayed prominently to support student ideas during day 2 conversations.

Day 1: Orientation to the Crater Size Investigation

Prior to the investigation

- Watch https://youtu.be/Ou34k8J_9pk for additional guidance on how to prepare the flour for each test.
- Watch https://youtu.be/HBs4S8AHk5g?si=Lc8iC4i2frbm9wUR for additional guidance on how to use the spreadsheet to record the measurements students will collect during this investigation.
- Watch https://youtu.be/_jwtVu39zOI for additional guidance on how to use the crater measuring tool.
- See https://docs.google.com/spreadsheets/d/1XSbAlV9eW2vPNDGV5tOkF-aurCG_qu0SqFsn0wNP_-0/copy for a sample of data collected using the same materials and guidelines described in this lesson. This spreadsheet will give you an idea of the results you should expect from this investigation.

During the investigation

- **Group size:** 4-5 students
- **Setup:** Look at *Preparing Crater Lab* for instructions of how to create the impactors and the crater measuring tool. This document will also give you guidance on how to create the lab setup for each group.
- **Notes for during the lab:** Place butcher paper on the floor. This will make cleaning afterwards much easier.
- **Safety:** All students must wear sanitized safety glasses with side shields or indirectly vented chemical splash goggles. If possible, each student should use a lab coat as well, as this will cover their clothes to protect from flour. Any student with asthma or gluten allergies must wear a mask at all times.
- **Storage:** Store the flour in a dry place to be used with other classes. While the flour will get mixed with the cocoa powder as students use it, it will not affect the results.
- **Disposal:** Discard the flour 12 months after first use.

General safety protocols for demonstrations and hands-on activities:

- **Set up expectations:** Communicate the potential messiness of the investigation to students beforehand, setting expectations for responsible conduct.
- **Protective measures:** Advise students to wear appropriate safety gear, including vented chemical splash goggles, facemasks, and aprons, to shield themselves from flour particles.
- **Lab station preparation:** Set up the lab stations with butcher paper covering the floor to minimize the impact of any mess generated.
- **Laptop protection:** Be mindful that the dust or flour may affect laptops. Place the laptops the class will use to record their data away from the primary investigation area.
- **Ventilation:** Ensure good ventilation in the room to minimize the accumulation of flour. If possible, conduct the investigation in a well-ventilated space or near open windows.
- **Clean-up procedures:** Provide clear instructions for proper cleanup after the investigation. Encourage students to clean their workspace thoroughly, disposing of any excess flour in designated bins.
- **Active flames:** Make sure there are no active flames to prevent risk of explosion with accumulation of flour dust in the air.
- **Material considerations:** Wheat flour can be substituted by corn flour if you have students who have gluten allergies.
- Wash hands with soap and water once the activities have been completed.

Lesson 10 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently build ideas related to the following disciplinary core idea:

- **PS3.B.4: Conservation of Energy and Energy Transfer:** The availability of energy limits what can occur in any system. (HS-PS3-1)

In Lesson 5, students explored the idea of conservation of energy. They also considered how the energy stored in fields (potential energy) transfers to the orbiting object as kinetic energy. In this lesson, we are investigating how the mass and the velocity of an object affects its kinetic energy. This is an important idea that will allow students to explain matter changes in the system caused by large meteors in Lessons 14 and 15.

Students use the science and engineering practice "planning and carrying out investigations". While it is not a focal practice in this unit, investigating the role of mass and velocity in this context presents a meaningful opportunity to discuss ideas related to accuracy of data and experimental design.

Students use the crosscutting concept "energy and matter". In line with the M-E-F triangle used in OpenSciEd High school, students continue using the idea that changes in matter and energy happen together. They also consider how the amount of energy in the meteor-Earth system determines the subsequent changes in matter and energy. This is an important idea that will help them during the final transfer task to make sense of the effect that the meteor that caused the Chicxulub crater had on our planet and the formation of the Moon.

This lesson also revisits the crosscutting concept of "patterns", asking students to go a step further by using the coefficient of correlation to analyze these patterns.

Students will encounter definitions for the following words in this lesson: *impactor, ejecta, crater.* **Do not** post any words or ask students to add them to their Personal Glossary until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

Although the kinetic energy equation is introduced as a way to make sense of the role of energy and mass of the impactor, no attempt is made to apply kinetic energy-related equations or conservation of energy relationships in this lesson.

LEARNING PLAN for LESSON 10

1 · NAVIGATE

4 min

MATERIALS: Driving Question Board

Reference the Driving Question Board, noting that we developed a whole series of new questions and ideas for investigations from the mathematical model we developed over the last two lessons.

Revisit the mathematical model from prior lessons. Display **slide A**. Discuss the question on the slide as a class:

- *What new questions or ideas for investigation and data did we have that were related to the amount of damage meteors can cause?*

Accept all answers. Say, *Let's start by reminding ourselves of the damage the Chelyabinsk meteor caused.*

Link to the anchoring phenomenon. Display **slide B**. Say, *The largest fragment of the Chelyabinsk meteor left an 8-meter (26-foot) diameter hole in the ice of the lake it hit.*

Discuss the questions on the slide as the class:

- *What do we think the outcome would have been if it had hit the land?*
- *Do we think the mass or the speed of a meteor has a bigger impact on the damage it causes when it hits the surface?*

Sample student responses include the following:

- If it had hit the land, it could have caused more damage, maybe injured people.
- Maybe there would have been a large explosion.
- Accept all responses for the second prompt.

Transition to the next slide by saying, *This is not the first time we have talked about the amount of damage during a collision. Let's investigate this further.*

2 · DETERMINING DAMAGE CAUSED BY METEOR

5 min

MATERIALS: None

Remind students about tools we have used to quantify damage. Present **slide C**. Have students turn and talk with the prompts:

- *What have we used to quantify the amount of damage a meteor can have?*
- *Why is it important to study the factors that can make meteors more damaging?*

After a minute, invite students to share. Look for the following ideas:

- We have used the kinetic energy of an object to quantify the amount of damage it can produce.
- Knowing the factors that can make meteors more damaging can help inform defense strategies or predict the consequence of a meteor impact.

The second prompt is intended to support students in making connections between this lesson's question and part of the unit's question: *How could collisions with objects from space affect our future?*

Revise the kinetic energy equation. Present **slide D**. Use the slide prompts to remind students about the relationship between the mass and velocity of an object and its kinetic energy.

- *When did we use the equation below to quantify the possible damage caused by a meteor impact?*

*kinetic energy = ½(m*v^2)*

- *Which changes in the meteor better predict the damage it causes--mass or velocity?*

ADDITIONAL GUIDANCE

If students find the second prompt challenging, guide them to use algebraic thinking. This approach will help them understand that changes in both the mass and the velocity of the meteor influence its kinetic energy, though these changes don't have equal effects on the kinetic energy of the meteor. You can use the following prompts:

- *How would the kinetic energy of the meteor change if*
  - *its velocity is twice as fast?*
  - *its mass is twice as large?*

Use simple numbers for mass and velocity to provide concrete examples of the effect of doubling mass or velocity.

Say, *Let's investigate how the changes in the meteor's properties relate to changes in kinetic energy and the size of the crater.*

3 · PLAN CRATER INVESTIGATION

20 min

MATERIALS: None

Introduce the investigation materials. Present **slide E**. Say, *We are going to be using a plastic capsule to represent any space object that hits the surface of Earth; scientists call these types of space objects* impactors*. The flour will represent the surface of Earth and allow us to create craters of different sizes. The cocoa powder represents the top layer of Earth's surface. It will help us see how material is ejected during the formation of the impact crater. It will also make it easier for us to study the size of the crater.*

Design investigations to change velocity and mass. Ask students to work with a partner to define in their notebook a protocol to change the mass and a protocol to change the velocity of the impactor, using some of the materials for this investigation. Instruct them to indicate the variables that they will control, manipulate, and measure.

After a few minutes, invite them to share their protocol with the class. These are possible ideas they might share:

- We can place more or less stuff inside the impactor to change its mass.
- We can throw the impactor from different heights.
- We can throw the impactor using different force.

As students share, use the following prompts to elicit as many ideas as possible:

- *Who has a different way to change the velocity of the impactor?*
- *What variables should we keep constant while we investigate velocity?*
- *What variables should we keep constant while we investigate mass?*

Help the class consider the option of changing the height as a means to alter the velocity of the impactor. If students don't suggest changing the height to change the velocity of the impactor, use the following prompt:

- *How did we change the velocity of the pendulum we used to examine energy transfer? Could we do something similar with these materials to change the velocity of the impactor?*

✱ SUPPORTING STUDENTS IN ENGAGING IN PLANNING AND CARRYING OUT INVESTIGATIONS

This is a good opportunity to help students make sense of issues of reliability and precision of data, as they will experience firsthand how setting the experimental conditions (calibrating the level of compactness of the surface), dropping the impactor, and measuring the crater dimensions will influence the precision of the data they obtain.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- Include how to change the independent variable (velocity or mass of the impactor), the variable that will be controlled (mass or velocity of the impactor), and the measurements that will be collected about the dependent variable (crater size). (SEP: 3.1; CCC: 1.5; DCI: PS3.B.4)

What to do: Use the following prompts to support groups in discussing each of their protocols:

- *What specific question about the mass and the velocity of the impactor are we trying to address with this protocol?*
- *Are there any potential confounding variables that could impact your results? How can you control for them?*
- *How can you measure how much larger or smaller the crater is when you change your independent variable?*

If your students feel comfortable designing investigations, ask them to make a directional hypothesis that predicts the relationship between the independent and dependent variables.

Building toward: 10.A.1 Plan an investigation in groups and as a class to produce data to serve as the basis for evidence regarding the relationship between the kinetic energy of the impactor and the size of the crater it produces and how changes in the mass and the velocity of the impactor do not have equal effects on its kinetic energy. (SEP: 3.1; DCI: PS3.B.4; CCC: 1.5)

Use equations to find the velocity of an object at the moment of impact. Present **slide F**. Highlight the difficulty of measuring the velocity of an object in free fall, as it happens too fast to measure it accurately. Use the equation on the slide to help the class see how we can find the velocity of the object:
$m*g*h = \frac{1}{2}(m*v^2)$

Use the slide prompt during this discussion:

- *How is this relationship similar to one we used to predict changes in the pendulum and orbiting objects?*

Accept all answers.

ALTERNATE ACTIVITY

If your students feel comfortable manipulating variables in an equation, suggest they rearrange this equation on their own to solve for velocity.

Say, *This means we don't need to measure the velocity ourselves, but we need to measure the height very accurately. Let's see how we can double the velocity by changing the height of the drop.*

Discuss the heights the class will use for the drop. Present **slide G**. Use the slide prompt and accompanying table to consider the heights to be used during this investigation. This table is also intended to help students recognize how changes in height are related to changes in velocity:

- *What heights should we use to investigate the role of velocity on the damage it can cause on impact?*

Ask students to use the measuring tape to get an idea of the height dimensions displayed on the table. If students say they should use every height on the table, remind them that it will take a significant amount of time to test them all. Suggest we use the following drop heights: 0.4, 0.8, 1.2, 1.6 m. Show students how to measure the height from the top of the flour layer.

ADDITIONAL GUIDANCE

The shape of craters made by throwing the impactor at drop heights lower than 0.4 m will resemble the shape of the impactor, not the velocity. The variation in crater size from impactors dropped at heights larger than 2 meters will decrease the accuracy of the data.

Carry out a measurement to refine protocol. Present **slide H**. Rearrange the class into small groups of 4-5 students. Assign each group a lab station. Ask every group to sprinkle an even layer of cocoa powder over the flour. Then instruct them to carry out an impactor drop following the class protocol using the 30 g impactor and 0.8 m of dropping distance.

Ask them to remove the impactor from the flour carefully. Use the slide prompt to have students consider the easiest and most accurate way to measure the damage:

- *Amount of material thrown across the surface (ejecta)*
- *How far the material was thrown across the surface (ejecta)*
- *The size of the crater*

Then, invite them to share their ideas. They should say the size of the crater.

ADDITIONAL GUIDANCE	The cocoa powder increases the contrast of the crater edges when the ejecta is produced, making it easier to collect measurements. Remind students that they should sprinkle an even layer of cocoa powder over the flour before every drop.

Consider the accuracy of preliminary results. Present **slide I**. Mention that we have some tools to measure the size of the crater. Demonstrate how to use the crater measuring tool, the 6" ruler, and the skewer to measure the diameter and depth of the crater, respectively.

ALTERNATE ACTIVITY	Instead of showing students how to use the crater measuring tool yourself, you can share the following video that demonstrates its use: https://youtu.be/_jwtVu39zOI

Ask each group to measure the depth and diameter of their crater and report their measurements. Write these measurements on the board.

Use the slide prompts and the depth and diameter results to discuss how to refine the investigation protocol:

- *What can cause the variations in the crater measurements we found in trials using the same mass and the same drop height?*
- *What can we change to increase the accuracy of our results?*✱

Listen for the following ideas in response to the second question:

- We can conduct several trials.
- We can discard trials we believe were done wrong.
- We can discard outliers.

Use the class ideas to refine the investigation and to discuss the limitations on the precision of the data. Listen for the following ideas:

- While we all used the same height, small variations persist that may result in changes in the size of the crater.
- Measuring the crater dimensions with high accuracy is challenging.
- The impactors did not hit the surface at precisely the same point, potentially altering the crater's size.
- Perhaps the flour was more compacted in some containers than in others.

At the end of this discussion, highlight the importance of resetting the flour.

ALTERNATE ACTIVITY	There is an optional video you can use to further orient students to how to reset the flour surface before each trial: https://youtu.be/Ou34k8J_9pk

4 · CARRY OUT INVESTIGATION

16 min

MATERIALS: Crater Size Investigation, 2 laptops

Carry out the investigation. Present **slide J** and distribute *Lab Data Sheet* to every group. Remind students that we also thought the mass of the impactor was related to the amount of damage it can cause on the surface during a collision. In order to investigate the role of mass and velocity, assign each group an impactor of a given mass. We recommend using four different masses: 15 g, 30 g, 45 g, and 60 g. For example, group A will collect measurements using an impactor of 15 g, while group B will collect measurements using an impactor of 30 g. This handout also includes the general safety protocols for this activity and the protocol for measuring the size of the crater.

ADDITIONAL GUIDANCE	These are sample results using the materials highlighted in the materials preparation section: https://docs.google.com/spreadsheets/d/1XSbAlV9eW2vPNDGV5tOkF-aurCG_qu0SqFsn0wNP_-0/copy. For these sample tests, four impactors were used--15 g, 30 g, 45 g, and 60 g--dropped from four different heights (40 cm, 80 cm, 120 cm, 160 cm). These results will allow you to collect enough data to observe trends related to the role of mass and velocity in determining the size of the crater (volume). You can vary the weight of the impactors by adding or removing more dough inside them. However, impactors weighing above 65 grams tend to form tunnels rather than craters on the flour. We don't recommend using drop heights lower than 40 cm. Craters formed by the impactors at lower heights are more likely to reflect the size of the impactor, potentially misleading students into thinking that the size of the crater directly measures the size of the meteor that created it.

Ask groups to follow the instructions to collect their results:

- *Collect additional trials to collect data about the impactor's variable assigned to your group.*
- *Wear safety equipment at all times during this investigation.*
- *Use the* Lab Data Sheet *to record your data.*
- *Copy your data into the Class Results spreadsheet.*

Before students begin their data collection, display **slide K** and review the general safety protocols for the activity.

Assign one laptop or two in the classroom, each one with access to the master copy you created of the https://docs.google.com/spreadsheets/d/1DnA5xImtGnQJVHRq60N4XQEUWa2MLSc8QNDR9v7JnTs/copy, for students to copy their results on the digital spreadsheet as they finish their data collection. Help students to record their results in this digital spreadsheet. Give students the rest of the class to collect and record their data.

ADDITIONAL GUIDANCE

To ensure a smooth and safe investigation, consider the following guidance:

- **Set up expectations:** Communicate the potential messiness of the investigation to students beforehand, setting expectations for responsible conduct.
- **Protective measures:** Advise students to wear appropriate safety gear, including vented chemical splash goggles, facemasks, and aprons, to shield themselves from flour particles.
- **Lab station preparation:** Set up the lab stations with butcher paper covering the floor to minimize the impact of any mess generated.
- **Laptop protection:** Be mindful that the dust or flour may affect laptops. Place the laptops the class will use to record their data away from the primary investigation area.
- **Ventilation:** Ensure good ventilation in the room to minimize the accumulation of flour. If possible, conduct the investigation in a well-ventilated space or near open windows.
- **Clean-up procedures:** Provide clear instructions for proper cleanup after the investigation. Encourage students to clean their workspace thoroughly, disposing of any excess flour in designated bins.
- **Active Flames:** Make sure there are no active flames to prevent risk of explosion with accumulation of flour dust in the air.
- **Material considerations:** Wheat flour can be substituted by corn flour if you have students who have gluten allergies.
- Wash hands with soap and water once the activities have been completed.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- Use *Lab Data Sheet* to record the data. (SEP: 3.1)
- Include at least two trials for each height or mass tested. (SEP: 3.1)
- The variation in the data lies within an acceptable margin. (SEP: 3.1)

What to do: Some groups may solely record their results without evaluating the accuracy of their data. In such instances, establish an acceptable error margin. While there is significant variation in the data for this investigation, advise students to collect an additional measurement if the difference in diameter exceeds 2 cm for trials under the same conditions.

Building toward: 10.A.2 Plan an investigation in groups and as a class to produce data to serve as the basis for evidence regarding the relationship between the kinetic energy of the impactor and the size of the crater it produces and how changes in the mass and the velocity of the impactor do not have equal effects on its kinetic energy. (SEP: 3.1; DCI: PS3.B.4; CCC: 1.5)

End of day 1

5 · NAVIGATE

4 min

MATERIALS: None

Navigate. Present **slide L**. Use the slide prompt to remind students about the purpose of the Crater Size Investigation:

- *What was the purpose of investigating the mass and velocity of the impactor?*

Accept all answers. Say, *Let's see what our results suggest about the relationship between the impactor properties we measured and the size of a crater.*

6 · ANALYZE AND INTERPRET DATA

20 min

MATERIALS: computer, copy of https://docs.google.com/spreadsheets/d/1DnA5xImtGnQJVHRq60N4XQEUWa2MLSc8QNDR9v7JnTs/copy you shared with the class

Analyze and interpret data. Display **slide M**. Distribute a computer to every student. Give students a few minutes to consider the slide prompts and record their ideas in their science notebook:

- *Look at the class results in the first tab of the spreadsheet. This tab shows the following results:*
  - *Crater volume vs. Impactor mass*
  - *Crater volume vs. Impactor velocity^2*
- *What patterns do these graphs help us identify?*✱

Invite a couple of volunteers to share their ideas. Accept all responses.

Say, *I think we can see that increasing the mass and velocity of the impactor results in larger craters. No surprise here. But which of these variables better explains the size of the crater? To answer this question, it is better if we use a mathematical tool we have used in the past, the coefficient of correlation.* ✱

Introduce the coefficient of correlation. Present **slide N**. Read aloud the description of the coefficient of correlation at the top of the slide:

The coefficient of correlation (R^2) is a measure of the strength of the relationship between two variables. The closer R^2 is to 1, the stronger the relationship between the independent and dependent variables. ✱

Ask students to use these ideas to answer the following questions:

- *Which variable--velocity or mass--has a stronger correlation with the size of the crater?*
- *What does this mean?*

Give them a few minutes to record their ideas in their science notebook.

Invite students to share their ideas after a few minutes. Project the first tab of the copy of https://docs.google.com/spreadsheets/d/1DnA5xImtGnQJVHRq60N4XQEUWa2MLSc8QNDR9v7JnTs/copy for students to reference as you discuss the patterns in the data. See assessment box for student ideas you should look for.

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING PATTERNS

This is another opportunity students have in this unit to use the following CCC element: Mathematical representations are needed to identify some patterns.

✱ SUPPORTING STUDENTS IN ENGAGING IN ANALYZING AND INTERPRETING DATA

Students are engaging in this common core standard for math in this unit: *Represent data on two quantitative variables on a scatter plot, and describe how the variables are related: Informally assess the fit of a function by plotting and analyzing residuals (CCSS.MATH.CONTENT.HS.S-ID.6a).*

Students will use this practice to compare different graphs, using the concept of the coefficient of correlation to evaluate the strength of the relationship between two variables. Use proportional reasoning to help students identify that the size of the crater changes faster with changes in velocity than with changes in the mass of the impactor. For example, ask students whether doubling the mass or velocity of the impactor will double the volume of the crater.

✱ SUPPORTING STUDENTS IN ENGAGING IN ANALYZING AND INTERPRETING DATA

Students used the correlation coefficient in *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- These graphs help us see that increases in the velocity and the mass of the impactor result in larger craters (larger volume). (SEP: 4.2; CCC: 1.5)
- The velocity of the impactor has the strongest relationship with the crater size, as reflected by the coefficient of correlation. This means that the size of the crater is better explained by the velocity and/or kinetic energy of the impactor. (SEP: 4.2; CCC: 1.5; DCI: PS3.B.4)

What to do: If students have difficulty explaining the meaning of the correlation coefficient in terms of the independent and dependent variables, ask them to read again the text on **slide M**.

For students who feel comfortable with manipulating equations, ask them to use the KE = ½(m*v^2) equation to make sense of these results. They would say something like: since velocity is squared, increases in velocity cause larger changes in the kinetic energy of the impactor compared to increases in mass. As shown by the graphs, the larger the velocity, the larger the crater because it has more energy to transfer to the surface. (SEP: 4.2; DCI: PS3.B.4; CCC: 1.5)

Building toward: 10.B.1 Apply the correlation coefficient to analyze the relationship between changes in the mass and the velocity of an impactor and the size of the crater it produces and use these ideas to refine an explanation about the changes in matter and energy within the meteor-Earth system. (SEP: 4.2, 4.5; DCI: PS3.B.4; CCC: 1.5, 5.2)

Revise predictions based on the kinetic energy equation. Present **slide O**. Say, *Last time, we made some predictions about the changes in the kinetic energy of the impactor due to changes in its velocity or its mass.* Use the slide prompts to revise these predictions:
What did we initially predict about our investigation question below?

- *Which changes in the meteor better predict the damage it causes, mass or velocity?*

kinetic energy = ½(mv^2)

- *Do our results support this prediction?*

Look for students to say that the velocity of the impactor better predicts the damage it causes.

7 · CONSIDER CHANGES IN MATTER OF METEOR

6 min

MATERIALS: None

Make sense of the ejecta. Present **slide P**. Say, *We can explain the factors that affect the size of the crater, but we also observed other crater features that we have not explained yet.*

Elicit 1-2 ideas with the prompts:
Which of the following is also related to the amount of kinetic energy of the impactor?

a. *Amount of material thrown across the surface (ejecta)*
b. *How far the material was thrown across the surface (ejecta)*

Look for students to suggest both.

Consider the absence of the meteor in the craters we have explored. Present **slide Q**. Say, *Now we can support our ideas about what the size of the crater says about the impactor that created it. Let's see if we can use our ideas to explain one of our observations.*

Have students turn and talk with the prompt:

- *Why don't we usually find the meteors in the craters they form upon impact?*

After a few seconds, invite students to share. Accept all answers.

Continue with **slide R**. Say, *In the smaller-scale system of our investigation, the impactor was fully intact. But in a larger-scale system, like the craters on the Moon, we do not see evidence of this.*

Elicit 1-2 ideas with the prompt:
- *What do you think might happen to the matter of the meteor during the collision and after it?*

Accept all answers again.

Use evidence from a scientific investigation. Present **slide S**. Say, *We cannot study the changes in matter using our lab setup because we are working with a system that is many times smaller than the real meteor-Earth system, so the changes in energy are not large enough to cause these changes in matter. Scientists have found some evidence in actual impact craters that can help explain what happens with large meteors during a collision.*

Give students a few moments to read the text on the slide:

Most craters lack evidence of the meteor that created them, but a recent study by Nicholas Timms and coworkers found cubic zirconia in a Canadian crater. This material forms when zircon, a common mineral on Earth, is heated to at least 2370°C (4298°F). This suggests that intense heat is generated upon some meteor impacts--enough to vaporize a meteor!

Then ask them to turn and talk with the prompt:
- *Where does the energy to generate this intense heat come from?*

When you invite students to share, they should mention that the energy to generate the high heat comes from the kinetic energy of the meteor.

8 · REVISE EXPLANATION

10 min

MATERIALS: 8.5" x 11" copy paper, M-E-F poster

Revise explanation of meteor collision. Present **slide T**. Remind students that we have seen evidence of fragments from mid-size meteors that hit Earth (10,000,000 kg), but as we have seen before, scientists rarely find large fragments of big meteors that hit Earth.

Give students a minute of individual thinking time to consider the prompt:
- *How can you explain why it is easier to find large fragments of smaller meteors than large fragments of large meteors?*

Present **slide U** and have students read the prompts:
- *Use words, mathematical symbols, and/or drawings to explain why finding large fragments of smaller meteors is easier than finding large fragments of larger meteors.*
- *Use ideas related to M-E-F to account for this difference.*

Ask students to write these explanations on a separate piece of paper. Collect these as a formative assessment.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: Look for the revised explanation to include the following elements:

- Differences in the kinetic energy of a small meteor and a large meteor due to their mass (SEP: 4.5; CCC: 1.5, 5.2)
- Changes in the surface due to the kinetic energy of the meteors (SEP: 4.5; CCC: 1.5, 5.2, DCI: PS3.B.4)
- Some of the energy is transferred to the surroundings as sound and heat. (SEP: 4.5; CCC: 5.2)
- The initial kinetic energy of the large meteor results in more heat in the system upon surface impact, which vaporizes the meteor, while the kinetic energy of a small meteor does not result in enough heat to vaporize it. (SEP: 4.5; DCI: PS3.B.4; CCC: 5.2)
- Matter from the meteor vaporizes, so it might disperse throughout the surroundings. Some matter from the surface is ejected out to the surroundings. Some matter on the surface is broken down and maybe vaporized as well. (SEP: 4.5; CCC: 5.2)

What to do

- Ask students to use the matter and energy connection on the M-E-F poster: *Energy transfers and matter changes happen together.* Instruct them to first track the changes in matter and then describe where the energy related to these changes transferred from and to.
- Switch back to **slide S** to support students in making connections between the amount of energy transferred by a meteor and the changes in matter observed in the system. Suggest they include this idea in their Progress Tracker, as it will support their sensemaking in Lessons 14 and 15.
- Energy loss to the surroundings as heat is an idea that students have explored during *OpenSciEd Unit P1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*. This is a good opportunity to see if students can apply this idea in a very different context.
- Students will use these ideas about how the amount of energy in a system can determine the observed changes in matter during the summative end-of-unit transfer task in Lesson 15. Provide prompt feedback on these explanations to give students enough time to identify areas where they may need support before the assessment.

Building toward: 10.B.2 Apply the correlation coefficient to analyze the relationship between changes in the mass and the velocity of an impactor and the size of the crater it produces and use these ideas to refine an explanation about the changes in matter and energy within the meteor-Earth system. (SEP: 4.2, 4.5; DCI: PS3.B.4; CCC: 1.5, 5.2)

9 · NAVIGATE

5 min

MATERIALS: 8.5" x 11" copy paper, Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster

Identify areas of uncertainty. Display **slide V**. Say, *We can explain why we could find a meteor fragment after the Chelyabinsk event. Scientists estimate that the Chelyabinsk meteor had an initial mass of 12 tons (11,000 kg) when it first reached Earth's atmosphere. But, they recovered only 1 ton of solid remnants.*

Point to frame A of the Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster to remind students about some of the changes we observed during the Chelyabinsk meteor event. Ask students to turn and talk with the prompt:

- *What happened to the missing matter?*
- *How could interactions with the atmosphere produce this outcome?*

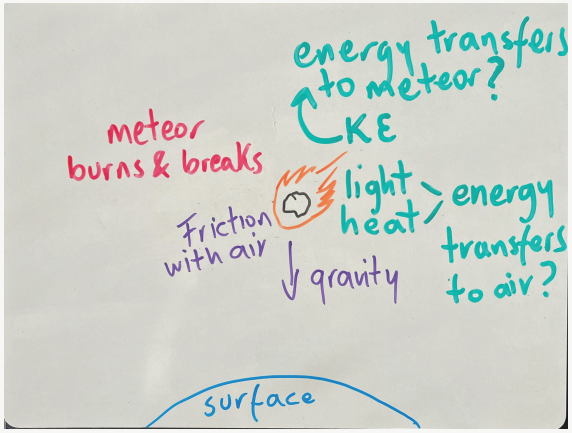
After a minute, invite students to share their ideas. Listen for the following ideas:

- Some of the matter burned.
- Maybe it vaporized too.
- Friction with the atmosphere could have caused that.

Navigate into the next lesson. Present **slide W**. Have students turn and talk with the prompt:

- *Do we think the same interactions with Earth's atmosphere happen with meteors smaller than the Chelyabinsk meteor?*

Give students a few minutes to discuss this prompt with their partner. Say, *We are going to investigate this next!*



Additional Lesson 10 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

Statistics and Probability
CCSS.MATH.CONTENT.HS.S-ID.6a **Interpreting Categorical and Quantitative data:** Represent data on two quantitative variables on a scatter plot, and describe how the variables are related: Informally assess the fit of a function by plotting and analyzing residuals.

Students compare different graphs, using the concept of coefficient of correlation to evaluate the strength of the relationship between two variables. Use proportional reasoning to help students identify that some variables change faster by changes in mass or velocity of the impactor. For example, ask students whether doubling the mass or velocity of the impactor will double the volume of the crater.

LESSON 11: What happens to the thousands of objects the size of the Chelyabinsk meteor and smaller that enter Earth's atmosphere every year?

PREVIOUS LESSON

We investigated whether a meteor's velocity or mass better predicts its crater size. We analyzed our results using the coefficient of correlation, and we established that the velocity of an impactor better predicts the crater's size. We learned that meteors with sufficient kinetic energy could vaporize upon surface impact. We refined an explanation about the changes in matter and energy within the meteor-Earth system.

THIS LESSON

INVESTIGATION

1 day



© ESA/DLR/Belstead Research, Jon Larson, Project Stardust

We analyze data from a video of a satellite being tested in a high-speed wind tunnel. We develop an explanation for why only a relatively small amount of the Chelyabinsk meteor's matter was still in solid pieces when it reached the surface. We argue that only a small fraction of the matter that most frequently enters Earth's atmosphere actually ends up leaving an impact on its surface.

NEXT LESSON

We will examine images of objects in space that lack atmospheres to see what happens when objects fall into them without burning up in an atmosphere. We will make observations about patterns of cratering activity on the Moon over its history and will identify periods with high and low cratering activity. We will consider why we don't see evidence of large meteor impacts on the Moon.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

11.A Apply scientific ideas and principles related to changes in matter and energy to provide an explanation for why much of the matter that makes up the objects that enter Earth's atmosphere end up not leaving an impact on the surface. (SEP: 6.3; CCC: 3.1, 5.2; DCI: PS3.A.2, PS3.A.4)

WHAT STUDENTS WILL FIGURE OUT

- As objects from space move through the atmosphere at high speeds, they collide with air particles, causing changes in both matter and energy along their paths.
- All the matter that melts, vaporizes, or breaks off in solid pieces in this process will eventually end up deposited across Earth's surface.
- Only a fraction of the matter that enters Earth's atmosphere leaves an impact on the surface because it either has so little mass to begin with or is in really small pieces by the time it reaches the surface.

Lesson 11 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	5 min		**NAVIGATE** Recall the role of mass in the patterns and predictions we made for the outcome of objects that reach Earth's atmosphere.	A	Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster
2	7 min		**ANALYZE AND INTERPRET DATA** Discuss possible causes for why the phenomena from the first lesson produce streaks of light at some point as they move through the atmosphere.	B-D	M-E-F poster
3	8 min		**ANALYZE DATA FROM A HIGH-SPEED WIND TUNNEL** As a class, analyze a video of testing a satellite in a high-speed wind tunnel. Have students make predictions about how many objects enter Earth's atmosphere each year.	E-F	computer, https://youtu.be/AneXvUxXCmA?si=8z0qTmcHVfDDBnTn, M-E-F poster
4	7 min		**MAKE PREDICTIONS AND ANALYZE DATA** Have students make predictions and consider the make up of meteorite remnants and inspect the shape of them. Discuss how this connects to particle-level interactions in the atmosphere.	G-J	M-E-F poster
5	7 min		**CONSTRUCT EXPLANATIONS** Introduce a related prompt for individual explanations and collect responses as a formative assessment.	K	piece of 8.5" x 11" paper, M-E-F poster
6	5 min		**ARGUE FROM EVIDENCE** Discuss why most objects that enter Earth's atmosphere end up leaving no noticeable effect or impact on the surface.	L	1 3x3 sticky note (optional), fine-tip colored marker (optional), white board marker
7	4 min		**NAVIGATE** Consider how frequency and impacts of meteors would compare with planets or moons that have little or no atmosphere.	M	*Magnetosphere*
8	2 min		**HOME LEARNING: SELF REFLECTION** Return the model students developed in Lesson 1 about the interactions of the Chelyabinsk meteor with the atmosphere (frame A).	N	student models from Lesson 1 (frame A and frame B)

End of day 1

Lesson 11 • Materials List

	per student	per group	per class
Lesson materials	• piece of 8.5" x 11" paper • 1 3x3 sticky note (optional) • fine-tip colored marker (optional) • *Magnetosphere* • student models from Lesson 1 (frame A and frame B)		• Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster • M-E-F poster • computer • https://youtu.be/AneXvUxXCmA?si=8zOqTmcHVfDDBnTn • white board marker

Materials preparation (15 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Test the video: https://youtu.be/AneXvUxXCmA?si=8zOqTmcHVfDDBnTn.

Post the M-E-F poster you referenced in the prior lessons that you developed from this prior unit: *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*.

Make sure to have the Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster displayed prominently to support student ideas during this lesson's conversations.

Print enough copies of the following reading:

- *Magnetosphere*

Lesson 11 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently build on ideas related to the following disciplinary core ideas in a new context:

- **PS3.A.2** At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. (HSPS3-2) (HS-PS3-3)
- **PS3.A.4** These relationships are better understood at the microscopic scale, ~~at which all of the different manifestations of energy can be modeled as either motions of particles or energy stored in fields (which mediate interactions between particles). This last concept includes radiation, a phenomenon in which energy stored in fields moves across space. (HS-PS3-2)~~

In prior units, including *Electricity Unit* and *Earth's Interior Unit*, students have developed ideas about energy transfer and the way energy manifests itself as well as types of particle-level changes that occur with matter along with such energy transfers. In this lesson, we are revising this idea and applying it in a new context to explain how the large amount of energy of some meteors can help explain their absence from the crater they form.

In this lesson, students will also have the opportunity to explore an idea related to the following disciplinary core idea:

- ~~Evidence from deep probes and seismic waves,~~ reconstructions of historical changes in Earth's surface and its magnetic field, ~~and an understanding of physical and chemical processes~~ lead to a model of Earth ~~with a hot but solid inner core, a liquid outer core, a solid mantle and crust. Motions of the mantle and its plates occur primarily through thermal convection, which involves the cycling of matter due to the outward flow of energy from Earth's interior and gravitational movement of denser materials toward the interior~~. (HS-ESS2-3)

Students apply the same crosscutting concept they used in Lessons 8 and 9, that the significance of a phenomenon is dependent on the scale, proportion, and quantity at which it occurs. They do this when they explain why most objects from space lose a large fraction of matter as they pass through Earth's atmosphere. They also argue that this is what happens to most of the meteors, since most are relatively small in size when they reach Earth, based on the mathematical model (*Frequency vs. Mass*) they developed in the last lesson. There is also support at the end of this lesson for making an explicit reference to the idea that the significance of a phenomenon is dependent on the scale, proportion, and quantity at which it occurs.

Students will encounter or co-develop definitions for the following word in this lesson: *vaporize.* Students should add *vaporize* to their Personal Glossary. **Do not** post any words or ask students to add them to their Personal Glossary until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

This lesson does not focus on the formation of Earth or active geologic processes, such as erosion and deposition, though it does begin to lay hints related to erosion and deposition processes that will be followed up on in future lessons.

Toward the end of the lesson students may raise questions about whether the planet has been growing over its lifetime due to accumulation of matter from meteors or whether we can find meteorite material in the rock layer or the role of water and wind in altering the record of impacts. If these questions come up, encourage students to write these new questions on sticky notes and add them to the Driving Question Board so we can remind ourselves to investigate them in subsequent lessons.

LEARNING PLAN for LESSON 11

1 · NAVIGATE

5 min

MATERIALS: Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster

Link to the ideas developed in the prior lesson. Display **slide A**. Say, *Last time, we investigated how mass and velocity of a meteor help explain the damage it can cause.*

Discuss the question on the slide as the class:

- *What ideas did we have in our last lesson about what happens to all these objects as they enter Earth's atmosphere every year?*

Point to the Initial Consensus Model: Observed Phenomena During the Chelyabinsk Event poster during this conversation to elicit additional ideas.

Sample student responses include the following:

- They burn up in the atmosphere.
- They do not make it to the surface.
- They melt.
- They disappear.

2 · ANALYZE AND INTERPRET DATA

7 min

MATERIALS: M-E-F poster

Discuss observations. Display **slide B**. Discuss what we see happening to these objects in the images shown on the slide as they move through the atmosphere.

Sample student responses include the following:

- One of the objects is breaking into smaller pieces.
- Both of the objects are glowing or giving off light.
- Both objects are leaving a trail of stuff behind them.

Explain one aspect of the phenomena from the prior lesson. Display **slide C**. Give students a half a minute to consider the question on the slide on their own and then discuss it as a class:

- *Why would these different objects be producing light at some points as they travel through the atmosphere?*

Listen for the following ideas:

- They get really hot.
- They catch fire.
- Things heat up when they (re)enter the atmosphere.
- They collide with air particles, which creates friction.
- The interaction with the air is transferring energy from or to it.

✱ SUPPORTING STUDENTS IN THREE-DIMENSIONAL LEARNING

A PS4.B-related DCI that students should develop by the end of grade 2 is that very hot objects give off light (e.g., a fire, the Sun). If students have experienced (material.co.n) and [material.ce.n], they will also have ideas about lightning and fire to bring to the table. Support students in making those connections by asking them about what they figured out in chemistry related to glowing air.

Connect to prior experiences. Reference the energy corner of the M-E-F poster. Remind students that earlier in the course we explained many other phenomena in terms of energy transfers that we could observe occurring as light or heat given off by matter in the system, such as when a lightbulb goes on, a wire heats up, or even when radioactive materials decay to cause convection deep within Earth's mantle. Suggest that we consider a bit further these two ways that we know energy can be transferred to the surroundings--light and heat.

Say, *Many of the objects that we looked at last time were made of rock. That is true for the majority of the meteors that enter Earth's atmosphere from space. The rest are made of either ice or metal. And all the manufactured materials we looked at also had some parts of them that were made of metal. Let's consider what experiences we've had related to seeing what happens to rocks and metals when they get really hot.*

Brainstorm examples of things that glow when they are hot. Display **slide D**. Give students a minute to discuss the questions on the slide with a partner and then discuss it as a class to elicit some examples:

Suggested prompt	Sample student response
What are some examples where you've seen metal or rock material glowing when it was heated to really hot temperatures?	Blacksmith Stovetop Iron poker in a fire Lava or magma
Can anything other than rock and metal glow when it gets hot? How do you know?	Air that produces the flash during lightning Light given off by gasses in the flame of a fire

ADDITIONAL GUIDANCE

Only address questions about the color of light given off by meteors if they came up in your Driving Question Board. If they did, share the following information now; otherwise do not introduce this line of ideas:

- Different types of atoms in the material that is heating up affect the color of light it gives off.
- When there is sodium in the material that makes up a meteor, those atoms will give off an orange-yellow glow at high temperatures.
- Other types of atoms produce different colors of light. For example, iron produces a yellow glow, magnesium atoms will glow a blue-green, while calcium atoms produce violet-colored light.

Motivate exploring these relationships further. Suggest that if temperature and light are somehow related to the interaction between the atmosphere and the matter of these objects as they move at high speeds through the atmosphere, it would be helpful if we could watch those objects up close to see what changes in the matter might be occurring that are leading to these energy transfers.

3 · ANALYZE DATA FROM A HIGH-SPEED WIND TUNNEL

8 min

MATERIALS: computer, https://youtu.be/AneXvUxXCmA?si=8zOqTmcHVfDDBnTn, M-E-F poster

Orient to a high-speed wind tunnel. Present **slide E**. Read the text on the top of the slide. Explain that scientists and engineers have built a device that allows them to simulate what happens to the matter that makes up the objects we launch into space when they reenter Earth's atmosphere. Explain that this device is called a *high-speed wind tunnel* and that is what is shown on the slide.

Describe what happens in the high-speed wind tunnel. Say, *Let's orient ourselves to the views we will see in a video where scientists are testing a part of a satellite in a high-speed wind tunnel to see what will happen to it when it reenters Earth's atmosphere.* Point out the still image on this slide that shows different camera views that students will see in the video.

ADDITIONAL GUIDANCE	If students ask about how a high-speed wind tunnel can simulate an object traveling through the air at fast speeds if that object is stationary in the wind tunnel, you can emphasize the following: • In a high-speed wind tunnel air is blown thousands of meters per second over a stationary object that scientists and engineers want to test. • This relative difference in velocity is designed to simulate the interactions that would happen if the object was moving through the air at that speed.

Analyze data. Present **slide F**. Say, *The video will show the results of testing a part of a satellite in the high-speed wind tunnel. As you watch the video, consider what changes you see happening as well as what interactions might be causing this.*

Play the video: https://youtu.be/AneXvUxXCmA?si=8zOqTmcHVfDDBnTn. After playing the video, ask students to discuss the two questions on the slide with a partner for three minutes. Then discuss the first question from **slide F** as a class.

Suggested prompt	Sample student response
What changes did you notice happening to matter in the system over time?	It got hot. The surface appeared to move. Glowing pieces flew away. Some parts of the surface looked like it was melting or flowing away.

If students don't mention the size of the object decreasing over time, ask them, *What do we notice happening to the size of the object over time?* If it hasn't come up yet, ask students whether any parts of the object could be turning to gas too. Students should say yes. Name the process of conversion of a substance from the liquid or solid phase into the gaseous phase as *vaporization*.

Discuss the second question on **slide F** as a class. Follow up with the additional questions listed below.

Suggested prompt	Sample student response
Why would collisions with air particles at these high speeds be causing this? Use M-E-F thinking.	Collisions transfer energy, and the faster the particles or the object is moving relative to what it is colliding with, the more energy that would be transferred.
How are forces related to collisions?	(Listen for ideas about force interactions in collisions related to the work students did in their prior unit.)
How could such collisions cause a temperature increase in the particles along the surface of a meteor as well as in the air particles colliding with it?	(Accept all answers.)
How would all those collisions with air particles affect the speed of the incoming meteor?	It would slow it down.

Suggested prompt	Sample student response
In addition to this increase in the kinetic energy of the surrounding air particles and the decrease in the kinetic energy of the meteor, what other evidence do we have that energy transfer is occurring in the system?	The meteor is glowing. It is making sound as it travels through the air.

Point out that we now have a lot of ways to account for where the light is coming from for many different types of objects that enter our atmosphere as well as to account for what is happening to the matter as it does so.

4 · MAKE PREDICTIONS AND ANALYZE DATA

7 min

MATERIALS: M-E-F poster

Make predictions. Display **slide G**. Read the text at the top of the slide to emphasize the following:

- *Vaporization* describes the process that occurs when all the bonds between neighboring particles in a solid break and the particles that fly away are in gas form.
- Some meteors are made mostly of rock, some mostly of iron, and some mostly of water.

Discuss the question on the slide as a class:

- *Why would all the matter that is vaporized from these meteors eventually end up deposited over some part of Earth's surface?*

Sample student responses include the following:

- When the vaporized particles cool down and clump back together, they might turn back into a solid or a liquid.
- Gravity pulls everything downward.
- Really small particles of stuff, like ash, eventually settle out.
- Even water vapor eventually comes out of the sky in the form of precipitation.
- Precipitation (or water in clouds) might collect, wash, dissolve, or remove those substances from the air.
- It might eventually get deposited on land or in the water (oceans, lakes, or rivers).

Consider the makeup of meteorite remnants. Display **slide H**. Give students two minutes to discuss the two questions on the slide with a partner, but do not have them share responses with the whole class:

- *Which of these materials would tend to vaporize less readily?*
- *What tools could people use to try to find any of the remnants of these meteors?*

Inspect the shape of meteor remnants. Display **slide I**. Introduce one method for finding meteor remnants and their typical size by reading the text on the top of the slide:

- *Some amateur collectors search for remnants of iron meteorites using magnets wrapped in plastic bags to help easily peel off what they collect.*
- *The remnants they typically find are smaller than a millimeter in diameter and have shapes similar to those shown to the right.*

Then prompt students to take a half a minute on their own to consider the question on the slide:

- *What do you notice about the shape of these remnants?*

ADDITIONAL GUIDANCE	The word *remnant* is used to describe the images shown on slide I rather than *pieces* or *parts*. This was chosen because the word *remnant* seems to invite the possibility that the material underwent a phase change, whereas the words *pieces* or *parts* do not. If needed, explain that *remnant* means a small, remaining quantity of something.

Connect to particle-level interactions in the atmosphere. Display **slide J**. Have students discuss the related question on the slide with a partner for two minutes:

- *What particle-level interactions in the atmosphere could cause remnants from the meteor to form into these shapes?*

ADDITIONAL GUIDANCE

This Turn and Talk is designed as a quick warm up before the individual explanation students will write on the next slide. It is designed to get some new ideas on the table such as the following:

- Air friction wore away the rough edges of these.
- These are droplets of iron that condensed from a liquid or gas form as that matter cooled down (like hail).
- The surface of these remnants melted when they were moving quickly through the air and then solidified as the remnants slowed down.

None of these ideas are must-haves in the explanation that students are about to write, which is why you are not discussing them as a whole class at this point.

5 · CONSTRUCT EXPLANATIONS

7 min

MATERIALS: piece of 8.5" x 11" paper, M-E-F poster

Construct individual explanations. Display **slide K**. Read the text at the top of the slide and the related prompt: *Scientists estimate that the Chelyabinsk meteor had a mass of 12 tons (11,000 kg) when it first reached Earth's atmosphere. But, they recovered only 1 ton of solid remnants.*

- *How can you explain what happened to the 11 tons of missing matter?*

Emphasize that students should use ideas related to M-E-F to account for this discrepancy.

Ask students to write these individual explanations on a separate piece of notebook paper. Collect these as a formative assessment.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: Students apply some of the ideas outlined below related to changes in matter and energy and any force interactions that would have caused these. (SEP: 6.3, DCI: PS3.A.2, PS3.A.4)

- **Matter changes**
  - There are many more small-size pieces of material that reach the atmosphere than large ones over a year.
  - Pieces of the material moving through the atmosphere break off, melt, and/or vaporize (turn to gas).
  - The scale (size and mass) and material of the meteor would affect how much of it remains in a single piece by the time it reaches the surface.
  - Some parts of the meteor might condense into droplets or solids after being vaporized.
- **Energy**
  - Higher meteor speeds produce higher heat loads as it moves through the atmosphere at very high speeds.
  - The temperature of the meteor's surface and the air around it increases as this happens.
- **Forces**
  - Collisions with air particles produce forces on the meteor.
  - These forces slow the meteor down and heat its surface up.
  - Gravity would pull all the matter that is lost off the meteor downward over time.
  - Smaller-mass, slower meteor remnants have much less momentum when they impact the surface and therefore produce smaller-magnitude forces upon impact and result in less-noticeable damage to any solid material(s) on the surface.

- Students account for where all the missing matter could have gone to in Earth's systems. (CCC: 5.2)
  - The 11 tons of missing matter did not disappear.
  - It must be in one or more Earth systems. This could include having been deposited on solid ground, falling into and settling to the bottom of a body of water, or being suspended in the atmosphere for a while.

What to do: Do not expect every student to use every idea. Rather, use this to determine which new ideas students are using in their explanations. Look for students to use more of the ideas above than they did in their Lesson 1 models. Photocopy student explanations and return them to students before the end of this lesson set so they can have them as an artifact they will use in their summative assessment.

Building toward 11.A.1 Apply scientific ideas and principles related to changes in matter and energy to provide an explanation for why much of the matter that makes up the objects that enter Earth's atmosphere ends up not leaving an impact on the surface. (SEP: 6.3; DCI: PS3.A.2, PS3.A.3; CCC: 3.1, 5.2)

6 · ARGUE FROM EVIDENCE

5 min

MATERIALS: 1 3x3 sticky note (optional), fine-tip colored marker (optional), white board marker

Argue from evidence. Display **slide L**. Discuss the two questions on the slide as a class:

- *Why does only a small amount of the matter that enters Earth's atmosphere end up leaving a noticeable impact on its surface?*
- *What part of the mathematical model have we now explained?*

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING SCALE, PROPORTION, AND QUANTITY

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- Students describe how the reduction of size, mass, and/or speed of the remnants that reach the surface would result in each having less kinetic energy and/or less momentum and therefore would result in no (or negligible) damage or effects. (PS3.A.2, CCC: 3.1)
- Students identify that the objects that most frequently reach Earth's atmosphere are ones that are much smaller in mass than the Chelyabinsk meteor (the top-left portion of the graph shown on **slide L**). (CCC: 3.1)

What to do: If students do not mention kinetic energy or momentum, ask them how mass is related to both of these. Ask them to connect this to what they recall about damage from their prior unit of study *OpenSciEd Unit C.1: How can we slow the flow of energy on Earth to protect vulnerable coastal communities? (Polar Ice Unit)*. Follow up by asking how this is related to the really-small-mass remnants that we know are typically produced through interactions with the atmosphere.

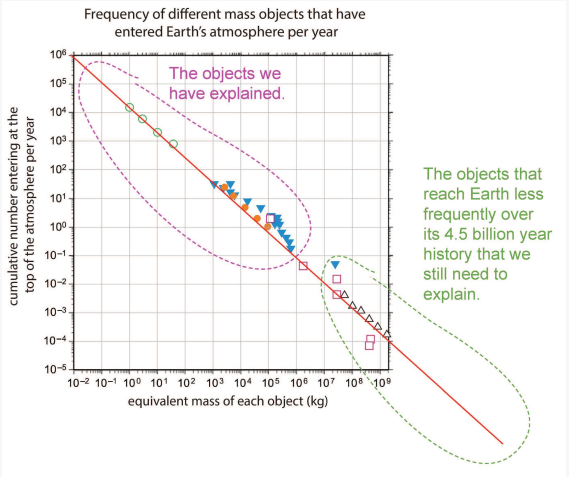
Building toward 11.A.2 Apply scientific ideas and principles related to changes in matter and energy to provide an explanation for why much of the matter that makes up the objects that enter Earth's atmosphere ends up not leaving an impact on the surface. (SEP: 6.3; DCI: PS3.A.2, PS3.A.4; CCC: 3.1, 5.2)

Use white board markers with the graph on slide L projected on a white board to highlight and annotate the portion of the graph that reflects what students have identified in their response to the second question. Extend the graph's line of best fit to remind students that the mathematical model has some concerning predictions for the frequency of events that would occur over longer period of time, like the age of the Earth.

Highlight, annotate, and point out that we still have the remaining part of the graph to investigate and explain (the bottom-right corner and beyond--deeper into Earth's history and future), and since our initial ideas about what happens to those meteors are very different for objects at that scale, many of our questions are also about that. ✱

Here is an example annotation of slide L that shows all this is provided to.

Emphasize that all this air-interaction thinking raises some new questions for us to consider as a class. If time permits, distribute a sticky note and fine-tip colored marker to record a new question they have.



There are opportunities at two points in the lesson, including here, to make an explicit reference to this element of this crosscutting concept:

- The significance of a phenomenon is dependent on the scale, proportion, and quantity at which it occurs.

7 · NAVIGATE

4 min

MATERIALS: *Magnetosphere*

Navigate into the next lesson. Display **slide M**. Give students two minutes to discuss the two questions on the slide with a partner and then discuss them as a class.

Suggested prompt	Sample student response
What would happen to many of these objects if we did not have an atmosphere?	They would impact the surface. The size of the effects on the surface, like craters or damage, would be larger. There might not be streaks of light, though, because there wouldn't be heating through atmospheric interactions.
Some objects in our solar system, like Earth, have significant atmospheres while others do not. Can we explain why?	Accept all answers
What other planets or moons do you know of that could provide us data to test our predictions?	Our Moon. Mercury or Mars. Some other moons of other planets.

Suggest that in our next lesson we investigate data from some of the places students suggested to see if they confirm or refute our predictions.

Distribute *Magnetosphere* and mention that this reading explains why some planets have atmospheres and others do not. Ask students to read it as home learning.

ADDITIONAL GUIDANCE

This reading will help students develop the following part of this disciplinary core idea:

- **ESS2.A.2** ~~Evidence from deep probes and seismic waves,~~ reconstructions of historical changes in Earth's surface and its magnetic field~~, and an understanding of physical and chemical processes~~ lead to a model of Earth ~~with a hot but solid inner core, a liquid outer core, a solid mantle and crust. Motions of the mantle and its plates occur primarily through thermal convection, which involves the cycling of matter due to the outward flow of energy from Earth's interior and gravitational movement of denser materials toward the interior~~. (HS-ESS2-3)

8 · HOME LEARNING: SELF REFLECTION

2 min

MATERIALS: student models from Lesson 1 (frame A and frame B)

Describe home learning. Present **slide N**. Say, *I think we made a lot of progress since we started this unit. I will give you back the models that you developed in the first lesson to explain some of the things we have investigated so far.*

Explain to students that as a home learning, they will reflect on how their ideas changed since the start of the unit. Use the prompts to describe the focus of their self-reflection:

- *How have your ideas changed since then?*
- *What activities, discussions, or investigations have helped you change the way you understand this phenomenon now?*

ADDITIONAL GUIDANCE	Self-reflection is an essential part of learning, as it helps students think about their own thinking process, preferences, and strategies that work best for them.

LESSON 12: What happens when rocks hit planets or moons with minimal atmosphere?

PREVIOUS LESSON

We analyzed data from a video of a satellite being tested in a high-speed wind tunnel. We developed an explanation for why only a relatively small amount of the Chelyabinsk meteor's matter was in solid pieces when it reached the surface. We argued that only a small fraction of the matter that most frequently enters Earth's atmosphere actually ends up leaving an impact on its surface.

THIS LESSON

INVESTIGATION

2 days



NASA Visualization Technology Applications and Development (VTAD)

We examine images of objects in space that lack atmospheres to see what happens when objects fall into them without burning up in an atmosphere. We make observations about patterns of cratering activity on the Moon over its history and find periods with high and low cratering activity. We consider why we don't see evidence of large meteor impacts on the Moon.

NEXT LESSON

We will analyze Earth's cratering data and will find visible impact cratering is present in recent history but absent in over half of Earth's timeline. We will use images of terrestrial craters to observe that older ones have less-clear features. We will use an erosion model to test how the surface can change. We will read about geological processes and will use these ideas to explain differences in cratering evidence between the Moon and Earth.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

12.A Analyze empirical evidence to identify patterns in cratering on solar system objects without atmospheres that can support claims about the changes in cratering activity on Earth. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2)

WHAT STUDENTS WILL FIGURE OUT

- There are a lot of craters on other space objects, suggesting there have been a lot of collisions on everything.
- Evidence from other space objects suggests there must have been a large number of things that came towards Earth too (many of which probably burned up in the atmosphere).
- There are very large craters on other space objects, so there should be some large craters on Earth.
- Craters have been created over billions of years.
- The age distribution of large craters on the Moon has decreased over time, while the age distribution of small and medium-size craters has fluctuated.

Lesson 12 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	4 min		**NAVIGATE** Discuss how looking at the surfaces of space objects with no atmosphere can help us understand impacts and make sense of what happens on Earth.	A	
2	15 min		**INVESTIGATE IMAGE DATA** Distribute image sets to small groups or pairs and provide guiding prompts for student observations.	B-C	https://www.openscied.org/EmpiricalEvidence, computer, physical copies of https://www.openscied.org/EmpiricalEvidence (optional)
3	7 min		**DRAW INFERENCES FROM DATA** Facilitate a discussion of student noticings about the craters on solar system objects without atmospheres and guide students in making inferences.	C-F	chart paper (optional), chart paper markers (optional)
4	16 min		**INVESTIGATE LUNAR DATA** Distribute *Moon Timeline* and *Lunar Time Periods* to each student. Instruct students to use the information in the reading to mark and label the duration of each time period on their timeline.	G-J	*Moon Timeline*, *Lunar Time Periods*, colored pencils in red/brown/yellow/teal or light blue/blue (optional)
5	3 min		**NAVIGATE** Complete an exit ticket to prepare students for the next class day, connecting the crater data we just looked at with our ideas and questions about collisions with Earth.	K	8.5" x 11" copy paper
					End of day 1
6	5 min		**NAVIGATE** Review exit ticket answers from last time to motivate the need for empirical data.	L	Exit ticket from day 1
7	20 min		**ANALYZE CRATER FREQUENCY DATA** Analyze crater frequency data showing the number of small, medium, and large craters during each of the Moon's major time periods. Create an annotated timeline describing the patterns in lunar crater frequency.	M-N	*Moon Timeline*, *Frequency of Small Craters on the Moon*, *Frequency of Medium Craters on the Moon*, *Frequency of Large Craters on the Moon*, *Lunar Time Periods*, Moon timeline poster, chart paper markers, https://www.youtube.com/watch?v=ANYxkwvb8pc (optional)
8	10 min		**REVISE DATA SET** Reconsider the data set we saw previously showing the frequency of different-size meteors approaching Earth. Develop the idea that the pattern captured by this graph would look different for times billions of years ago and will likely look different in the future as well.	O-R	Moon Timeline poster
9	4 min		**NAVIGATE** Navigate into the next lesson by considering why we don't see evidence of large or old craters on Earth's surface.	S	

Part	Duration		Summary	Slide	Materials
10	6 min		**UPDATE PROGRESS TRACKER** Update Progress Trackers with ideas from this and recent lessons.	T	*Progress Tracker*, colored pencils

End of day 2

Lesson 12 • Materials List

	per student	per group	per class
Lesson materials	• science notebook • *Moon Timeline* • *Lunar Time Periods* • colored pencils in red/brown/yellow/teal or light blue/blue (optional) • 8.5" x 11" copy paper • Exit ticket from day 1 • *Frequency of Small Craters on the Moon* • *Frequency of Medium Craters on the Moon* • *Frequency of Large Craters on the Moon* • *Progress Tracker* • colored pencils	• https://www.openscied.org/EmpiricalEvidence • computer • physical copies of https://www.openscied.org/EmpiricalEvidence (optional)	• chart paper (optional) • chart paper markers (optional) • Moon timeline poster • chart paper markers • https://www.youtube.com/watch?v=ANYxkwvb8pc (optional) • Moon Timeline poster

Materials preparation (30 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch all the images and handouts so they can be added to students' notebooks.

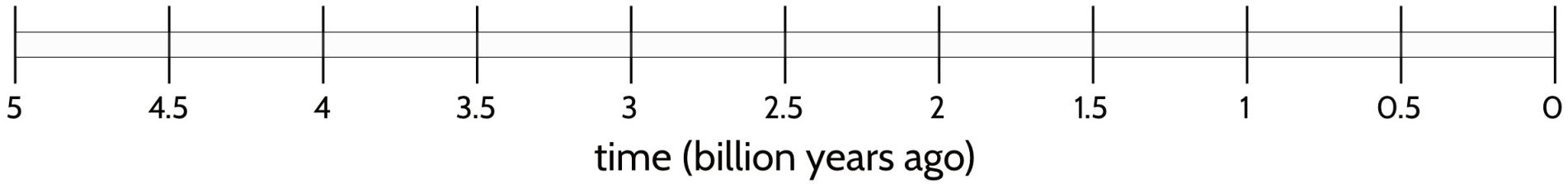
Prepare the image sets for students. This can be done in two ways:

1. Electronically, by sharing the slide deck on this link: https://www.openscied.org/EmpiricalEvidence. This link will spring a copy of the slide deck. Give your students view access to this copy.
2. Physically, by printing out the slide deck onto paper or cards to be provided to groups. You will need to print enough copies for groups in your largest class. Do not three-hole punch these printouts, as they will be used by other classes.

The activity group size is flexible and should be adjusted to best fit the medium in which the images will be viewed.

If you have not already, prepare to distribute the colored pencils to students. For setting up their Progress Tracker, students will each need access to multiple colors. One option is bundling colors together in boxes or with rubber bands with enough for small groups or individual students. Each student should have access to at least 5-6 colors.

Set up the blank class timeline by taping together two pieces of chart paper along the short ends. Draw a blank timeline horizontally to match the one provided to students on *Moon Timeline*. Title it "Moon Timeline".


5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
time (billion years ago)

Lesson 12 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently build new ideas related to the following disciplinary core idea:

- ESS1.C.2 **The History of Planet Earth.** Although active geologic processes, ~~such as plate tectonics and erosion,~~ have destroyed or altered most of the very early rock record on Earth, other objects in the solar system, such as lunar rocks, asteroids, ~~and meteorites~~, have changed little over billions of years. Studying these objects can provide information about Earth's ~~formation and~~ early history. (HS-ESS1-6)

The focus is on craters on planetary objects without atmospheres and how data from these can help us understand cratering on Earth over time.

Students will encounter a definition for *cratering activity* in this lesson. **Do not** post any words or ask students to add them to their Personal Glossary until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

This lesson does not focus on the formation of Earth or Earth processes. We are also not trying to understand the origin or properties of specific, different solar system objects--rather, we are looking for patterns in cratering that will allow us to make inferences about the change in bombardment patterns in the solar system over time, which will help us generate ideas about what to look for on Earth. The ideas not covered will be covered in later lessons.

LEARNING PLAN for LESSON 12

1 · NAVIGATE

4 min

MATERIALS: None

Consider what objects we could look at that have little to no atmosphere. Say, *We know that rocks burn up when they move through Earth's atmosphere. But not every planet or space object has an atmosphere. What would happen in a place like that?* Present **slide A**. Use the slide prompts to elicit 1-2 ideas:

- *Do rocks burn up as they approach planets or space objects that don't have an atmosphere?*
- *Why did we want to look at objects that have little to no atmosphere?*
- *What objects in our solar system have little to no atmosphere?*

Give students a couple minutes to discuss with someone near them and then solicit ideas. For the last prompt. students will likely say the Moon. They might not say anything else, and this is okay. Validate all students' ideas.

Say, *Over the years, we have sent a lot of spacecraft across our solar system to take images that are sent back to Earth. Now we have photos of moons around other planets as well as our own Moon. Some other objects with little to no atmosphere for which we have high quality surface images are the planet Mercury and some dwarf planets, such as Ceres. Let's take a look at some of these images.*

ADDITIONAL GUIDANCE

Some students may have heard that most of these objects have an exosphere, which is a very thin, sparse layer of gas. This is a transitional layer between the surface and pure space, but it's not substantial enough to be considered an atmosphere.

2 · INVESTIGATE IMAGE DATA

15 min

MATERIALS: science notebook, https://www.openscied.org/EmpiricalEvidence, computer, physical copies of https://www.openscied.org/EmpiricalEvidence (optional)

Introduce surface photos. Explain to students that you have a collection of photographs of the surfaces of some of these objects that we can look at. Present **slide B** and ask students to turn and talk with the prompts:

- *What surface features do you expect to see that would indicate a larger meteorite having hit the surface of a planet or moon?*
- *How would a meteorite impact be different when there is no atmosphere versus when there is?*

Invite students to share after a minute or two. Make a public record of students' ideas and title it: "Evidence of Impact Events."

Students might suggest the following:

- big rocks that hit in the past because they did not burn up
- craters, holes (or other words to describe this)
- bigger craters (or holes) than on Earth because the rocks won't have burned up
- might have more preserved craters (or holes) because no atmosphere means no weather

Some students may be using the word *crater* to describe the impact site of a rock. Highlight this word and ask students to describe what they mean, but continue to allow students to describe these sites in everyday language right now.

Introduce image investigation activity. Present **slide C**. Say, *In your group/with your partner, take 12 minutes to look at all the images. In your notebook, record responses to the slide prompts:*

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING PATTERNS

The focus in this investigation is that the patterns emerge from similarities across the data (images of different craters). The empirical evidence of the images is what allows us to identify these patterns.

Look at empirical evidence of crater images and record the following in your science notebook:
- *What patterns do these images help us identify?* ✱
- *What do you think this pattern means?*

Distribute computers with access to https://www.openscied.org/EmpiricalEvidence to each pair of students. If you printed the slide deck, distribute a copy of the set of cards to every pair of students. If your students are viewing the images digitally, encourage them to zoom in to see more detail. This is a flexible activity, so do what works best for your class. Give students about 12 minutes to engage with the images and consider the prompts.

3 · DRAW INFERENCES FROM DATA

7 min

MATERIALS: science notebook, chart paper (optional), chart paper markers (optional)

Discussing patterns observed in image data. Use the prompts from **slide C** to guide the conversation:
Look at empirical evidence of crater images and record the following in your science notebook:
- *What patterns do these images help us identify?*
- *What do you think this pattern means?*

Solicit ideas from the students using the first prompt. Record ideas publicly on the left side of a T-chart, either on the board or other convenient medium. The left column of the T-chart should be labeled "Observed Patterns." For each identified pattern, prompt the students to share what they think the pattern means. Record these ideas on the right side of the T-chart, which should be labeled "Inferences".

ALTERNATE ACTIVITY

Consider displaying https://www.openscied.org/EmpiricalEvidence and having students come up to the front of the room and examine the images together on the screen.

KEY IDEAS

Purpose: Establish some key ideas about cratering and the inferences those ideas help us make.

Key patterns to look/listen for
- There are a lot of craters on all these objects (especially as seen from the wide view, we can see they are all over the objects).
- There are many sizes of craters, including some *really* big ones.
- The things that hit the object don't seem to be in the middle of the craters, although sometimes there is a kind of peak or mountain in the middle.
- There are overlapping craters.

Build inferences from patterns in the data. Explain to students that to establish shared meaning for the observed patterns in the data, we will discuss each of the major patterns they observed. As the class discusses each pattern, record the established inferences on the right of the T-chart.

ADDITIONAL GUIDANCE

It is important to note that this discussion is about proposing ideas and drawing inferences that lead to possible explanations, not evidence-based arguments. For example, we will discuss impactor vaporization or breaking as something that *could* explain why we don't see impactors in the middle of craters, but we don't have clear evidence for this. The point in this lesson is to develop ideas and possibilities to then further think about and investigate.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Look for students to discuss the following ideas:

- Connections between specific empirical observations from the data and patterns across the set of crater images (CCC: 1.5; DCI: ESS1.C.2)
- The surface of planets and moons without an atmosphere is covered by craters of different sizes, from small to very large ones. (CCC: 1.5; DCI: ESS1.C.2)

What to do: Guide students towards noticing any patterns that they do not bring up on their own by asking questions related to how the patterns appear in the image data, for example:

- *Did you notice any patterns related to the size of the craters?*
- *Did anybody see evidence of the impactors, the rocks themselves?*
- *Is there a pattern in the way the craters are arranged? Is there always space between them? Do they ever happen in the same place?*

Building toward 12.A.1 Analyze empirical evidence to identify patterns in cratering on solar system objects without atmospheres that can support claims about the changes in cratering activity on Earth. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2)

Consider the number of craters. Display **slide D**. Ask students to turn and talk with the prompt:

- *What inferences can we make about Earth's history based on the patterns we found from these space objects?*

Invite a few volunteers to share their ideas. Look for students to draw connections with Earth and how if a lot of objects hit these other things in space, many must have come towards Earth too. If students start to dig into thinking about why Earth doesn't have so many craters, ask them to jot down these thoughts so we can remember them in our next lesson.

Consider how craters overlap. Display **slide E** and use the prompts to guide discussion:

- *What information in these images can help us make inferences about which impacts happened before others?*
- *Does this information tell us exactly when these impacts happened?*

Look for students to mention something about them happening at different times, with some being more recent but some being very old. Help students connect this to the idea that craters are still being made in recent history and may be made in the future. Highlight the idea that while we may be able to tell which ones are relatively older or younger, we don't know exactly when any of these impacts happened based on the images of craters alone.

Present **slide F**. Use the slide prompts to elicit 1-2 ideas:

- *What tools have we encountered in prior units that could tell us the age of the rock in each crater?*
- *How might that help us reconstruct the history of these impacts on the Moon?*

Don't play "guess what's in my head" at this point. If the students don't remember, say, *It turns out that for the Moon, we can use radioactive dating on some craters to determine their ages.*

Collect devices or physical copies of the slide deck. Ask students to return to their normal seats

ALTERNATE ACTIVITY

This is a great opportunity to make a connection back to the rock dating discussion in *Earth's Interior Unit*. Say, *So we know that all the craters couldn't have happened at the same time. What can we infer about the order in which the craters occurred?* Solicit ideas from students, looking for ideas about how the whole ones must have occurred after the ones they disrupted. Say, *In the Afar unit we talked about dating rocks using radioactive dating processes. This could give us specific ages for rocks. These overlapping patterns can't tell us the exact age of the craters, but they do allow us to use relative dating to understand the order in which the craters were formed.* Ask students to look back at the overlapping craters and think about in what order they must have been created.

4 · INVESTIGATE LUNAR DATA

16 min

MATERIALS: *Moon Timeline*, *Lunar Time Periods*, colored pencils in red/brown/yellow/teal or light blue/blue (optional)

Establish a lunar timeline. Present **slide G**. Distribute *Moon Timeline* and *Lunar Time Periods* to each student. Say, *The Moon's history is divided into different time periods. Understanding these lunar time periods will help us make sense of the crater data.* Instruct students to use the information in the reading to mark and label the duration of each time period on their timeline. Ask students to work with a partner, and give them 8-10 minutes to complete this task.

ALTERNATE ACTIVITY

If time and materials allow, you may choose to have the students color-code their timelines so that their annotated time periods match the lunar crater data they are about to look at. In this case, the colors should be as follows: pre-Nectarian period = red, Nectarian period = brown, Imbrian period = yellow, Eratosthenian period = teal or light blue, Copernican period = blue.

Look at lunar crater ages. Present **slides H-J**, spending no more than a few minutes on each of these slides. Ask students, *What do you notice about the dating of these craters?* Give students a couple moments to look at each slide and think, then ask students to share. Look for students to talk about some being more recent but some being very old. Help students connect this to the idea that craters are still being made in recent history and may be made in the future. Highlight ideas about the relative sizes of craters. For example, students may notice that while there are many craters from the recent past (the Copernican time period, shown in blue), all these craters are relatively small. If students wish to jot down notes on their timelines, encourage them to do so.

5 · NAVIGATE

3 min

MATERIALS: 8.5" x 11" copy paper

Connect to ideas about Earth. Present **slide K**. Distribute a sheet of copy paper to every student. Ask students to write down their ideas about the two prompts on the slide.

- *Do these data help us identify the frequency of large versus small impacts over time on the Moon?*
- *How could understanding the frequency of large versus small impacts over time help us reconstruct the history of Earth and predict its future?*

Collect these exit tickets as students leave the classroom.

End of day 1

6 · NAVIGATE

5 min

MATERIALS: Exit ticket from day 1

Review exit ticket answers. Present **slide L**. Say, *I went through your exit tickets, and many of you thought the data did **not** help us identify the frequency of large versus small craters on the Moon.* Return the exit tickets to students. Then ask them to share their answers to the prompts on the slide. Use this discussion to establish the idea that the Moon is particularly useful for helping us make inferences about Earth, and we need empirical evidence to do so.

Suggested prompt	Sample student response
Why did we look at images of other planets and moons that don't have an atmosphere?	• Earth's atmosphere causes the craters on Earth to be destroyed over time. • Space objects without atmospheres have a more-complete record of the history of meteor collisions over time.
Why would the Moon provide us the best data for understanding Earth's cratering activity over time?	• The Moon is right next to Earth. • The Moon orbits Earth. • The Moon and Earth are in the same place in the solar system.
How could understanding the history of large versus small impacts on the Moon help us reconstruct the history of Earth and predict its future?	• It could help us know if large meteors are coming towards Earth with more frequency. • It could help us understand whether the frequency of impacts has changed. It can also help us find evidence of small impacts because there is no atmosphere there.

Say, *I have data about the frequency of impacts of different sizes on the Moon.*

ADDITIONAL GUIDANCE

Share a definition of cratering activity with your students. You can say something like, *Cratering activity is the process of forming craters on a planetary surface, typically resulting from the impact of meteorites. As we saw last time, this activity can vary in scale, from small impact craters to large impact basins.*

7 · ANALYZE CRATER FREQUENCY DATA

20 min

MATERIALS: *Moon Timeline*, *Frequency of Small Craters on the Moon*, *Frequency of Medium Craters on the Moon*, *Frequency of Large Craters on the Moon*, *Lunar Time Periods*, Moon timeline poster, chart paper markers, https://www.youtube.com/watch?v=ANYxkwvb8pc (optional)

Analyze crater frequency data. Present **slide M**. Organize the class into groups of 2-3 students. Assign each group one of the following data sets:

- *Frequency of Small Craters on the Moon*
- *Frequency of Medium Craters on the Moon*
- *Frequency of Large Craters on the Moon*

Each group should get copies of the bar graph for only one crater-size range (small craters, medium craters, or large craters). Provide one copy to each student so everyone can annotate their ideas on their graph. If your students are comfortable reading and analyzing the graphs on their own, have them do this annotation step individually before discussing with their group members.

Say, *Look at how often craters of a specific size were formed during each lunar time period.* Then ask students to answer the following prompts in their handout:

- *Write a description of the change in the number of moon craters you see on the graph.*
- *What patterns do this empirical evidence help us see that we couldn't tell from the images alone?*

Give 5-10 minutes to students in their groups to respond to the slide prompts so that they are prepared to share with the class about craters in their assigned size range. As students discuss the graphs in their groups, circulate the room. Listen for students to describe the patterns in the crater graphs in both relative and absolute terms. If the students are comfortable reading and interpreting the graphs, encourage them to make connections between the patterns they see and what they read about the different time periods in lunar history. ✱

ALTERNATE ACTIVITY

Consider presenting https://www.youtube.com/watch?v=ANYxkwvb8pc as an alternate or additional way to provide student access to the changes in the frequency of cratering activity over time. While this video only represents lunar impact craters that are younger than about 1 billion years old, it will help students identify patterns of large versus small craters. The creators of this video use louder and deeper notes for larger craters.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment

- Use the graphs to identify patterns of the crater activity on the Moon throughout time, highlighting periods of increasing, decreasing, or relatively constant crater activity. (DCI: ESS1.C.2; CCC: 1.5)
- The frequency of large meteors was much higher around 4.5 billion years ago and has been decreasing ever since. (DCI: ESS1.C.2; CCC: 1.5)
- The frequency of small and medium-size meteors has fluctuated over the Moon's history. (DCI: ESS1.C.2; CCC: 1.5)

What to do

- Encourage students to use the Identify and Interpret (I^2) strategy as they analyze their data, annotating their graphs to keep a record of their ideas.
- If your students feel comfortable analyzing data, ask them to examine these graphs individually first and then discuss with a partner what they see.
- If students feel less comfortable analyzing the data, direct them to work together to identify and describe what they see on the graph.

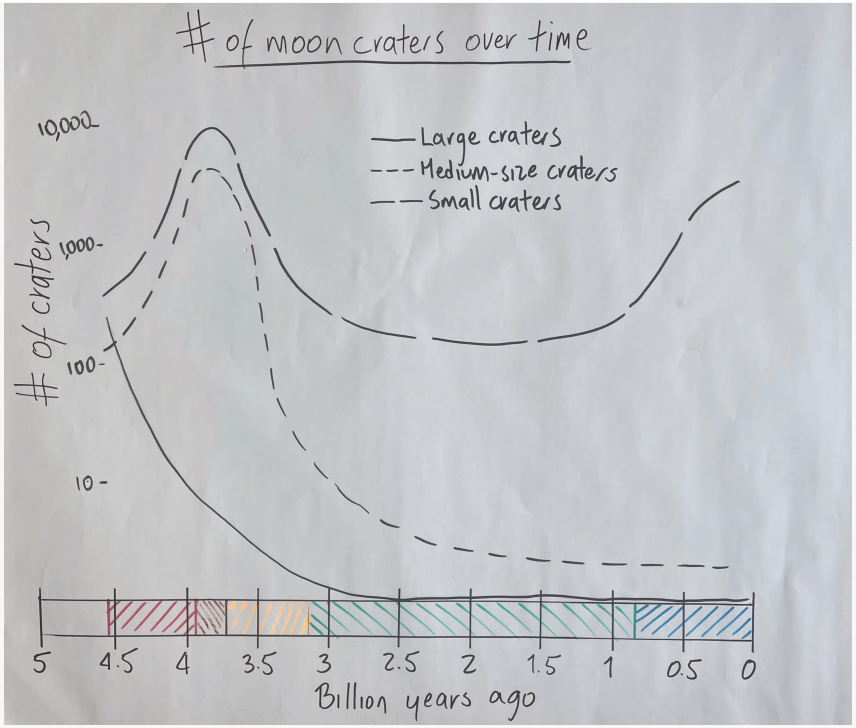
Building toward 12.A.2 Analyze empirical evidence to identify patterns in cratering on solar system objects without atmospheres that can support claims about the changes in cratering activity on Earth. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2)

Create a timeline of cratering frequency on the Moon. Present **slide N**. Use the Number of moon craters over time poster with the blank timeline you created. Ask students to use their *Moon Timeline* to take notes during this discussion. Identify a student volunteer to accurately label the divisions of lunar geologic time on the poster timeline. Ask the rest of the class to check their timelines for agreement.

Say, *Let's add a little more information to this timeline. Where should we label the present day?* Add a "present day" label at the far right of the timeline, where 0 billion years ago is indicated.

Invite students to share their findings from their graph analysis, starting with those who analyzed the frequency data of the small craters, then those who analyzed the frequency data of the medium craters, and finally, those who analyzed the frequency data of the large craters.

Use the timeline you prepared ahead of time to keep a record of students' ideas. This is an example of how this graph might look at the end of this discussion.



Once the timeline is complete, pose the last prompt:

- *What did these graphs help us see that we couldn't tell from last class's crater images alone?*

Listen for these ideas:

- We see that the frequency of meteor impacts has changed.
- Large meteors were more frequent billions of years ago.
- There have been periods on the Moon with a higher frequency of impacts from small meteors.

ADDITIONAL GUIDANCE

You will continue using the Moon Timeline poster during the next lesson.

8 · REVISE DATA SET

10 min

MATERIALS: science notebook, Moon Timeline poster

Revise data set of meteors approaching Earth's atmosphere. Present **slide O**. Elicit 1-2 ideas using the data set for frequency of space objects entering the top of Earth's atmosphere and the prompt:

- *What do these data on Earth say about the frequency of small and large meteors approaching Earth now and in the recent past?*

Look for students to mention the following ideas:

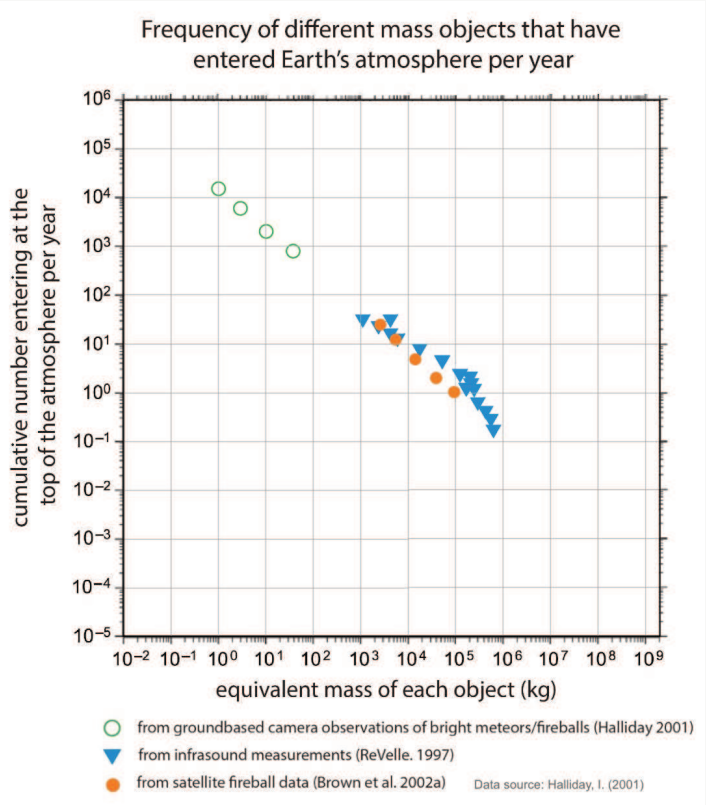
- The data say that the frequency of large meteors approaching Earth now is low.
- The data say that the frequency of large meteors approaching Earth in the past was low.
- It is not possible to make inferences about the past using these data.

If students are struggling in making inferences about what the graph on the slide says about the frequency of small versus large meteors in the past, remind students that this data set was constructed from relatively recent observations of objects approaching Earth.

Present **slide P**. Give students a few minutes with a partner to discuss the prompt on the slide:

- *Based on the patterns in the data from the Moon, do we think the frequency of meteor interactions with Earth has remained constant or changed over time?*

Invite students to share their ideas. Emphasize the idea that the history of meteor interactions with the Moon should be very similar to the history of meteor interactions with Earth since they are located in the same part of the solar system.



Use evidence to support claims. Present **slide Q**. Give students a few minutes to make sense of the data we have analyzed so far. Read the slide prompt aloud to orient students:

Based on the patterns in the data from the Moon, which claims can we make about

- *the changes in the frequency of small meteors approaching Earth over time?*
- *the changes in the frequency of large meteors approaching Earth over time?*

Write your claims and the evidence that supports them in your science notebook.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- The frequency of small meteors approaching Earth has changed over time, and it is currently higher than the frequency of medium-size and large meteors. The frequency of small craters on the Moon and the frequency of objects entering Earth's atmosphere support this claim. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2)
- The frequency of large meteors hitting Earth was much higher 4.5 billion years ago. This is supported by the frequency of large craters on the Moon. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2)

What to do

This is an important sensemaking opportunity, as it will help students to further grasp the idea that the Moon provides a record of cratering activity that can help us make sense of Earth's past.

As you walk around the classroom, ask students the following questions to get an idea about the claims they are making and the evidence they are using to support them:

- *How has the frequency of small/large meteors changed on Earth over time?*
- *What evidence are you using to support this?*

Point to the Number of moon craters over time poster for students who are not citing concrete evidence.

Building toward 12.A.3 Analyze empirical evidence to identify patterns in cratering on solar system objects without atmospheres that can support claims about the changes in cratering activity on Earth. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2)

Discuss the limitations of available data. Present **slide R**. Ask students to turn and talk with the prompts:

- *Is it valid to use this graph to make inferences about the frequency of meteor impacts billions of years ago?*
- *Is it valid to use this graph to make predictions about future meteor impacts?*

Invite them to share after a minute or two. Listen for students to say that it is not valid to extend this model into the past or the future because the frequency of meteors of all sizes has changed over time.

KEY IDEAS

Purpose of this discussion: The second lesson set is focused on addressing ideas about the possibility of a future meteor impact on Earth. By referencing the data set about the frequency of space objects entering Earth's atmosphere, the aim of this discussion is to establish connections back to the anchoring phenomenon.

Listen for these ideas:

- Making predictions about future meteor collisions is limited with the current data.
- Extending our understanding of the frequency of past meteor impacts on Earth can help us make better predictions.

9 · NAVIGATE

4 min

MATERIALS: None

Navigate into the next lesson. Present **slide S**. Ask students to turn and talk with the prompt:

- *We figured out that there is a connection between what we see on the Moon and what we see on Earth. What from our own experience, or from the stories of our communities, tells us that the Moon is connected to Earth?*

There is no right or wrong answer to this question. Listen for ideas about Indigenous origins stories, pseudo-scientific rumors about violence being correlated with the full Moon, or ideas about the menstrual cycle. Say, *It sounds like helping us understand Earth's history is just one way that the Moon is connected to life on Earth. Some of these ideas may be backed by evidence, and others may not, but clearly the connection we feel with the Moon is universal. Let's think more next time about the craters we know about on Earth.*

10 · UPDATE PROGRESS TRACKER

6 min

MATERIALS: *Progress Tracker*, colored pencils

Add to Progress Tracker. Present **slide T**. Give students about five minutes to use the ideas developed in the last few lessons to update their Progress Trackers. Distribute or have them collect colored pencils. Remind students that they should be using their coding system and updating it or adding to it as they need to.

ALTERNATE ACTIVITY	If questions come up about why some planets have atmospheres and others do not, you could offer this optional reading to interested students: *Magnetosphere*.

Additional Lesson 12 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH	**Number and Quantity** CCSS.MATH.CONTENT.HS.N-Q.2 **Quantities:** Reason quantitatively and use units to solve problems. Define appropriate quantities for the purpose of descriptive modeling. Students use this idea to interpret the relative size of craters related to other craters and to the objects they are on.
SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA	**Key Ideas and Details** **CCSS.ELA-LITERACY.RST.11-12.2:** Determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms. Students will read about the different time periods of the Moon and use a timeline to summarize these ideas.

LESSON 13: Why don't we see many craters on the surface of Earth?

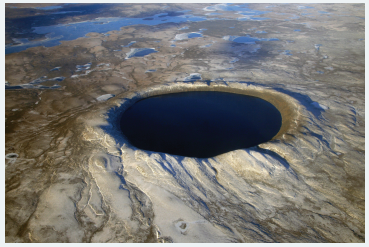
PREVIOUS LESSON

We examined images of objects in space that lack atmospheres to see what happens when objects fall into them without burning up in an atmosphere. We made observations about patterns of cratering activity on the Moon over its history and found periods with high and low cratering activity. We considered why we don't see evidence of large meteor impacts on the Moon.

THIS LESSON

INVESTIGATION

2 days



We analyze Earth's cratering activity data and find that visible impact cratering is present in relatively recent history but absent in over half of Earth's timeline. We analyze images of terrestrial craters and find the older craters have less-clear features. We brainstorm mechanisms that can explain this and use a model of erosion to test our ideas. We read about additional geological processes that have shaped our planet's landforms and apply that information to explain the differences in cratering evidence between the Moon and Earth. We learn that 65 million years ago, a meteor with enough kinetic energy to create a crater 112 miles (180 km) in diameter collided with Earth.

NEXT LESSON

We will analyze a graph showing mass extinctions in Earth's history. We will develop a model to explain how an impactor collision led to mass extinctions. We will gather information about the Chicxulub crater formation. We will revise our initial model to explain how the impactor led to both short-term and longer-term effects that caused the extinction of only some types of organisms and not others.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

13.A Use a small-scale model to illustrate how erosion, acting over long periods of time, can alter the evidence of cratering activity on Earth's surface. (SEP: 2.3; DCI: ESS1.C.2; CCC: 3.2)

13.B Read scientific literature to determine how geological processes over long periods of time can help explain the stability of the Moon's surface as it compares to Earth's changing surface. (SEP:6.4, 8.1; DCI: ESS1.C.2; CCC: 3.2, 7.1)

WHAT STUDENTS WILL FIGURE OUT

- We see that visible Earth craters have been found mostly in the last 650 Million years of our 4.5 Billion year history.
- We see that Earth's craters are less well defined than those of the Moon.
- We learn about four Earth processes or mechanisms which shaped Earth's landform throughout its history.
- 65 million years ago, a meteor with enough kinetic energy to create a crater 112 miles (200 km) in diameter, collided with Earth.

Lesson 13 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	5 min		**NAVIGATE** Discuss personal experiences with meteor craters on Earth and consider the difference between Moon and Earth' craters.	A-C	
2	15 min		**COMPARE AGE DISTRIBUTION OF CRATERS** Distribute *Terrestrial Craters Record*. Have students analyze this graph to search for patterns in Earth's cratering activity over time.	D-F	*Terrestrial Craters Record*
3	15 min		**ANALYZE CRATER CARDS** Students analyze Earth crater pictures that represent cratering activity from recent times to about 2.5 billion years old. Use the timeline you developed in Lesson 12 to keep a record of the patterns students identify from these pictures.	G-I	computer, *Earth Craters Cards* (optional), https://www.openscied.org/CraterCards, Number of moon craters over time poster, 3x3 sticky notes
4	10 min		**USE MODEL TO TEST IDEAS ABOUT EROSION** Students model an erosion event with earth materials (sand) and water. They make observations of the effect of erosion of the crater in their small stream tables.	J	Modeling the Effect of Erosion on Craters
					End of day 1
5	3 min		**NAVIGATE** Have students share their ideas about the timescale of erosion.	K	
6	2 min		**EXPLORE EARTH PROCESSES THAT CAN ALTER EVIDENCE OF CRATERING ACTIVITY ON EARTH** Brainstorm additional Earth processes that affected landforms. Students will be introduced to a jigsaw reading strategy about four major Earth processes.	L	
7	18 min		**OBTAIN AND COMMUNICATE INFORMATION ABOUT EARTH PROCESSES** Students will individually read one of the Earth processes handouts. They will be reading for understanding as well as thinking about when this process likely happened during Earth's history as represented by the timeline. They will share their thinking in their small groups and look for how each process could be integrated with other processes.	M-O	Highlighter, *Moon Timeline* from Lesson 12, *Terrestrial Craters Record*, *Accretion (A)*, *Plate Tectonics*, *Weathering, Erosion, and Deposition*, *Glaciation*, *Accretion (B)* (optional)
8	10 min		**CREATE A TIMELINE OF GEOLOGIC PROCESSES ACTING ON EARTH'S SURFACE** Use the Number of moon craters over time poster you developed in Lesson 12 to illustrate the timescale of geologic processes on Earth.	P	Number of moon craters over time poster (from Lesson 12), 3 x 3 sticky notes, permanent marker
9	6 min		**EXPLAIN PATTERNS IN EARTH'S CRATERING ACTIVITY** Have students write an explanation about the differences in the surfaces of the Moon and Earth.	Q	

Part	Duration		Summary	Slide	Materials
10	4 min		**UPDATE PROGRESS TRACKER** Update Progress Trackers with ideas from this lesson.	R	colored pencils, *Progress Tracker*
11	2 min		**NAVIGATE** Motivate the need to look at larger craters. Have students turn and talk about the consequences on Earth of a meteor that left a crater with a diameter of 112 miles 65 million years ago.	S	

End of day 2

Lesson 13 • Materials List

	per student	per group	per class
Modeling the Effect of Erosion on Craters materials		• 2.5 kg of sand • paint tray • 1000 mL beaker full of water • plastic sphere • plastic fast food tray (14" x 10")	
Lesson materials	• *Terrestrial Craters Record* • science notebook • Highlighter • *Moon Timeline* from Lesson 12 • colored pencils • *Progress Tracker*	• computer • *Earth Craters Cards* (optional) • https://www.openscied.org/CraterCards • *Accretion (A)* • *Plate Tectonics* • *Weathering, Erosion, and Deposition* • *Glaciation* • *Accretion (B)* (optional)	• Number of moon craters over time poster • 3x3 sticky notes • Number of moon craters over time poster (from Lesson 12) • 3 x 3 sticky notes • permanent marker

Materials preparation (15 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch all the images and handouts so they can be added to students' notebooks.

Hang the Number of moon craters over time poster you created in Lesson 12 in a visible area of the room.

Prepare the image sets for students. This can be done in two ways:

1. Electronically, by sharing the slide deck at this link: https://www.openscied.org/CraterCards. A shortened url was added in slide G as well that students can type on their device. When students open this link, it will create their own copy of the slide deck.
2. Physically, by printing *Earth Craters Cards*.

Day 1: Modeling the Effect of Erosion on Craters

- **Group size:** 4-5 students
- **Setup:** For each stream table, you will need a plastic paint tray (4" W x 8" L) and around 2.5 kg of sand, and a plastic sphere (the same used to make the impactors in Lesson 2 and Lesson 10). Drill ¼-inch holes, separated by half an inch, at the lower end of the paint tray. Fill the paint tray with enough sand until you are about 1/2 inch from the edge. Bury the sphere half way. Sprinkle some water around the sphere, to compact the sand. Remove the sphere. See *Building Stream Table* for additional guidance.
- **Notes for during the lab:** Place a plastic fast food tray (14" x 10") under the stream table. This will collect the water that students will use during the investigation. Provide students with a plastic sphere to create additional craters as they test their ideas.
- **Safety:** All students must wear sanitized safety glasses with side shields or indirectly vented chemical splash goggles.
- **Disposal:** Discard water collected on the trays. Provide students with paper towels for cleaning up.
- **Storage:** Allow the sand to dry on the trains for a few days before storing it for next year.

Lesson 13 • Where We Are Going and NOT Going

Where We Are Going

The goal of this lesson is to build on the physics concepts developed in this unit and make connections to the early history and formation of Earth. Students will look at distribution of Earth's visible terrestrial craters on a timeline of the history of Earth. They will identify patterns of erosion among terrestrial craters. They will observe that most of the last 4.5 billion years shows little activity and about the last 650 million years of recent history represents the majority of the 190 known impact sites.

Students will read about Earth's processes or mechanisms that shape the lithosphere's surface and integrate those processes into an explanation of how they have erased this crater evidence from the surface of Earth.

Students will complete a reading jigsaw that has been designed to help them weave together the timeline of Earth and integrate the processes of glaciation, weathering, erosion, and deposition along with plate tectonics to make a claim about their role in reshaping Earth's surface to eliminate impact cratering.

They will use past understanding about cratering activity on the Moon, Earth's atmosphere, and these processes to make a claim about Earth's history having active cratering and surface processes that are reshaping the face of Earth.

This lesson is designed to coherently build new ideas related to the following disciplinary core idea:

- ESS1.C.2: Although active geologic processes, such as plate tectonics and erosion, have destroyed or altered most of the very early rock record on Earth, other objects in the solar system, such as lunar rocks, asteroids, and meteorites, have changed little over billions of years. Studying these objects can provide information about Earth's formation and early history. (HS-ESS1-6)

This lesson is designed to coherently build new ideas related to the following science and engineering practices:

- **Obtaining, Evaluating, and Communicating Information:** Critically read scientific literature adapted for classroom use to determine the central ideas or conclusions and/or to obtain scientific and/or technical information to summarize complex evidence, concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.
- **Constructing Explanations and Designing Solutions:** Apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.

This lesson is designed to coherently build new ideas related to the following crosscutting concepts:

- **Stability and Change:** Much of science deals with constructing explanations of how things change and how they remain stable.
- **Scale, Proportion, and Quantity:** Some systems can only be studied indirectly as they are too small, too large, too fast, or too slow to observe directly.

Students will encounter or co-develop definitions for the following words in this lesson: *accretion* and *glaciation.* **Do not** post any words or ask students to add them to their Personal Glossary until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

We are not developing the idea that geoscience processes have changed Earth's surface at varying time and spatial scales (MS-ESS2-2). Instead, we are utilizing this middle school concept to make sense of patterns in cratering activity on both Earth and the Moon.

LEARNING PLAN for LESSON 13

1 · NAVIGATE

5 min

MATERIALS: None

Navigate into the lesson. Present slide **A**. Say, *Last time, we saw craters, large and small, on different planets and moons without an atmosphere. Let's focus back on Earth.* Elicit 1-2 ideas with the prompts:

- *The Chelyabinsk meteor left an 8-meter (26-foot) diameter crater. What evidence have we explored in this unit that suggests there could be meteor craters on Earth much larger than this?*
- *What evidence do you have from your experience, or stories you have heard, that there might be large meteor craters on Earth?*

Encourage students to think about both the phenomena we have explored together and their own experiences. Accept all responses. Look for some students to have visited Meteor Crater in Arizona or heard stories about craters, such as the Chicxulub crater in Mexico or the Chesapeake Bay.

Use a mathematical model. Present **slide B**. Use the slide image to discuss with your class the prompt:

- *Based on this model, should we expect to find large craters on Earth?*

Ask students to identify what part of the graph they are referring to and how it supports their thinking

Listen for responses such as these:

- The largest mass objects have the lowest probability of entering the atmosphere of Earth.
- As the mass becomes smaller the probability increases of the objects entering the atmosphere of Earth.

Say, *I think I hear you saying that there is a low probability of finding large craters on the surface of Earth, but it's not impossible, right?*

Discuss evidence of cratering activity on the Moon. Present **slide C**. Continue this discussion using the prompts:

- *Based on the frequency of craters on the Moon, should we expect to find evidence of large craters on Earth?*
- *What data would help us support our ideas?*

Look for students to suggest that we should expect to find evidence of large craters on the surface of our planet because the Moon's surface is covered in craters, and since the Moon is the closest space object to Earth, both should be similarly affected by meteors.

They should suggest looking for evidence of actual cratering activity on Earth. Say, *Let's look at the empirical evidence scientists have collected so far.*

2 · COMPARE AGE DISTRIBUTION OF CRATERS

15 min

MATERIALS: *Terrestrial Craters Record*

Introduce terrestrial craters data set. Present **slide D**. Pass out *Terrestrial Craters Record*. Ask students to use these data and individually think about the prompts on the slide:

- *Identify and interpret any changes, trends, or differences you see.*
- *What patterns does this graph help us identify?*

After a minute or two, invite a few volunteers to share. Listen for these ideas:

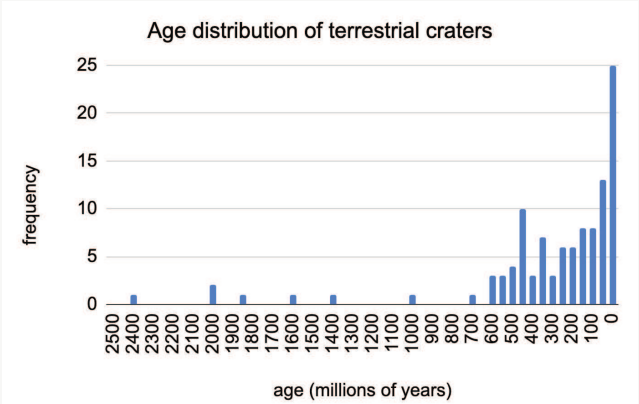
- There are a lot of craters at the right side of the graph.
- Then in the rest of the graph there is a lot of space in between individual craters.
- It looks like the early part of Earth's history didn't have much activity.

Compare age distribution of terrestrial craters. Present **slide E**. Ask students to work with a partner to answer the following prompts:

- *What do you think explains the difference in the data from the left panel to the right panel?*
- *What does this make you wonder?*

Give them a couple minutes before inviting them to share. Listen for the following ideas:

- There was not a lot of cratering activity in the past.
- There was a lot of cratering activity in the past 600 million years.
- Was the evidence of all earlier cratering activity destroyed?
- Why were there fewer impacts in the past?
- Why is there so much activity closer to the present?



Data source: Terada, K. et al. (2020)

ADDITIONAL GUIDANCE

The idea of splitting this graph into two sections is to guide students to compare the most recent crater activity (the last one-half billion years of Earth's history) with the oldest records of cratering activity we have (2.4 billion years ago).

Motivate looking at images of terrestrial craters. Present **slide F**. Say, *Last time, we looked at images of cratered surfaces on different moons and planets to identify patterns.* Then use the slide prompts:

- *How would looking at images of Earth's craters from today to 2.4 billion years ago help us make sense of this graph?*
- *How would a crater that was formed 2.4 billion years ago compare to a crater that was formed a few thousand years ago?*

Students should say that it will help them see patterns, features, or any differences that can help explain the patterns in the graph of Earth's cratering history and how craters have physically changed over long periods of time.

Accept all responses to the second question.

ADDITIONAL GUIDANCE

This part of the lesson is leading towards this DCI: ESS1.C.2: Although active geologic processes, such as plate tectonics and erosion, have destroyed or altered most of the very early rock record on Earth, other objects in the solar system, such as lunar rocks, asteroids, and meteorites, have changed little over billions of years. Studying these objects can provide information about Earth's formation and early history. (HS-ESS1-6)

3 · ANALYZE CRATER CARDS

15 min

MATERIALS: science notebook, computer, *Earth Craters Cards* (optional), https://www.openscied.org/CraterCards, Number of moon craters over time poster, 3x3 sticky notes

Sort the cards into categories. Display **slide G**. Organize the class in pairs and distribute a computer to every pair with access to https://www.openscied.org/CraterCards. The slide also includes a shortened URL that students can type on their device to access the crater cards. Every pair will have their own digital copy of the slides which they can create using the link above.

ALTERNATE ACTIVITY	If you prefer to use physical cards, or you think some students might benefit from them, print the cards directly from the slide deck or from this document: *Earth Craters Cards*.

Read the instructions on the slide out loud to guide students' work during this task:

- *Organize the crater cards by age.*
- *Record what similarities and differences you see across the craters in the cards.*
- *Record what patterns you see.*

Emphasize the importance of recording their observations and findings in their notebooks as they go. The goal of sorting the cards is to identify patterns in the surface features they see across the craters, not to place the cards in chronological order starting with the oldest meteor.

After 5 minutes or so, invite students to share the patterns they saw in the cards. Use the following prompts to gather as many voices and ideas as possible:

- *Who else saw similar patterns?*
- *Who saw different patterns?*

Listen for these ideas:

- Some craters look very eroded.
- They have different sizes.
- All of them seem pretty big.
- Some have very defined features, and some are very hard to see.

Mark craters cards on students' timelines. Display **slide H**. Say, *I think it would be useful to place these craters on a timeline to see what new patterns we can find.*

Follow the slide directions:

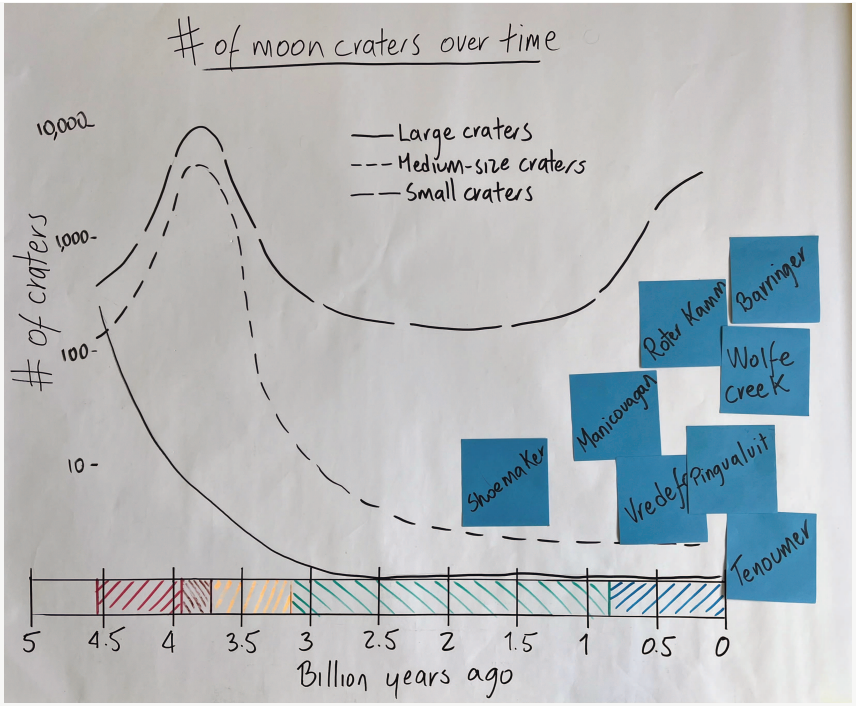
- *Use the crater cards to mark on your timeline when these terrestrial craters were formed*
- *Discuss the observations and patterns.*

Use students' ideas to build this timeline. Start by asking:

- *Where should we mark the oldest crater on the timeline?*
- *Where should we mark the youngest crater on the timeline?*

Use the Number of moon craters over time poster to add sticky notes that mark when some of these craters were formed.

This is how the poster will look at the end of this discussion.



Then discuss the observations and patterns that emerge from this timeline. Listen for these ideas:

- There are more younger craters than older craters.
- There are no craters older than 2.5 billion years in the data set.
- Younger craters are more defined than older ones.

Brainstorm Earth processes and mechanisms explaining patterns in craters. Display **slide I**. Say, *This is not the first time we have explored changes on the surface of Earth that take millions of years.* Then use the prompts to elicit 1-2 ideas:

- *What Earth processes and mechanisms do you think might change Earth's surface features over time?*
- *How might these processes and mechanisms help explain the differences in the features between old versus new craters?*

Invite a few volunteers to share their ideas. Possible answers include the following:

- Erosion
- Weathering
- Earthquakes
- Convection in the mantle
- Plate tectonics

ADDITIONAL GUIDANCE

The role of Earth's processes on the surface is related to the following middle school standard:

- **ESS2.C:** Water's movements—both on the land and underground—cause weathering and erosion, which change the land's surface features and create underground formations. (MS-ESS2-2).

Students explored these ideas in the *6.4 Plate Tectonics and Rock Cycling unit*.

4 · USE MODEL TO TEST IDEAS ABOUT EROSION

10 min

MATERIALS: Modeling the Effect of Erosion on Craters, science notebook

Use a model to test ideas. Present **slide J**. Say, *I have some materials that will help us test some of our ideas about erosion that we think help explain why it is hard to find craters on Earth's surface.*

Distribute materials to every pair of students. Instruct them to use the water on the beaker to test their ideas about how erosion can help explain the patterns in the craters we observed. Show them how to use their materials in order to create additional craters in the steam table (see *Building Stream Table*

Read the slide instruction aloud:

- *Use the physical model to test your ideas about how erosion can affect surface features of craters over time.*
- *Use your observations to answer the following questions in your notebook:*
  - *Which of the changes you observed in the craters using this physical model do you think could be observed in real craters on Earth? Why?*
  - *How much time would it take to observe similar changes in the surface features of real craters on Earth?*

This should be a quick activity, as their goal is to simulate erosion over time. Walk around the classroom as they work on this and use these prompts to elicit their ideas.

- *How are you showing the passage of time with your model?*
- *Where does the matter in the crater go?*
- *What additional changes do you see?*
- *How does this help explain some of our observations about old terrestrial craters?*

Have students write their answers on their science notebook.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- Use a physical model to illustrate the effect of erosion or other Earth processes on craters over time. (SEP: 2.3; DCI: ESS1.C.2)
- Discuss the differences in the timescale between the physical model and the real Earth surface system. (CCC: 3.2)

What to do

If students are having difficulties considering the scale needed to identify changes in real craters, display a couple of crater cards on the screen, and point out the age of these craters. Ask them:

- *Do you think we could see evidence of these craters if they changed as fast as the craters in our model?*
- *If we can see some craters, even some that are millions of years old, what does that say about the scale at which they change over time?*

Building toward 13.A Use a small-scale model to illustrate how erosion, acting over long periods of time, can alter the evidence of cratering activity on Earth's surface. (SEP: 2.3; DCI: ESS1.C.2; CCC: 3.2)

End of day 1

5 · NAVIGATE

3 min

MATERIALS: None

Remind students where we left off. Present slide **K**. Say, *Last time, we saw data about craters on Earth, and we used a model of erosion to show our ideas about why it is hard to find older craters on the surface of our planet.*

Elicit 1-2 ideas with the prompts:

- *Which of the changes you observed in the craters using this physical model do you think could be observed in real craters on Earth? Why?*
- *How much time would it take to observe similar changes in the surface features of real craters on Earth?*
- *What sorts of data do scientists use to study changes in Earth's systems over this timescale?*

Look for the following ideas:

- We saw the features (shape, size) of the craters changing. This should happen to the real craters.
- It would take millions of years for real craters to change in the same way the craters in our physical model did.
- Scientists study rock samples, the fossil record, and radiometric data.

6 · EXPLORE EARTH PROCESSES THAT CAN ALTER EVIDENCE OF CRATERING ACTIVITY ON EARTH

2 min

MATERIALS: None

Brainstorm additional processes. Present **slide L**. Say, *We just explored erosion, but Earth is a complex system, and there might be other mechanisms that could change the features of surface craters.* Ask students to turn and talk with the prompt:

- *Besides erosion, what other Earth processes might affect the surface of the land where cratering occurred?*

Give students a minute to share with their partner about processes and mechanisms that affect Earth's landforms. Then invite a few volunteers to share their ideas with the class.

Look for these ideas:

- Rain events and floods
- Volcanos
- Earthquakes
- Tsunami

Say, *It seems we have some ideas that can help us make sense of the low number of old craters on Earth. Let's explore some of these processes and mechanisms to see if they can help us answer our lesson question: Why don't we see many craters on the surface of Earth?*

7 · OBTAIN AND COMMUNICATE INFORMATION ABOUT EARTH PROCESSES

18 min

MATERIALS: Highlighter, *Moon Timeline* from Lesson 12, *Terrestrial Craters Record*, *Accretion (A)*, *Plate Tectonics*, *Weathering, Erosion, and Deposition*, *Glaciation*, *Accretion (B)* (optional)

Introduce the jigsaw protocol for reading. Project **slide M**. Say, *In a moment, you are going to read an article individually. Afterwards, we will break into groups of four and use the jigsaw strategy to share what we have each learned in our reading.*

Provide each student with a highlighter and one of the following readings:

- *Accretion (A)*

✱ SUPPORTING STUDENTS IN ENGAGING IN OBTAINING, EVALUATING, AND COMMUNICATING INFORMATION

- *Plate Tectonics*
- *Weathering, Erosion, and Deposition*
- *Glaciation*
- *Accretion (B)* (optional)

ADDITIONAL GUIDANCE

The articles in these handouts were written at different reading levels: *Accretion (A)* and *Accretion (B)* contain the same content but are written at different levels. *Accretion (A)* is more challenging, with longer sentences and more complex vocabulary. *Accretion (B)* is more accessible for readers.
Plate Tectonics, *Weathering, Erosion, and Deposition*, and *Glaciation* should be accessible for readers at this grade level.

Describe the task. Present **slide N**. Read the instructions for this task aloud:
Read your individual reading. As you read:

- *Look for and highlight any information that helps answer our question.*
- *Annotate your reading with any new information that describes the duration of Earth's processes which could be added to our timelines.*

Instruct students to write a version of the lesson question at the top of the handout, reminding them that being mindful of the question before reading will help them be more attentive to the information they read. Give them about 8 minutes to complete the reading and a few more minutes to answer the question on their handout.✱

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

- Students annotate the reading and apply their understanding to the timeline of Earth's cratering history. (SEP:8.1; DCI: ESS1.C.2; CCC: 3.2, 7.1)
- Use ideas from the reading to annotate the graph of the age distribution of terrestrial craters to show periods where glaciation, erosion, plate tectonics, or accretion could have changed Earth's surface and periods when these processes were less likely to change the surface. (SEP:8.1; DCI: ESS1.C.2; CCC: 7.1)
- Make a claim about whether the reading provides evidence to help answer the question: Why don't we see many craters on the surface of Earth? (SEP:6.4; DCI: ESS1.C.2)

What to do

- Walk around the classroom to get an idea of how students are marking their graphs. If you notice that students are struggling to show periods when the geologic process they read about affected Earth's surface, have a class discussion modeling how to annotate the graph using an example.
- If students are having difficulty making a claim, look at the question students wrote at the top of their handout. Help them rephrase the question if it does not focus on the lesson question: *Why don't we see many craters on the surface of Earth?*

Building toward: 13.B.1 Read scientific literature to determine how geological processes over long periods of time can help explain the stability of the Moon's surface as it compares to Earth's changing surface. (SEP:6.4, 8.1; DCI: ESS1.C.2; CCC: 3.2, 7.1)

Communicate ideas from the readings. Present **slide O**. Organize the class in groups of 4, making sure all 4 members of each group have read a different article. Read the instructions aloud:

Each person will have 1 minute to share the summary of their article.

- *When you are all finished, spend 3 minutes discussing your ideas about how these Earth processes help explain the patterns we see on the Age distribution of terrestrial craters graph.*
- *Each person should take notes on their timeline as others share their summaries.*

Students will continue using this practice in Lesson 14. The ideas students highlight from the readings will provide you with quick evidence of their use of this practice.

Give them 8 minutes to share their ideas and discuss the slide prompts.

8 · CREATE A TIMELINE OF GEOLOGIC PROCESSES ACTING ON EARTH'S SURFACE

10 min

MATERIALS: Number of moon craters over time poster (from Lesson 12), 3 x 3 sticky notes, permanent marker

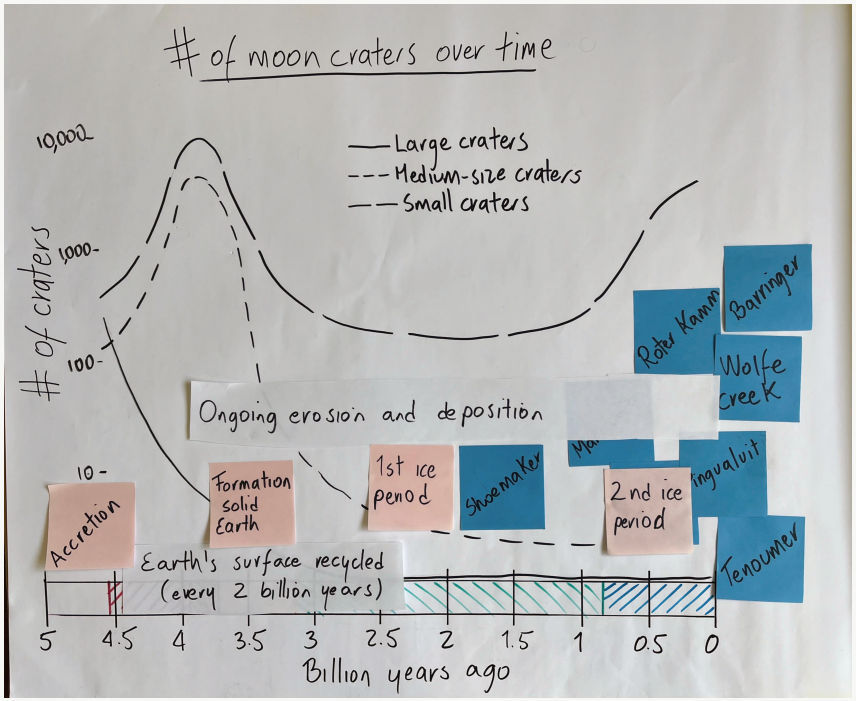
Use a timeline to illustrate the timescale of geologic processes. Project **slide P**. Say, *Now that we have learned about different geologic processes, let's see if we can better explain the patterns in Earth's cratering activity.*

Use the Number of moon craters over time poster you developed in Lesson 12. Use sticky notes to mark where the oldest craters on the Moon and Earth are located.

Say, *Let's take each process separately and create a class timeline to gather ideas from many groups. I will chart specific events or time spans.*

For each process you discuss, mark time periods described in the readings that signal when they were most active and the time spans for each process. It might be easier to use longer strips of paper to write these processes on, and then remove them for the next class. In this way, you can continue reusing the same Number of moon craters over time poster for all classes.

This is an example of how this poster might look at the end of this discussion.



For a larger version of this image, see *Example Student Timeline*

9 · EXPLAIN PATTERNS IN EARTH'S CRATERING ACTIVITY

6 min

MATERIALS: science notebook

Write an explanation to explain patterns of cratering activity. Present **slide Q**. Say, *Much of science deals with constructing explanations about how things change and how they remain stable. Let's take this opportunity to put together our thoughts to answer the following question.*

Ask students to use their ideas about Earth's processes to explain:

- *Why has the Moon's surface remained relatively stable (unchanged) while Earth's surface has changed in the last 4.5 billion years?*

Encourage them to use any combination of words, drawings, or symbols in their explanations.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment

Walk around the classroom as students complete their explanations. Pay attention if students students answers:

- Include information from the readings about how plate tectonics, erosion, weathering, glaciation, and accretion contribute to the change in Earth's surface at different scales. (SEP:8.1; DCI: ESS1.C.2; CCC: 3.2, 7.1)
- Explain why the lack of these mechanisms on the Moon help preserve cratering evidence on its surface. (SEP:6.4; DCI: ESS1.C.2; CCC: 7.1)
- Explain how different geologic processes on Earth have erased evidence of cratering activity. (SEP:6.4; DCI: ESS1.C.2; CCC: 7.1)

What to do: Some students might need to be reminded that most of the geologic processes that we read about don't act on the Moon. Explanations require students to include mechanisms to account for some of the patterns they observed in the data. You might want to scaffold this practice by asking students to (1) describe a pattern from terrestrial cratering activity data (e.g., left versus right panels, as shown in slide E) and (2) then include the geological mechanism(s) that help explain this pattern.

During the final summative task in Lesson 15, students will consider why it is hard to find evidence of a hypothesized collision between Earth and another planet. Provide feedback that have students considering the changes in matter that take place as a result of these processes.

Building toward: 13.B.2 Read scientific literature to determine how geological processes over long periods of time can help explain the stability of the Moon's surface as it compares to Earth's changing surface. (SEP:6.4, 8.1; DCI: ESS1.C.2; CCC: 3.2, 7.1)

10 · UPDATE PROGRESS TRACKER

4 min

MATERIALS: science notebook, colored pencils, *Progress Tracker*

Add to Progress Tracker. Present **slide R.** Give students a few minutes to use the ideas developed in this lesson to update their Progress Tracker. Distribute colored pencils or have them collect colored pencils. Remind students that they should be using their coding system and updating it or adding to it as they need to.

11 · NAVIGATE

2 min

MATERIALS: None

Navigate into the next lesson. Present **slide S**. Say, *Some of us wondered what could happen to Earth if a large meteor hit the surface.* Ask students to turn and talk with the prompt:

Around 65 million years ago, a meteor with enough energy to create a crater 112 miles (180 km) in diameter collided with Earth.

- *What do you think would happen to our planet if a similar meteor hit the surface today?*
- *What evidence could provide us with some ideas about the impact this meteor could have had on the planet back then?*

Tell students that we will follow up on their ideas on the next lesson.

Additional Lesson 13 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

Key Ideas and Details
CCSS.ELA-LITERACY.RST.11-12.2: Determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.

Students read individually about different geologic processes and summarize these ideas on a graph of the age distribution of terrestrial craters.

Integration of Knowledge and Ideas
CCSS.ELA-LITERACY.RST.11-12.9: Synthesize information from a range of sources (e.g., texts, experiments, simulations) into a coherent understanding of a process, phenomenon, or concept, resolving conflicting information when possible.

Students will integrate ideas from different readings to explain how Earth processes have changed the evidence of craters on Earth's surface.

LESSON 14: How could an impactor have killed off some types of life on Earth but not all?

PREVIOUS LESSON

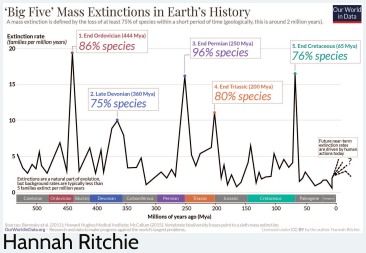
We analyzed Earth's cratering data and found visible impact cratering is present in recent history but absent in over half of Earth's timeline. We used images of terrestrial craters to observe that older ones have less-clear features. We used an erosion model for testing how the surface can change. We read about geological processes and used these ideas to explain differences in cratering evidence between the Moon and Earth.

THIS LESSON

INVESTIGATION

3 days





Hannah Ritchie

We analyze a graph of mass extinction events over Earth's history. We develop an initial model to explain how an impactor collision would have led to the extinction of some types of organisms and not others. We gather and communicate information about matter changes, force interactions, and energy transfers related to the formation of the Chicxulub crater. We revise our initial model to explain how the impactor led to both short-term and longer-term effects that caused the extinction of only some types of organisms and not others.

NEXT LESSON

We will return to the DQB to evaluate which questions we have answered in this unit. We will work through an assessment task where we will assess whether the evidence from moon rocks supports scientists' ideas about the formation of the Moon from a giant impact between Earth and another planet known as Theia.

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

14.A Read scientific literature to determine the central ideas and summarize the different changes in earth systems due to the Chicxulub meteor impac and their effects on different types of organisms and ecosystems across different spatial and temporal scales by paraphrasing them in simpler but still accurate terms. (SEP: 8.1, CCC: 2.4, DCI: ESS1.C.2)

14.B Compare and evaluate competing arguments for different mechanisms for how energy was transferred and matter changed across different earth systems as a result of the formation of the Chicxulub crater. (SEP: 7.1, CCC: 5.2, DCI: PS3.A.2)

14.C Develop and revise a model to provide a mechanistic account of how energy was transferred and/or matter was changed by the formation of the Chicxulub crater in such a way that it resulted in the extinction of certain types of organisms (change) and not others (stability) 65 million years ago. (SEP: 2.3, CCC: 5.2, 7.1, DCI: PS3.A.2, ESS2.A.3)

WHAT STUDENTS WILL FIGURE OUT

- The fossil record provides evidence that some types of organisms went extinct around the time of the impact (e.g., dinosaurs, herbivores, terrestrial plants), while others survived.
- There are alternate mechanisms to explain how the impactor affected energy transfers and matter flows in and through other earth systems (global forests, oceans, mantle, atmosphere).
- There would be longer-term effects on how energy flows to photosynthetic organisms and through food chains due to the longer-term changes in matter in different earth systems, that would have resulted from the meteor's impact.

Lesson 14 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	6 min		**NAVIGATE** Review prior ideas about why we thought the impact from this Chicxulub meteor might be related to the extinction of the dinosaurs and identify lines of evidence needed to support or refute these ideas.	A-B	
2	8 min		**DEVELOP LESSON DRIVING QUESTION** Use analysis of a timeline of past mass extinctions to generate the lesson driving question.	C-E	*Extinction Evidence Organizer*, *Mass Extinctions Data Analysis*
3	12 min	☑	**EXPLORE MATTER AT THE CHICXULUB CRATER** Analyze data to learn about the material composition in the fossil record that corresponds to the end-cretaceous event that occurred 65 million years ago. Share questions raised.	F-G	*Extinction Evidence Organizer*, *Chicxulub #1: K-Pg Fossil Record*
4	10 min		**CREATE INITIAL MODEL** Draw an initial model to show the cause(s) and effect(s) to explain how the Chicxulub impactor led to extinction of certain types of organisms.	H-I	*Extinction Evidence Organizer*, *Timeline*, *Moon Timeline*, M-E-F poster
5	9 min	☑	**USE JIGSAW STRATEGY FOR CHICXULUB CRATER READINGS** Read one of four different articles to learn about the K-Pg layer associated with the Chicxulub impact. Discuss in small groups the key ideas from the different readings.	J-K	
					End of day 1
6	13 min		**HAVE GROUP DISCUSSION ON GEOLOGICAL EVIDENCE** Develop a list of evidence from fossil data that connects the mass extinction of dinosaurs 65 million years ago to the Chicxulub impactor collision.	L-N	
7	10 min		**EVALUATE ADDITIONAL MECHANISMS** Read and annotate four alternate mechanisms that describe the energy transfer through different earth systems related to the Chicxulub impactor. Evaluate which of these could help explain the patterns in the fossil data.	O	*Alternate Mechanisms (A-D)*, *Evaluate Alternate Mechanisms*
8	8 min		**SHARE ALTERNATE CLAIMS** Discuss competing arguments as a group and continue to add to and/or remove ideas from *Evaluate Alternate Mechanisms*.	P	*Evaluate Alternate Mechanisms*
9	10 min	☑	**ARGUE FOR OR AGAINST MULTIPLE MECHANISMS** Evaluate competing arguments by explaining which claim best supports evidence from the K-Pg layer.	Q	*Evaluate Alternate Mechanisms*
10	4 min		**NAVIGATE** Prompt students to think about why it is important to consider how energy transfers affect Earth's systems in both the short and long term.	R	
					End of day 2

Part	Duration		Summary	Slide	Materials
11	7 min		**OBTAIN INFORMATION ABOUT PAST MASS EXTINCTIONS** Read an article to learn about the long-term matter changes and energy transfers in Earth's systems associated with past extinctions.	S	*Past Mass Extinctions*, *Extinction Evidence Organizer*
12	3 min		**SHARE INFORMATION ABOUT PAST MASS EXTINCTIONS** Have pairs of students discuss new ideas about energy transfers across earth systems related to mass extinctions.	T	
13	15 min		**DEVELOP A FINAL MODEL** Have students revise their initial model to show how the Chicxulub impactor could lead to only certain types of organisms becoming extinct.	U	*Timeline*
14	6 min		**LEAVE FEEDBACK IN A GALLERY WALK** Cue students on how to leave feedback on a silent gallery walk.	V	*Timeline*, 5 3x3 sticky notes, pencil
15	7 min		**RESPOND TO QUESTIONS** Have students review the questions others left for them and select 3 to answer.	W	*Timeline*, tape
16	7 min		**DISCUSS THE IMPLICATIONS FOR THE FUTURE AND IDENTIFY A NEW QUESTION** Discuss how developing models for explaining past mass extinctions can help society better prepare for and maybe even prevent such events in the future. Students share the pressing questions they are leaving this unit wondering about.	X-Y	

End of day 3

Lesson 14 • Materials List

	per student	per group	per class
Lesson materials	• *Extinction Evidence Organizer* • *Mass Extinctions Data Analysis* • *Chicxulub #1: K-Pg Fossil Record* • *Timeline* • *Moon Timeline* • *Alternate Mechanisms (A-D)* • *Evaluate Alternate Mechanisms* • *Past Mass Extinctions* • 5 3x3 sticky notes • pencil • tape		• M-E-F poster

Materials preparation (20 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole punch all the images and handouts so they can be added to students' notebooks.

Print one copy, in color if possible, for each pair of students in your largest class:
- *Mass Extinctions Data Analysis*

Print one copy of each of these handouts for each student:
- *Extinction Evidence Organizer*
- *Chicxulub #1: K-Pg Fossil Record*
- *Alternate Mechanisms (A-D)*
- *Timeline*
- *Evaluate Alternate Mechanisms*
- *Past Mass Extinctions*

Print one copy of each of the following handouts for each group of four students in each class. Each member of the group will work with a different reading:
- *Chicxulub #2: Seafloor*
- *Chicxulub #3: Cenotes*
- *Chicxulub #4: Iridium*
- *Chicxulub #5: Sediment*

M-E-F poster

Lesson 14 • Where We Are Going and NOT Going

Where We Are Going

Students develop and use these CCCs across this lesson:

- Changes in systems may have various causes that may not have equal effects.
- Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system.

Students developed these ideas in Lesson 11 in the context of explaining what is happening to meteors moving through the atmosphere. In this lesson, students will be applying these ideas to explain matter changes after the moment of impact.

Students develop and use this DCI across this lesson:

- PS3.A.2 At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy.

Students developed this idea in Lesson 10 in the context of explaining what is happening to meteors moving through the atmosphere. In this lesson, students will be applying the idea to explain matter changes occurring in the crust, ejecta, and sediments as well as energy transfers related to tsunamis, seismic waves, and heat emitted from debris traveling through the atmosphere.

Students develop and use these elements of these DCIs across this lesson:

- ESS2.A.3 The geologic record shows that changes to global and regional climate can be caused by interactions among changes in the sun's energy ~~output or Earth's orbit,~~ tectonic events, ocean circulation, volcanic activity~~, glaciers, vegetation, and human activities.~~
- ESS1.C.2 Although active geologic processes, such as plate tectonics and erosion, have destroyed or altered most of the very early rock record on Earth~~, other objects in the solar system, such as lunar rocks,~~ asteroids, and meteorites, ~~h~~have changed little over billions of years. Studying these objects can provide information about Earth's ~~formation and~~ early history.

Students develop and use these ideas when they interpret studies on the various possible impacts to earth systems and use these to argue for how the Chicxulub impactor affected the climate. Students also have developed the idea of how radioactive dating works in this prior unit: *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*.

Students will encounter or co-develop definitions for the following words in this lesson: *mass extinction, K-Pg boundary.* **Do not** post any words or ask students to add them to their Personal Glossary until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

Some additional lines of evidence regarding the effects of the Chicxulub meteor impact not cited in the related readings that students use in this lesson and that are not a focus of this lesson include vaporized sulfates in the bedrock at the impact site likely resulting in worldwide acid rain for a number of days. The longer-term global warming effects of adding large amounts of carbon dioxide produced from things like worldwide forest fires, combusted fossil fuel at the crater site, and increased volcanism at the Deccan trap are not considered in this lesson. The biosphere impacts of ocean acidification from increased carbon dioxide levels and acid rain are also not considered in this lesson. Both of those climate-level impacts, however, are ones that students who have completed the OpenSciEd chemistry course have explored in depth in a different context . If your students have have explored those climate-level impacts, then coordinating with their prior teachers to build out an extension to enable students to explore the impacts and outcomes listed above while also reusing the models they developed in *OpenSciEd Unit C.1: How can we slow the flow of energy on Earth to protect vulnerable coastal communities? (Polar Ice Unit)* and *OpenSciEd Unit C.4: Why are oysters dying, and how can we use chemistry to protect them? (Oysters Unit)* could provide a very rich, cross-curricular, multiyear extension opportunity.

The definitions included in the Glossary sections of *Alternate Mechanisms (A-D)* are provided to simply help students translate the meaning of what may be unfamiliar words, while still providing students experience with making sense of the verbatim text used in scientific papers. Students do not need to add these to their Personal Glossary.

LEARNING PLAN for LESSON 14

1 · NAVIGATE

6 min

MATERIALS: None

Activate student prior knowledge about impactor collisions. Display **slide A**. Remind or ask students what we figured out last time about meteor impacts. Use the prompt on the slide to have students connect back to the previous lesson. Last time, students considered why it is harder to find fragments of larger meteors in such impacts.

Suggested prompt	Sample student response
What evidence could help us understand the impact this meteor had on the planet?	We could look for evidence that there was a change in one or more of Earth's systems 65 million years ago.

Elicit initial ideas about the Chicxulub crater. Display **slide B**. Say, *At the beginning of Lesson 12, we observed an abundance of craters on the Moon, but let's now pivot to considering Earth. What makes it difficult to find evidence of impactor collisions on Earth?* Ask students to share their ideas about the prompts below, first as a Turn and Talk and then in a whole-class discussion.

Suggested prompt	Sample student response
What Earth processes could make it hard to find evidence of an event that occurred 65 million years ago?	The event that occurred 65 million years ago was caused by a massive impactor. In Lesson 13, we learned that deposition and erosion could disperse or bury the matter from a meteor throughout the surrounding environment. Natural processes in Earth's systems--such as plate tectonics and erosion--have destroyed or altered most of the very early rock record on Earth.
what kind of evidence could we look at to determine the effects of the impactor collision on life on Earth at that time?	We could look back at the fossil record from 65 million years ago to understand the short- and long-term effects of the impactor collision on Earth.

Say, *I have data about the fossil record that might give us an idea about the effects of such impact.*

2 · DEVELOP LESSON DRIVING QUESTION

8 min

MATERIALS: *Extinction Evidence Organizer*, *Mass Extinctions Data Analysis*

Analyze evidence from the fossil record about mass extinctions. Present **slide C**. Distribute to each pair of students the *Mass Extinctions Data Analysis* handout, which shows a graph of the fluctuation of extinction events in the fossil record. Instruct students to focus on the part of the graph that corresponds to the impactor collision that occurred 65 million years ago. Give students a couple of minutes to work with their partner to record on the handout their thinking about the questions there and then bring students together to share with the class.

Suggested prompt	Sample student response
What do these data from the fossil record tell us about what might have happened around the time of the meteor impact?	The Chicxulub crater is related to the extinction of the dinosaurs. This is because the crater is the same age as the end-cretaceous event that caused the sudden mass extinction of dinosaurs and three-quarters of the plant and animal species on Earth.
What new questions do they raise?	Were the other extinction events caused by meteors? Why did some things die and not others?

Discuss fossil record data as a whole group. Present **slide D** for a large-size version of the handout's graph. In a whole-group discussion, call on 2-3 students to share their answers to the questions on the handout. For the second question, if students do not land on a variation of "Why did some things die and not others?," then go back to the data and ask follow-up questions such as: *What does this mean about the 24% of organisms that did not go extinct? Why didn't 100% of organisms go extinct? Which organisms do you think survived this impactor?* Student answers to the second handout question are key to the navigation into the next lesson activity.

Generate the lesson driving question. Present **slide E**. Distribute *Extinction Evidence Organizer*. Say, *Earlier today, you suggested that we should look into the fossil record that corresponds to the end-cretaceous event. It is notable that during the end-cretaceous event 65 million years ago, there was a mass extinction of dinosaurs and three-quarters of the plant and animal species on Earth. Before we look at this evidence, let's define our lesson driving question*.

Remind students that thinking of the question we are trying to answer helps us establish a purpose for our learning. Ask students to record at the top of the *Extinction Evidence Organizer* one question we can answer with fossil data from 65 million years ago. Student-generated questions may vary slightly but are key to the navigation into the rest of the lesson and should be a variation of the following question: How can a meteor impact cause the extinction of some organisms but not others?

3 · EXPLORE MATTER AT THE CHICXULUB CRATER

12 min

MATERIALS: *Extinction Evidence Organizer*, *Chicxulub #1: K-Pg Fossil Record*

Read an article to learn about the K-Pg layer. Present **slide F** and distribute *Chicxulub #1: K-Pg Fossil Record*. Say, *This article represents our first source of information that will help us learn more about Earth's fossil record 65 million years ago.*

Read the slide instructions aloud:

- *Read Chicxulub #1: K-Pg Fossil Record.*
    - *Underline ideas that help answer your question.*
    - *Complete each of the columns in row 1 of Extinction Evidence Organizer.*

Give students 4 minutes to complete this task, as it is a short reading.

Give students 4 minutes to share what they learned from the article in a whole-group discussion. As students share, refer to anticipated student responses found in the *Extinction Evidence Organizer Key*.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: See anticipated student responses found in the *Extinction Evidence Organizer Key*.

What to do: Ask the student how the K-Pg layer connects mass extinctions to a massive impactor collision. Prompt students to generate wonderings and new questions about the K-Pg layer.

Building towards 14.A.1 Read scientific literature to determine the central ideas and summarize the different changes in earth systems due to the Chicxulub meteor impac and their effects on different types of organisms and ecosystems across different spatial and temporal scales by paraphrasing them in simpler but still accurate terms. (SEP: 8.1, CCC: 2.4, DCI: ESS1.C.2)

Identify lenses used to gather information. Present **slide G**. Say, *We read this article to learn more about what occurred during the massive impactor collision that killed the dinosaurs.* Then elicit 1-2 ideas with the prompt:

- *Which M-E-F perspective did this article focus on?*

Students should note that data source #1 mostly focused on matter changes and matter interactions during the impactor collision. Say, *We will take on multiple lenses as we learn more.*

Generate new questions. Give students 2 minutes to turn and talk with the second slide prompt:

- *What new questions does this reading raise for you?*

Call on 2-3 students to share their questions in a whole-group discussion. Listen for the following ideas:

- What do the organisms that went extinct 65 million years ago have in common?
- What do the organisms that survived during the end-cretaceous event have in common?
- What did scientists find in the K-Pg fossil layer?

4 · CREATE INITIAL MODEL

10 min

MATERIALS: *Extinction Evidence Organizer*, *Timeline*, *Moon Timeline*, M-E-F poster

Draw an initial model to explain the dinosaur extinction. Present **slide H**. Say, *This was not just one instantaneous event. Let's create a model to show the chain of causes and effects that led certain types of organisms to become extinct*. Distribute *Timeline*, a blank timeline to help students use ideas they have learned thus far in the unit to create their initial model.

Generate new questions about the K-Pg layer. Present **slide I**. Say, *Scientists have used a variety of methods to study the K-Pg layer, including gravimetry and seismic imaging, and we now have a lot more information about what is in this layer. What additional evidence do we need to refine our initial models?* Call on a few students to share their thoughts in a whole-group discussion. Listen for the following ideas:

- Are the K-Pg layers found worldwide identical? Are there any differences in the K-Pg layer based on geography?
- What materials and fossils were found in the K-Pg layer (Earth's fossil record 65 million years ago)?
- Do the materials in the K-Pg layer show evidence of phase changes such as evidence of melted minerals at high temperatures?
- Can we radar underground to find the crater?

✱ SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

Students develop an initial model of how the Chicxulub impactor led to mass extinctions. While students generate their initial timeline of events, ask questions like these:

- What events must have caused some, but not all, organisms to become extinct?
- Refer students to *Moon Timeline*. How can we build on the model we created in Lesson 12 to show what occurs when an impactor collides with a planetary surface?

- How might the information in *Extinction Evidence Organizer* inform our model?
- What do you think were the short-term effects of the Chicxulub impactor? What were the long-term effects?
- Refer students to the M-E-F poster. Did you represent all of these perspectives in your model?

5 · USE JIGSAW STRATEGY FOR CHICXULUB CRATER READINGS

9 min

MATERIALS: None

Assign students to read articles. Present **slide J**. Before starting the reading, say, *We are going to learn more about the worldwide K-Pg layer so we can answer the lesson driving question. These data will give us clues as to why some but not all organisms went extinct 65 million years ago. Let's focus on matter changes as the lens for these readings. Make note of whether the information you learn helps you to understand the immediate or long-term effects of the impactor collision.* ✱

Obtain information about the K-Pg layer. Present **slide K**. Distribute one of each of these reading to each group of four students:

- *Chicxulub #2: Seafloor*
- *Chicxulub #3: Cenotes*
- *Chicxulub #4: Iridium*
- *Chicxulub #5: Sediment*

Ask groups to split up the articles so that each person reads one and identifies key ideas to share with the group. These articles are all 1-1.5 pages long, so give students about 8 minutes for this portion of the task.

ADDITIONAL GUIDANCE

The articles in these handouts were written at different reading levels: *Chicxulub #2: Seafloor* is more accessible for readers, while the other readings are more challenging, with longer sentences and more complex vocabulary.

✱ SUPPORTING STUDENTS IN ENGAGING IN OBTAINING, EVALUATING, AND COMMUNICATING INFORMATION

Students engage with readings to gather multiple pieces of evidence about the composition and prevalence of the K-Pg layer worldwide. Use this opportunity to broaden students' understanding of the nature of science: science includes the process of coordinating patterns of evidence with current theory. In particular, the readings detail a triangulation of geological findings that point to a massive impactor collision as the cause of the mass extinctions that took place 65 million years ago. It's important to also share that science arguments are strengthened by multiple lines of evidence supporting a single explanation.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: As students are reading and annotating their article and then sharing with their group, look for students to articulate some of the main ideas listed in *Extinction Evidence Organizer Key*.

What to do: If students don't identify at least two of the main ideas, have them move into a new jigsaw group with other students who read the same reading to share ideas and add 1-2 new ones that weren't in their original list.

Ask accessing questions to guide students in naming the matter interactions that occurred as a result of the Chicxulub impactor collision. Ask the following prompts:

- *What evidence do we have in the K-Pg layer of a massive impactor collision?*
- *Recall what you learned in the crater lab in the last lesson. What may have happened to the matter that originated from the impactor?*
- *The Chicxulub crater was found underneath Yucatán Peninsula in Mexico. What matter interactions may have led to the formation of a global K-Pg layer?*

Use advancing questions so students paraphrase the complex ways the impactor affected Earth at different spatial and temporal scales. Ask the following prompts:

- *Based on the evidence in the K-Pg layer, what were the instantaneous effects of the impactor collision? Which effects may have occurred over a longer period of time?*
- *What matter interactions occurred directly between the impactor and Earth's surface at the Chicxulub crater site? What matter interactions must have occurred at the moment of the collision? How did the impactor change matter at the surface of Earth?*
- *What must have occurred for an impactor collision to cause a global effect on Earth?*

Building towards 14.A.2 Read scientific literature to determine the central ideas and summarize the different changes in earth systems due to the Chicxulub meteor impac and their effects on different types of organisms and ecosystems across different spatial and temporal scales by paraphrasing them in simpler but still accurate terms. (SEP: 8.1, CCC: 2.4, DCI: ESS1.C.2)

End of day 1

6 · HAVE GROUP DISCUSSION ON GEOLOGICAL EVIDENCE

13 min

MATERIALS: None

Have a small-group discussion. Display **slide L**. Give students 8 minutes to share in their group the key ideas from each of their articles and how they relate to the changes in matter related to the impactor.

Have a whole-group discussion. Display **slide M**. Invite students to share aloud with the class regarding the conclusions we can make based upon the readings about any important matter changes that occurred that are associated with the Chicxulub impactor. Prompt students to think about why it is important to consider the force interactions and energy changes that occurred during the massive impactor collision.

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING STRUCTURE AND FUNCTION

This is an explicit reference to an important part of this element of this crosscutting concept:

- *Energy cannot be created or destroyed--it only moves between*

Suggested prompt	Sample student response
What perspective did we take in gathering information from these readings?	We investigated the K-Pg layer by looking through just the M-E-F lens of matter changes.
Did these readings provide information to help explain why some organisms went extinct but not others?	After reading about the K-Pg layer, we know more about where this layer is located across the globe and what the layer is made of. However, we still need to learn more about how this layer was formed and how some organisms went extinct.

Prompt students to consider other M-E-F perspectives. Present **slide N**. Say, *Now, we will take on the force interactions and energy transfer lenses. In particular, think about what other Earth systems might have experienced a transfer of energy to or through them as a result of this impact that we haven't considered yet.*

one place and another place, between objects ~~and/or fields,~~ or between systems.

In our first unit of the year, *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*, we figured out that in every energy transfer process we can expect some energy to be transferred to the surroundings. Though it is difficult to detect energy transfers to the surroundings, we start to account for where all the energy came from and went to in a system since we know energy can't be created or destroyed. In order to understand the effects of the Chicxulub impactor, we need to consider all the ways energy was transferred to and through Earth's systems, resulting in planet-level effects.

7 · EVALUATE ADDITIONAL MECHANISMS

10 min

MATERIALS: *Alternate Mechanisms (A-D)*, *Evaluate Alternate Mechanisms*

Learn about alternate mechanisms to explain the end-cretaceous event. Display **slide O**. Say, *Our lesson driving question is something that continues to be debated in the scientific community. We will read four scientific papers that present alternate arguments for how some, but not all, organisms went extinct.* Distribute *Alternate Mechanisms (A-D)* and *Evaluate Alternate Mechanisms* to each student. Organize students in groups of 4 so each person in the group reads 1 alternate claim. Read the slide instructions aloud:

- *Read your assigned article in the Alternate Mechanisms (A-D) handout.*
    - *Which source of evidence from the K-Pg layer supports this alternate claim?*
    - *Each student in a group will read one alternate claim and fill in the corresponding row of the Evaluate Alternate Mechanisms handout.*

Give students 8 minutes to capture notes on 1 alternate claim, as it is a short reading.

✱ SUPPORTING STUDENTS IN ENGAGING IN ARGUMENT FROM EVIDENCE

Students read excerpts from four scientific journals that propose a variety of mechanisms to explain the end-cretaceous event. Use this opportunity to broaden students' understanding of the nature of science: scientific knowledge is subject to change based on new evidence and/or reinterpretation of existing evidence. In particular, the research studies propose alternate mechanisms based on analyses of geological evidence and a variety of simulations. It's important to also share that science argumentation is a mode of logical discourse used to clarify the strength of relationships between discrete pieces of evidence that may result in revision of an explanation.

8 · SHARE ALTERNATE CLAIMS

8 min

MATERIALS: *Evaluate Alternate Mechanisms*

Have a small-group discussion. Display **slide P**. Give each person 2 minutes to share with their group key ideas and how evidence from the K-Pg layer supports each alternate claim. They should record a brief summary of these ideas on *Evaluate Alternate Mechanisms*.

9 · ARGUE FOR OR AGAINST MULTIPLE MECHANISMS

10 min

MATERIALS: *Evaluate Alternate Mechanisms*

Develop an argument. Display **slide Q**.
Read the slide instructions aloud:

- *Develop an argument on Evaluate Alternate Mechanisms.*
    - *Compare and evaluate at least two alternate mechanisms. Which alternate mechanism is most probable?*
    - *Support your thinking with evidence from the K-Pg layer.*

Give students 6 minutes to write in the "Compare and evaluate" space provided on *Evaluate Alternate Mechanisms*.

Call on 2-3 students to share their arguments in a whole-group discussion. As students share, refer to anticipated student responses found in the *Alternate Mechanisms*.

ASSESSMENT OPPORTUNITY

What to look/listen for: Arguing for (or against) a new mechanism related to our question (SEP: 7.1). See anticipated student responses found in the *Alternate Mechanisms*.

What to do: Ask students to use evidence they learned about the K-Pg layer to defend their choice of the most compelling or believable mechanism. Ask assessing questions to support students in making connections between the various mechanisms and M-E-F perspectives. Ask the following prompts:

- *Which alternate mechanism best explains the matter changes present in the K-Pg layer?*
- *Based on this alternate mechanism, what energy transfers occurred on Earth as a result of the impactor collision?*
- *Which alternate mechanism best explains the energy transfers that likely altered Earth's systems on a global scale?*
- *Which alternate mechanism best explains the mass extinction of some but not all terrestrial and marine species?*

Building towards 14.B Compare and evaluate competing arguments for different mechanisms for how energy was transferred and matter changed across different earth systems as a result of Chicxulub crater's formation. (SEP: 7.1, CCC: 5.2, DCI: PS3.A.2)

10 · NAVIGATE

4 min

MATERIALS: None

Elicit students' thinking about Earth's systems. Present **slide R**. Motivate students to connect the mass extinctions that occurred 65 million years ago to a shift in one or more of Earth's systems. Read the slide questions aloud:

- *Based on the readings, which Earth systems do scientists think were affected by the meteor's impact?*
- *How could some of these changes in Earth systems have led to the extinction of some organisms but not others?*

Look for students to articulate potential ways that different Earth's systems were affected by a massive impactor collision. Examples include:

- The ejecta from the Chicxulub impactor may have deposited harmful pollutants in **Earth's atmosphere**.
- The massive impactor collision caused a high energy transfer to Earth's crust, fracturing the limestone in **Earth's geosphere**.
- The impactor likely caused a high degree of heat transfer to Earth or a blockage of sunlight, which directly affected the survivability of species in **Earth's biosphere**.

End of day 2

11 · OBTAIN INFORMATION ABOUT PAST MASS EXTINCTIONS

7 min

MATERIALS: *Past Mass Extinctions*, *Extinction Evidence Organizer*

Read about past extinctions. Present **slide S**. Say, *So far, we have investigated the K-Pg layer and learned about alternative mechanisms to piece together the short-term effects that the Chicxulub impactor had on Earth. It is important to also consider the long-term, system-level effects of this impactor collision. When scientists have narrowed down on explanations for mass extinctions, it has often involved global-level changes in energy transfers on Earth. Let's gather just a bit more information about what type of organisms would have been more affected than others due to some longer term energy transfer effects.*
Distribute the reading: *Past Mass Extinctions*. Give students about 5 minutes on their own to quietly read and follow the slide prompts.

12 · SHARE INFORMATION ABOUT PAST MASS EXTINCTIONS

3 min

MATERIALS: None

Revisit alternate explanations. Display **slide T**. Discuss the questions on the slide:

- *What are some new ideas we now have about how energy transfers across earth systems are related to mass extinctions?*
- *How would you revise your explanation of the end-cretaceous period?*

Listen for students identifying indirect, longer-term effects related to disrupting photosynthetic food chains--in and across different ecosystems, such as:

- The Chicxulub impactor must have affected one or more of Earth's systems.
- A disruption to one of Earth's systems likely either blocked Earth's sunlight or directly eliminated living plants and organisms that are critical to photosynthetic food chains.
- The organisms that survived lived in environments that were more shielded from temperature fluctuations and were more adaptable to low-oxygen conditions.

13 · DEVELOP A FINAL MODEL

15 min

MATERIALS: *Timeline*

Revise initial models. Display **slide U**. Have students look at their initial model from day 1 as you review the questions on the slide for them to consider in their revisions to the model. Emphasize that their revisions should include annotations to help make their thinking visible to others in an upcoming gallery walk. Give students the remaining time to complete this individual assessment.

ASSESSMENT OPPORTUNITY

What to look/listen for: See *Mass Extinction KEY*.

What to do: If student models are lacking some of the look-fors, spring off a student friendly version of *Mass Extinction KEY* and frame it as a Gotta-Have-It Checklist to use to guide their model revisions.

Building towards 14.C Develop a model to provide a mechanistic account of how energy was transferred and/or matter was changed from the formation of the Chicxulub crater in such a way that it resulted in the extinction of certain types of organisms (change) and not others (stability) 65 million years ago. (SEP: 2.3, CCC: 5.2, 7.1, DCI: PS3.A.2, ESS2.A.3)

14 · LEAVE FEEDBACK IN A GALLERY WALK

6 min

MATERIALS: *Timeline*, 5 3x3 sticky notes, pencil

Prepare for and carry out a silent gallery walk. Display **slide V**. Distribute 5 sticky notes and a pencil to each student as they review the directions on the slide. Have students lay their model on their desk so others can see it. Have students carry out a silent gallery walk for 5 minutes.

15 · RESPOND TO QUESTIONS

7 min

MATERIALS: *Timeline*, tape

Review and respond to questions. Display **slide W**. Give students 7 minutes to review the directions on the slide and respond to at least three of the questions other students left for them.

16 · DISCUSS THE IMPLICATIONS FOR THE FUTURE AND IDENTIFY A NEW QUESTION

7 min

MATERIALS: None

Discuss future implications. Display **slide X**. Discuss the questions on the slide as a class for three minutes:

- *How can developing models for explaining past mass extinctions help society better prepare for and maybe even prevent such events in the future?*
- *How might it help inform our models for predicting the long-term effects of human-induced climate change?*

Accept all responses.

Navigate. Display **slide Y**. Read the text on the top of the slide.

- *We explained the effects of a 10 km-wide meteor colliding with Earth 65 million years ago.*
- *Earth is currently about 7,900 km in diameter.*
- *Scientists believe that a 6,000 km-wide object collided with Earth 4.5 billion years ago.*

Discuss the question on slide:

- *What new questions does this raise for you?*

Accept all responses.

Emphasize that in the next lesson we will plan to investigate and answer some of these questions as part of a final transfer task and assessment to wrap up the unit.

Additional Lesson 14 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

CCSS.ELA-LITERACY.RST.9-10.2 Determine the central ideas or conclusions of a text; trace the text's explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.

Students obtain information from reading nonfiction texts in a jigsaw of four different readings: *Chicxulub #2: Seafloor*, *Chicxulub #3: Cenotes*, *Chicxulub #4: Iridium*, *Chicxulub #5: Sediment* on day 1. They do the same on day 2, when they read text extracted from scientific papers on *Unknown material with identifier: pg.l14.ho6*.

CCSS.ELA-LITERACY.RST.9-10.9: Compare and contrast findings presented in a text to those from other sources (including their own experiments), noting when the findings support or contradict previous explanations or accounts.

Students argue for which new mechanisms are sufficient (or irrelevant) to explain the lesson question in their discussion of *Evaluate Alternate Mechanisms* at the end of day 2.

CCSS.ELA-LITERACY.RST.9-10.7: Translate quantitative or technical information expressed in words in a text into visual form (e.g., a table or chart) and translate information expressed visually or mathematically (e.g., in an equation) into words.

Students develop a model to answer the lesson question on day 3. This model is a revision to the initial one they made on day 1. This modeling task provides students a framework to synthesize the ideas and findings they gathered from different sets of readings and peers as well as important mechanisms related to matter changes, force interactions, and energy transfers they developed in prior lessons.

LESSON 15: How can we use our science ideas to explain the formation of the Moon?

PREVIOUS LESSON *We analyzed a graph showing mass extinctions in Earth's history. We developed an initial model to explain how an impactor collision led to mass extinctions. We gathered and communicated information about M-E-F changes related to the Chicxulub crater formation. We revised our initial model to explain how the impactor led to both short-term and longer-term effects that caused the extinction of only some types of organisms and not others.*

THIS LESSON

PUTTING PIECES TOGETHER

1 day



NASA/JPL-Caltech

We return to the DQB to evaluate which questions we have answered in this unit. We work through an assessment task where we assess whether the evidence from moon rocks supports scientists' ideas about the formation of the Moon from a giant impact between Earth and another planet known as Theia.

NEXT LESSON *There is no next lesson.*

BUILDING TOWARD NGSS

HS-ESS1-4, HS-ESS1-6, HS-PS2-4, HS-PS3-1, HS-PS3-2

WHAT STUDENTS WILL DO

15.A Revise an explanation based on valid and reliable evidence to answer Driving Question Board questions that involve explaining the stability and/or change in the motion of space objects, the frequency of meteor collisions, and Earth's surface. (SEP: 6.2; CCC: 5.2, 7.1; DCI: ESS1.B.1, ESS1.C.2, PS2.B.1, PS3.A.2)

WHAT STUDENTS WILL FIGURE OUT

- The Moon was formed after Theia, a planet from the young solar system, collided with Earth.
- Ideas about matter changes, forces acting on matter, and energy flow can be used to assess whether the available evidence supports ideas about the formation of the Moon.

Lesson 15 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	15 min		**RETURN TO THE DQB** Return to the DQB to determine which questions we have answered. Reflect on experiences during the unit.	A-C	sticky dots in three colors, Driving Question Board, Take-aways poster, chart paper markers
2	30 min		**COMPLETE FINAL ASSESSMENT TRANSFER TASK** Distribute *Moon Formation* to every student to complete a final assessment about the formation of the Moon.	D	*Moon Formation*

End of day 1

Lesson 15 • Materials List

	per student	per group	per class
Lesson materials	• sticky dots in three colors • science notebook • *Moon Formation*		• Driving Question Board • Take-aways poster • chart paper markers

Materials preparation (15 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Prepare a piece of chart paper for a poster titled “Take-aways”.

Make sure all students will have access to sticky dots (green, yellow, and red) to revisit the Driving Question Board.

Consider gathering artifacts such as posters or timelines from previous lessons and positioning them around the DQB to help students make connections between what we have learned and the questions that we can now answer.

Make a copy of the *Moon Formation* for each student. Review the *Moon Formation KEY* prior to administering the assessment. Consider what modalities you want to provide for students to complete the assessment. See the Attending to Equity callout in the assessment section of this *Teacher Guide* for ideas of different ways to administer this assessment.

Lesson 15 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently build ideas related to the following disciplinary core ideas (DCIs):

- **ESS1.C.2: The History of Planet Earth:** Although active geologic processes, such as plate tectonics and erosion, have destroyed or altered most of the very early rock record on Earth, other objects in the solar system, such as lunar rocks, asteroids, and meteorites, have changed little over billions of years. Studying these objects can provide information about Earth's formation and early history.
- **PS2.B.1: Types of Interactions:** Newton's law of universal gravitation ~~and Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic~~ forces between distant objects. (HS-PS2-4)
- **PS1.C.1: Nuclear Processes:** ~~Spontaneous radioactive decays follow a characteristic exponential decay law. Nuclear lifetimes allow~~ radiometric dating to be used to determine the ages of rocks and other materials. (secondary)

This lesson also touches back on the questions posted on the Driving Question Board. Students can now answer questions around the DCIs from prior lessons, using their understanding of gravitational forces between objects, the motion of space objects, energy stored in fields, Earth's geologic processes, and the interactions of forces, matter, and energy that cause changes in the motion of space objects and Earth's surface over time.

This lesson is designed to support students toward the Next Generation Science Standards (NGSS) Nature of Science Understanding titled **Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena** (Appendix H). The relevant understanding element reads:

- Models, mechanisms, and explanations collectively serve as tools in the development of a scientific theory.

Where We Are NOT Going

In the assessment, students explain how the collision between Theia and Earth could have led to the formation of the Moon, also known as the Giant Impact hypothesis. While this hypothesis has gained popularity as a means to explain the low density of Moon materials and the similar chemical composition to Earth, it is still currently being debated by geologists. This hypothesis implies that a magma ocean on the surface would have formed as Earth became molten following the impact with Theia. Yet, scientists have not found evidence of a magma ocean on Earth. This complex process is not included in this assessment. Students are to explain the changes in matter, energy, and forces that could have led to the formation of the Moon and whether the available evidence supports this event. After the assessment, emphasize that this research is an ongoing geological endeavor.

LEARNING PLAN for LESSON 15

1 · RETURN TO THE DQB

15 min

MATERIALS: sticky dots in three colors, Driving Question Board, Take-aways poster, chart paper markers

Return to the Driving Question Board. Present **slide A**. Say, *This is the last lesson of this unit. In the past, we have looked at the progress we have made by looking at the questions from the Driving Question Board that we can now answer.*✱

Mark patterns in questions answered using the sticky dots. Facilitate identifying patterns in the DQB questions. Focus the discussion on identifying (1) questions we agree that we can answer, (2) questions that we have at least a partial answer to, and (3) questions we cannot answer at all. Use one color of sticky dots to mark each of these categories. Distribute a set of sticky dots to each student and have them come up to the DQB and add their dots to the posted questions. ✱

ALTERNATE ACTIVITY

If you have time, have students choose one question from the DQB that has sticky dots for either categories 1 or 2 to answer individually and then share their answer during the discussion.

Discuss the DQB questions we can answer. Present **slide B**. Gather the class in a Scientists Circle for a discussion of the questions we can now answer. Display the Take-aways poster to record the answers. Revisiting the DQB at the end of the unit helps students see the progress they have made toward answering questions that were important to them at the onset of the unit.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment

- Look for students to use multiple sources of evidence to explain the motion of space objects, falling or orbiting, and their stability and change over time, using matter changes and interactions, forces acting on matter, and/or energy flow. (SEP: 6.2; CCC: 7.1; DCI: ESS1.B.1, PS2.B.1, PS3.A.2)
- Listen for students to use multiple sources of evidence to explain how geologic processes, acting over a long time, may change early rock records on Earth. (SEP: 6.2; CCC: 5.2, 7.1; DCI: ESS1.C.2, PS3.A.2)

What to do

- If students are in disagreement about an answer, ask questions to seek clarification or more information, such as: *Can you tell me more? What investigation helped us figure out that piece of information? Can anyone point to evidence to support ___'s answer?*

Building toward: 15.A Revise an explanation based on valid and reliable evidence to answer Driving Question Board questions that involve explaining the stability and/or change in the motion of space objects, the frequency of meteor collisions, and Earth's surface. (SEP: 6.2; CCC: 5.2, 7.1; DCI: ESS1.B.1, ESS1.C.2, PS2.B.1, PS3.A.2)

Celebrate the class's accomplishments. Say, *I can't believe how far we've come since we first read about the Chelyabinsk meteor event in Lesson 1. We should be very proud of what we've accomplished.*

Have students reflect upon their experiences. Present **slide C**. Direct students to find a blank page in their notebook, label it "Reflection", and record their answers to the questions on the slide:

- *What was most challenging in this unit?*
- *What was most rewarding in this unit?*

✱ ATTENDING TO EQUITY

Revisiting the Driving Question Board is important for students to feel as though their questions are valued and recognized. While not all questions will have been addressed (it's more likely that 50–75 percent will be at least partially answered), this helps students see the hard work that they have done to answer many of their own questions.

After three minutes, ask each student to share a part of their reflection. Taking time to reflect upon the process of this unit allows them to think metacognitively about what works well for them as learners.

2 · COMPLETE FINAL ASSESSMENT TRANSFER TASK

30 min

MATERIALS: science notebook, *Moon Formation*

Administer the assessment individually to students. Present **slide D**. Say, *In this unit, we've figured out how scientists use evidence from Earth and other space objects to predict the future and understand the past. To wrap up our unit you will be asked to apply your understanding of everything we figured out to a new situation and to consider whether the available evidence supports a hypothesis about the formation of the Moon. This is our final individual assessment for the unit.* Project https://youtu.be/vAorgMubHOI to present a supercomputer simulation that NASA scientists carried out to test this hypothesis.

Have students prepare for the assessment. Distribute to each student one copy of the [materialPG:L15.SA] transfer task. Tell students they will be allowed to use the notes they recorded in their science notebook throughout the unit.

This assessment will take students the remainder of the class period to complete. Once completed, students should turn in their assessment to you for feedback.

ASSESSMENT OPPORTUNITY

What to look/listen for in the moment: See *Moon Formation KEY.*

What to do: Use the key to assess students and for suggestions on how to provide productive feedback for students who are working with foundational ideas but not yet linking them, for students who are linking ideas but not yet organizing them, and for students who are organizing their ideas and need an additional challenge.

This assessment is not building toward a lesson-level performance expectation. It is designed to assess the performance expectation from the NGSS noted below.

15.B Transfer Task PE: HS-ESS1-6 Apply scientific reasoning and evidence from ancient earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history. (SEP: 6.4; DCI: ESS1.C.2, PS1.C.1, PS2.B.1; CCC:5.2, 7.1)

At the end of the period, bring the class back together and point to the unanswered questions on the DQB. Tell students that, over the course of future units, we will need to keep these questions in mind to see whether we can eventually answer them.

ADDITIONAL GUIDANCE

Students may have questions, such as those focused on the formation of the universe, that require use of different disciplinary core ideas, crosscutting concepts, or science and engineering practices than those utilized in this unit. Keep these questions to revisit in later units. For instance, in *Cosmology Unit*, students will learn more about the history of Earth and the universe. This will allow some resolution on these unanswered questions in the future.

✱ ATTENDING TO EQUITY

Universal Design for Learning: Consider allowing students to *express* their understandings of the Moon formation in various ways. Some students may benefit from orally responding to the prompts or by using drawings to make their thinking visible. Online tools such as Flip can assist students in showing and explaining their ideas in more than just writing.

Additional Lesson 15 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA	**Integration of Knowledge and Ideas** **CCSS.ELA-LITERACY.RST.11-12.8:** Evaluate the hypotheses, data, analysis, and conclusions in a science or technical text, verifying the data when possible and corroborating or challenging conclusions with other sources of information. In the assessment, students will evaluate the Great Impact hypothesis using the evidence that supports it and their ideas about geologic processes, matter changes, and energy transfers.

Unit P.4 Teacher Reference Materials

ASSESSMENT SYSTEM OVERVIEW

Each OpenSciEd unit includes an assessment system that offers many opportunities for different types of assessments throughout the lessons, including pre-assessment, formative assessment, summative assessment, and student self assessment. Formative assessments are embedded and called out directly in the lesson plans. Please look for the "Assessment Icon" in the teacher support boxes to identify places for assessments. In addition, the table below outlines where each type of assessment can be found in the unit.

Overall Unit Assessment

When	Assessment and Scoring Guidance	Purpose of Assessment
Lesson 1	Initial models	**Pre-Assessment** The student work in Lesson 1 available for assessment should be considered a pre-assessment. It is an opportunity to learn more about the ideas your students bring to this unit. Revealing these ideas early on can help you be more strategic in how to build from and leverage student ideas across the unit. The initial model developed in Lesson 1 is a good opportunity to pre-assess student understanding of orbital motion and gravity. You will return these models in Lesson 6 and Lesson 11 for self-reflection.
	Driving Question Board	**Pre-Assessment** The Driving Question Board is another opportunity for pre-assessment. Reinforce for students to generate open-ended questions, such as how and why questions, to post to the board. However, any questions students share, even if they are close-ended questions, can be valuable. Make note of any close-ended questions and use navigation time throughout the unit to have your students practice turning these questions into open-ended questions when they relate to the investigations underway. In Lessons 9 and Lessons 15, students will revise the Driving Question Board. These lessons also present a self-reflection moment as students will see how many of their initial questions they are able to answer.
Lesson 2	Electronic exit ticket https://docs.google.com/forms/d/1jFVInZdCB4gqYLqNoVqq_S1jMYIgPuauX76VAgkv8Ns/copy and *Exit Ticket Key*	**Formative** This electronic exit ticket asks students to reason about forces of gravity. This serves as a quick check of how well students have grasped these concepts before using them in Lesson 3.
	Calculating Gravitational Forces	**Formative** In this handout, students will find information to calculate the force of gravity between Earth and different space objects. It will provide evidence of how students are using Newton's law of universal gravitation. Students will carry out similar calculations in the mid-unit transfer task.

When	Assessment and Scoring Guidance	Purpose of Assessment
Lesson 3	*Investigating Circular Motion*	**Formative** In this lab activity, students investigate relationships among force, radius, and velocity in circular motion. This is a good opportunity to get a sense of how comfortable students are getting with these concepts before using them later in the lesson to derive the relationship between orbital period and radius.
	Kepler's Third Law and *Kepler's 3rdLaw Key*	**Formative** Students will use a simulation to gather data that can help them investigate the relationship between orbital period and radius to derive Kepler's third law. This is also an opportunity to identify areas where students may need support before they apply the ideas in *Changing Asteroid Orbits* in Lesson 7.
Lesson 4	*Orbital Shapes* and *Orbital Shapes Key*	**Formative** In this lesson, students use a physical model to investigate the relationships among the eccentricity, distance between foci, semimajor axis, and the shape of the orbit.
	Students' models on butcher paper and *Example Collision Model*	**Formative** Students use the ideas about the parts of the orbit to reconstruct the orbits of the Peekskill meteor and Earth to explain why these two objects collided. They will also use this representation to identify the limitations of this model to predict when or where two space objects might collide in space.
Lesson 5	*Orbital Energy Transfer* and *Orbital Energy Key*	**Formative** Students develop a model for an object orbiting the Sun with a high eccentricity. They use this model to show their ideas about the kinetic energy of the object along the orbit, energy transfer, and how the magnitude of the force acting on this object might be involved. This is a good opportunity to identify students' ideas about matter, energy, and forces in a closed system.
	Energy Transfer Investigation and *Energy Transfer Investigation KEY*	**Formative** Students calculate the kinetic and potential energy (energy stored in fields) of a pendulum to make sense of energy transfer and energy conservation in a Sun-asteroid system. This is also an opportunity to identify areas where students may need support before they apply the ideas in *Changing Asteroid Orbits* in Lesson 7.
Lesson 6	*Redirection of Asteroids*	**Formative** In this lesson, students will develop two models to illustrate how the meteor that caused the Chelyabinsk event changed its orbital path. One model asks students to consider a scenario where the gravitational force from Jupiter could have caused this meteor to move from its orbit around the asteroid belt towards Earth. The second model asks students to consider how contact forces could have led the meteor to change its orbital path. These models are intended to help identify areas where students may need support before they apply the ideas in *Changing Asteroid Orbits* in Lesson 7.

When	Assessment and Scoring Guidance	Purpose of Assessment
Lesson 7	*Changing Asteroid Orbits* and *Key: Changing Asteroid Orbits*	**Summative Mid-Unit Task** At the end of the first lesson set, students will have the opportunity to demonstrate their competence with a transfer task, where they will use diagrammatic and mathematical models to explain how two asteroid-deflection strategies work to change the orbits of space objects. This task is robust and will take 30-45 minutes. The ideas, crosscutting concepts, and practices students engage with as part of completing this assessment can be found at the top of the scoring guidance (key). The scoring on this assessment represents our recommendation for how to weigh questions. Please use scoring that works for your class and your requirements. We strongly recommend that you encourage students to use their notebook as a resource for completing all assessments. The performance expectation being assessed in this task is **HS-PS2-4** Use mathematical representations of Newton's Law of Gravitation ~~and Coulomb's Law~~ to describe and predict the gravitational ~~and electrostatic~~ forces between objects.
Lesson 9	Driving Question Board	Students revisit the Driving Question Board. This is an opportunity for pre-assessment for concepts in Lesson Set 2. Reinforce for students to generate open-ended questions, such as how and why questions, to post to the board. However, any questions students share, even if they are close-ended questions, can be valuable. Make note of any close-ended questions and use navigation time throughout the unit to have your students practice turning these questions into open-ended questions when they relate to the investigations underway.
Lesson 10	Revise explanation of meteor collision	**Formative** In this lesson, students use their ideas about the mass and velocity of meteors to explain why finding large fragments of smaller meteors is easier than finding large fragments of larger meteors. For this explanation, students are asked to use ideas related to M-E-F to account for this difference. This is an opportunity to identify areas where students may need support before the final transfer task (Lesson 15), during which they apply the ideas about how the amount of energy in a system can determine the changes in matter that are observed.
Lesson 11	Explanation of changes in small rocks	**Formative** In this lesson, students will use M-E-F-related ideas to develop an explanation of the changes that small rocks experience as they enter Earth's atmosphere. This explanation is tied to the evidence students observed during the anchoring phenomenon about the changes as the Chelyabinsk meteor moved through the atmosphere.
Lesson 12	Claims about changes in frequency	**Formative** Students will be asked to write claims about the changes in the frequency of small and large meteors approaching Earth over time. They will use evidence from the age distribution of lunar craters to support these claims.

When	Assessment and Scoring Guidance	Purpose of Assessment
Lesson 13	Geological processes explanation	**Formative** Students will develop an explanation about how different geological processes on Earth help explain the patterns in the age distribution of terrestrial craters, which differ vastly from the record of lunar craters. This is an opportunity to identify areas where students may need support before they apply the ideas about how geological processes can alter surface features in *Moon Formation* in Lesson 15.
Lesson 14	*Extinction Evidence Organizer* and *Extinction Evidence Organizer Key* Science notebook and *Mass Extinction KEY*	**Formative** Students will determine the central ideas of an article and summarize the changes in Earth's systems caused by the Chicxulub impact. They will be provided with an organizer to summarize these ideas. Students will communicate their summary in a jigsaw group. The accompanying key will help you identify the main ideas from these readings. Students will compare different claims made about changes in matter and energy caused by the Chicxulub impact that help explain why some organisms went extinct and not others. **Formative** Students develop a model and use it in an explanation of how energy was transferred and/or matter was changed from the formation of the Chicxulub crater in such a way that it resulted in the extinction of certain types of organisms (change) and not others (stability) 65 million years ago. This modeling task provides students an opportunity to employ M-E-F ideas they developed in Lessons 11-13 as well as additional ones they identify in Lesson 14 readings. This context provides an opportunity to synthesize evidence from scientific studies from a physical science perspective, apply them to earth-system-scale interactions, and ultimately explain a life science outcome. Extension opportunities to connect to prior coursework in biology and chemistry are identified as well. A rubric is provided to support the scoring of this task.
Lesson 15	*Moon Formation* with *Moon Formation KEY*	**Summative End-of-Unit Transfer Task** At the end of this final lesson, students will have the opportunity to demonstrate their competence with a transfer task that focuses on the Giant Impact hypothesis that has been proposed by scientists to explain the formation of the Moon. This task is robust and will take 30-45 minutes. The ideas, crosscutting concepts, and practices students engage with as part of completing this assessment can be found at the top of the scoring guidance (key). The scoring on this assessment represents our recommendation for how to weigh questions. Please use scoring that works for your class and your requirements. We strongly recommend that you encourage students to use their notebook as a resource for completing all assessments. The performance expectation being assessed in this task is **HS-ESS1-6** Apply scientific reasoning and evidence from ancient earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history.
Embedded in each lesson	Lesson-by-lesson assessment opportunities (below)	**Formative Assessment** Use this document to see which parts of lessons or student activity sheets can be used as embedded formative assessments.

When	Assessment and Scoring Guidance	Purpose of Assessment
Occurs in several lessons	Progress Tracker *Progress Tracker KEY*	**Formative and Student Self-Assessment** The Progress Trackers are thinking tools designed to help students keep track of important discoveries that the class makes while investigating phenomena and figure out how to prioritize and use those discoveries to develop a model to explain phenomena. It is important that what students write in the Progress Trackers reflects their own thinking at that particular moment in time. In this way, the Progress Trackers can be used to formatively assess individual student progress or for students to assess their own understanding throughout the unit. Because the Progress Trackers are meant to be a thinking tool for students, we strongly suggest it is not collected for a summative grade other than for completion. Major moments for the Progress Tracker include Lessons 3, 4, 12, and 13. Examples of ideas that students may include in this tracker are embedded in these lessons, and an example of potential responses can also be found in *Progress Tracker KEY*.
Occurs in several lessons	Student self-assessment rubrics	**Self-Assessment** Student self-assessment rubrics for giving and receiving feedback can be used throughout the unit. Opportunities include after a discussion or at the end of a class period. The rubric helps students reflect on their participation in the class that day. Choose to use this at least once a week or once every other week. Initially, you might give students ideas for what they can try to improve for the next time, such as sentence starters for discussions. As they gain practice and proficiency with discussions, ask for their ideas about how the whole-class and small-group discussions can be more productive. Additional support can be found in the *OpenSciEd Teacher Handbook: High School Science.* In addition to this flexible resource, self-assessment has been written directly in the unit in Lessons 1, 6, and 11.
Occurs in several lessons	Routines and tools to support peer assessment	**Peer Assessment** There will be times in your classroom when facilitating students to give each other feedback will be very valuable for their three-dimensional learning and for learning to give and receive feedback. We suggest that peer feedback happen at least two times per unit. Peer feedback is most useful when there are complex and diverse ideas visible in student work and not all work is the same. Student models or explanations are good opportunities to use a peer feedback protocol. They do not need to be final pieces of student work; rather, peer feedback will be more valuable to students if they have time to revise after receiving it. This should be a formative rather than summative type of assessment. It is also necessary for students to have experience with past investigations, observations, and activities in which they can use these experiences as evidence for the feedback they give. Additional support can be found in the *OpenSciEd Teacher Handbook: High School Science.* In addition to this flexible resource, peer feedback has been written directly in the unit in Lessons 1 and 14.

For more information about the OpenSciEd approach to assessment and general program rubrics, visit the OpenSciEd Teacher Handbook.

Lesson-by-Lesson Assessment Opportunities

Every OpenSciEd lesson includes one or more lesson-level performance expectations (LLPEs). The structure of every LLPE is designed to be a three-dimensional learning, combining elements of science and engineering practices, disciplinary core ideas and cross cutting concepts. The font used in the LLPE indicates the source/alignment of each piece of the text used in the statement as it relates to the NGSS dimensions: alignment to Science and Engineering Practice(s), alignment to Cross-Cutting Concept(s), and alignment to the Disciplinary Core Ideas.

The table below summarizes opportunities in each lesson for assessing every lesson-level performance expectation (LLPE). Examples of these opportunities include student handouts, home learning assignments, progress trackers, or student discussions. Most LLPEs are recommended as potential formative assessments. Assessing every LLPE listed can be logistically difficult. Strategically picking which LLPEs to assess and how to provide timely and informative feedback to students on their progress toward meeting these is left to the teacher's discretion.

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 1	**1.A** Develop a model using evidence from the Chelyabinsk meteor event and related phenomena to illustrate how the interactions between different parts of the system at different scales help explain the changes in matter, energy, and/or motion of orbiting objects. (SEP: 2.3; CCC: 2.2; DCI: PS2.B.1, PS3.A.2, ESS1.B.1) **1.B** Ask questions that arise from careful observation of a meteor event at multiple scales and data from related events to clarify and seek additional information about the causes of the motions of orbiting objects, the effects of gravitational forces on these objects, and the consequences of their impact on our planet. (SEP: 1.1; CCC: 2.2; DCI: PS2.B.1, PS3.A.2, ESS1.B.1)	**1.A.1 When to check for understanding:** On day 1 after students complete and revise their models of the changes observed during the Chelyabinsk event **What to look/listen for in the moment:** Look for students' models to accomplish the following: • Use evidence about the Chelyabinsk event such as flashes of light, sound, smoke, or anything else they might have observed. • Label this evidence in some way to indicate changes in matter and energy in different parts of the system (SEP: 2.3; CCC: 2.2; DCI: PS3.A.2, PS3.A.2) • Represent forces such as gravity, friction, or other contact forces acting on the meteor and Earth's surface. (SEP: 2.3; DCI: ESS1.B.1, PS2.B.1) • Represent two different spatial scales--one where we are zoomed out enough to see the meteor above Earth and one where the meteor is close to the surface of Earth. (SEP: 2.3; CCC: 2.2) **1.A.2 When to check for understanding:** At the end of day 2, with students' completed second initial models that try to explain why some objects remain in orbit while others hit Earth **What to look/listen for in the moment:** This is a second formative assessment that will provide you with evidence of students' ideas about forces at a distance and changes in motion. Look for students' models to • represent forces acting on the meteor and how they can cause some objects to stay in orbit and others to hit Earth. (SEP: 2.3;CCC: 2.2; DCI: ESS1.B.1, PS2.B.1) • represent some differences in the force interactions occurring between Earth and orbiting objects as the distance between them changes. (SEP: 2.3; CCC: 2.2; DCI: ESS1.B.1, PS2.B.1) **1.B.1 When to check for understanding:** During day 2 when students record questions about the related phenomena after sorting them into different categories. **What to look/listen for in the moment:** Questions to clarify and seek additional information about • the causes of the motion of orbiting objects (SEP: 1.1; CCC: 2.2; DCI: PS2.B.1, ESS1.B.1) • the causes of observed effects from various orbiting objects on Earth's systems (SEP: 1.1; CCC: 2.2; DCI: PS3.A.2) **1.B.2 When to check for understanding:** On day 3, after students revise their second initial model that tries to explain why some objects remain in orbit while others hit Earth. **What to look/listen for in the moment** • Questions to clarify and seek additional information about interactions within the system that can cause different types of motion of space objects (SEP 1.1; CCC: 2.2; DCI: ESS1.B.1, PS2.B.1)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 2	**2.A** Use simple limit cases and mathematical representations to describe patterns in the change of magnitudes of magnetic and gravitational forces on two objects caused by changes in their distances from each other. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1, PS2.B.2) **2.B** Apply techniques of algebra to solve for the gravitational force between Earth and another space object using Newton's law of universal gravitation. (SEP: 5.3; CCC: 3.5; DCI: PS2.B.1, PS2.B.2)	**2.A.1 When to check for understanding:** On day 2, students record their ideas in their science notebooks regarding the patterns between magnetic force and distance from the Magnetic Force vs. Distance Investigation. **What to look for/listen for in the moment** • Use the graphs from the investigation results to describe the overall pattern in the changes of the magnetic force's magnitude acting on two magnets due to increases in the distance between them. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1) • Describe how, when the distance is doubled, the magnetic force decreases by more than half, indicating that this pattern does not follow a linear inverse relationship. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1) • Use the results from investigations 2A and 3A to conclude that the positions of the magnets do not influence the magnitudes of the forces acting on them. (SEP: 5.2, 5.4; DCI: PS2.B.1) **2.A.2 When to check for understanding:** At the end of day 2, after students annotate the patterns between the gravitational force experienced by objects of different mass based on their distance from Earth and the Moon on the *Calculating Gravitational Forces* handout **What to look for/listen for in the moment** • The *y* value decreases and approaches zero but does not reach zero as the *x* value increases. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.2). • There is a relationship (directly proportional) between the mass of an object and the strength of the gravitational forces on it (e.g., three times as much mass produced three times as much force whether it was measured on or above Earth or the Moon). (CCC: 1.4; DCI: PS2.B.1) • Earth produces larger gravitational forces than the Moon. (SEP: 5.2; DCI: PS2.B.1) **2.A.3 When to check for understanding:** At the end of day 3, after completing the copy of https://docs.google.com/forms/d/1jFVInZdCB4gqYLqNoVqq_S1jMYIgPuauX76VAgkv8Ns/copy **What to look/listen for in the moment:** See *Exit Ticket Key*. **2.B When to check for understanding:** When students use the information presented in the *Calculating Gravitational Forces* handout to calculate the force experienced by objects that have collided with Earth and objects that remain in orbit **What to look/listen for in the moment:** Documentation of all the steps to using the universal law of gravitation to solve for gravitational force between two objects (SEP: 5.3; CCC: 3.5; DCI: PS2.B.1, PS2.B.2) This could look like the following: • Writing the universal law of gravitation and the known variables, values, and units for G, m_1, m_2, and r • Substituting the known values into the corresponding location and order for the variables in the general equation • Performing the related calculations using order of operations • Reporting a predicted force value (F_g) in newtons See *Key: Calculating Forces* for sample answers.

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 3	**3.A** Use different models, including a physical manipulative and a computer simulation, to generate data supporting an explanation for how space objects can remain in stable orbits and how their orbits can change. (SEP: 2.6; CCC: 7.1; DCI: ESS1.B.1) **3.B** Use algebraic thinking to examine scientific data generated with a computer model to predict the effect of changes in the radius (a) on the period of revolution of an object in orbit around the Sun. (SEP:2.6; CCC: 3.5; DCI: ESSB.1)	**3.A. When to check for understanding:** At the end of day 1, when students write an explanation about how the relationship between distance, gravitational force, and velocity affects the motion of space objects **What to look/listen for in the moment** • Use evidence about velocity, distance, and gravitational force obtained from the physical and computer simulations to support their explanations. (SEP: 2.6; DCI: ESS1.B.1) • Account for the stability and change of orbits by describing the relationship between gravitational force and velocity. (CCC: 7.1; DCI: ESS1.B.1) • Use evidence to describe how the distance of an orbiting object influences the relationship between gravitational force and velocity. (SEP: 2.6; CCC: 7.1; DCI: ESS1.B.1) **3.B. When to check for understanding:** At the end of day 2, when students complete their data collection using the simulation **What to look/listen for in the moment:** As students work with the simulation tools to generate and record data, look for the following indications that they are making accurate measurements and calculations: • The values of both period (T) and radius (a) for Earth are 1. (SEP:2.6; CCC: 3.5; DCI: ESSB.1) • For orbits larger than Earth's, T/a is greater than 1. (SEP:2.6; CCC: 3.5; DCI: ESSB.1) • For orbits smaller than Earth's, T/a is less than 1. (SEP:2.6; CCC: 3.5; DCI: ESSB.1) • They describe the meaning of Kepler's third law in terms of the distance between the planet and the Sun and its period of revolution. (DCI: ESSB.1) • Changes in a cause exponential growth in T. (CCC: 3.5) • An object 3.5 AU from the Sun would take about 6.5 Earth years to complete one orbit. (CCC: 3.5) See *Kepler's 3rdLaw Key* for sample responses to all questions on *Kepler's Third Law*.

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 4	**4.A** Develop and revise a model based on evidence of the orbital features of space objects to explain why space objects can collide with Earth, highlighting the limitations of the model in predicting future collisions. (SEP: 2.3; CCC: 4.4; DCI: ESS1.B.1)	**4.A.1 When to check understanding:** On day 1, when students complete questions on part 4 of *Orbital Shapes* **What to look/listen for in the moment** • Develop a model that shows the orbits of Earth (low eccentricity) and a comet (high eccentricity). (SEP: 2.3; DCI: ESS1.B.1) • Include the Sun, Earth, and the comet in their model. (SEP: 2.3) • Use the model to describe how the shape of the orbit can influence the potential for a collision between Earth and a comet. (SEP: 2.3; DCI: ESS1.B.1) • Mention parts of the orbits, such as the semimajor axis, the eccentricity, or the location of Earth and the comet at different times, as information needed to make more-accurate predictions of a potential collision. (SEP: 2.3; CCC: 4.4; DCI: ESS1.B.1) **4.A.2 When to check understanding:** On day 2, when students develop a model of the Peekskill meteor and describe the limitations of this type of model to predict a future collision between Earth and a space object. **What to look/listen for in the moment** • Include evidence of the eccentricity of the orbits of Earth and the Peekskill meteor in a model of the orbits of each space object. (SEP: 2.3; DCI: ESS1.B.1) • Include different elements in the model, including the Sun, Earth, and the Peekskill meteor. (SEP: 2.3) • Use the model to show how the orbits of Earth and the Peekskill meteor help explain why these objects collided. (SEP: 2.3; DCI: ESS1.B.1) • Describe the limitations of this type of model to predict a potential collision between Earth and a space object with more accuracy, including lack of information about the actual position at different points in time, the velocity of the objects, or the plane of the orbits. (CCC: 4.4)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 5	**5.A** Develop and use an energy transfer model that illustrates how energy flows and is conserved within an elliptical orbital system between the orbiting object and the gravitational field. (SEP: 2.3, 5.2; CCC: 5.1, 5.3; DCI: ESS1.B.1, PS2.B.1, PS3.A.2, PS3.B.2)	**5.A.1 When to check for understanding:** As students are completing *Orbital Energy Transfer* and when reviewing their work after collecting it **What to look for/listen for in the moment** • Students mention where energy is transferred to when the orbiting object slows down. (CCC: 5.3; PS3.B.2) • Students mention where energy is transferred from when the orbiting object speeds up. (CCC: 5.3; PS3.B.2) • Students consider the forces acting on the orbiting object at different points and how the magnitude of the forces changes with distance. (PS2.B.1) • Describe how these forces can cause energy transfer in or out of the object according to the direction of the motion of the object. (PS2.B.1, PS3.B.2) **5.A.2 When to check for understanding:** As students are completing *Energy Transfer Investigation* and when reviewing their work after collecting it **What to look for/listen for in the moment** • Students develop a mathematical energy transfer model that shows an equal amount of energy transfer between the field and the object. (SEP: 2.3, DCI: PS3.B.2) • Students use their mathematical energy transfer model as evidence to show that the asteroid-Sun system is closed because there is an equal amount of energy transfer between the field and the asteroid. (SEP: 2.3, 5.2, CCC: 5.1, DCI: PS3.B.2, PS3.A.2) • Students use their mathematical energy transfer model as evidence to show that Kepler's law is valid because the object experiences high and low kinetic energy points along its path (SEP: 2.3, 5.2, DCI: ESS1.B.1, PS3.A.2) • Students identify that they can use their mathematical energy transfer models to predict where and how fast an orbiting object will be along its path. (SEP: 2.3, DCI: ESS1.B.1, PS3.B.2)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 6	**11.A** Develop models of the forces due to gravitational interactions from Jupiter and forces from collisions with other space objects and use these models to predict how the orbit of the Chelyabinsk meteor can be changed by different types of force interactions in space to evaluate our working model of space collisions. (SEP: 2.3, 4.5; CCC: 4.4; DCI: ESS1.B.1, PS2.B.1)	**11.A.1 When to check for understanding:** At the start of the lesson (**slide C**) **What to look/listen for:** • Students model a 2 body system with the Chelyabinsk meteor and Jupiter that can result in a redirection of the Chelyabinsk meteor (SEP 2.3,DCI: PS2.B.1) • Students are using an arrow facing toward Jupiter to model the gravitational force on the Chelyabinsk meteor from Jupiter. (SEP: 2.3; DCI: PS2.B.1) • Students label the force on the Chelyabinsk meteor from Jupiter as the force of gravity. (SEP: 2.3, DCI: PS2.B.1) • Students predict that the force they modeled will result in the Chelyabinsk meteor speeding up or slowing down and moving slightly more in the direction of Jupiter (a wider orbit than expected). (SEP: 2.3, DCI: ESS1.B.1, PS2.B.1) • Students predict that the force they modeled will result in minimal changes in the speed and direction of Jupiter. (SEP: 2.3 DCI: ESS1.B.1, PS2.B.1) • Students model a collision with an asteroid that will result in a change of the orbit of the Chelyabinsk meteor to be in the direction towards Earth. (SEP: 2.3; DCI: ESS1.B.1) • Students identify the force that results in the change in orbit to be a collision or impact force. (DCI: ESS1.B.1) • Students identify that our models inherently cannot be entirely accurate due to the limitations of our understanding in scale, our inconsideration of other space objects, and/or the precision in the changes in motion for the Chelyabinsk meteor. (CCC: 4.4)
Lesson 7	**Transfer Task PE: HS-PS2-4** Use mathematical representations of Newton's Law of Gravitation ~~and Coulomb's Law~~ to describe and predict the gravitational ~~and electrostatic~~ forces between objects**.** (SEP: 2.3, 5.2; DCI:PS2.B.1, PS2.B.2, PS3.B.2, ESS1.B.1; CCC:1.1, 3.5)	**Transfer Task:** **When to check for understanding:** When you administer *Changing Asteroid Orbits*. This assessment is not building toward a lesson-level performance expectation. It is designed to assess a performance expectation from the NGSS (HS- PS2-4). **What to look/listen for in the moment:** See *Key: Changing Asteroid Orbits* for responses.
Lesson 8	**8.A** Develop and use a mathematical model based on a function fit to data to predict the number, frequencies (proportions), kinetic energy, and scale of potential destruction from meteors of different sizes reaching Earth in the near future and the rate of such events in the past (SEP: 5.2; DCI: ESS3.B.1, PS3.B.3; CCC: 3.1).	**8.A.1 When to check for understanding:** When students are calculating the kinetic energy of the meteor (**slide H**) **What to look for/listen for in the moment** • Students accurately determining the frequency of larger-mass meteors reaching Earth in the past (SEP: 5.2; ESS3.B.1; CCC: 3.1) **8.A.2 When to check for understanding:** When students are calculating the kinetic energy of the meteor (**slide K**) **What to look for/listen for in the moment** • Students accurately applying the equation for kinetic energy and then converting these numbers into the equivalency decided on by the class to quantify the scale of destruction. In the example we use a WWII-era nuclear bomb as a real-life unit representing something powerful enough to destroy a city and wreak havoc on human life. (SEP: 5.2; DCI: PS3.B.3; CCC: 3.1)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 9	**9.A:** Ask questions that arise from using a mathematical model to predict the relative frequency, scale, and significance of impact or collisions from large meteors on the history of our planet and identify sources of evidence needed to answer these questions. (SEP: 1.2; CCC: 3.1; DCI: ESS1.C.2)	**9.A.1 When to check for understanding:** When students record a question on a pink sticky note (**slide B**) **What to look/listen for:** A question that arises from using a mathematical model on how the size or mass of meteors affects the frequency, scale, and significance of impacts or collisions. (SEP: 1.2; CCC: 3.1; DCI: ESS1.C.2) **9.A.2 When to check for understanding:** When students record a question on a yellow sticky note (**slide D**) **What to look/listen for:** A question that arises from using a mathematical model on how other factors related to scale (such as speed and density) or type of meteor material or impact location on Earth affect the significance or outcomes of impacts or collisions. (SEP: 1.2; CCC: 3.1; DCI: ESS1.C.2) **9.A.3 When to check for understanding:** When students record an idea for an investigation or data we could use on a green sticky note (**slide E**) **What to look/listen for:** Identifying investigation ideas or data that could provide evidence needed to answer questions about how the characteristics of meteors affect the frequency, scale, and significance of impact or collisions. (SEP: 1.2; CCC: 3.1; DCI: ESS1.C.2) **9.A.4 When to check for understanding:** When students record the sorts of data we would need to answer two new questions on a blue sticky note (**slide G**) **What to look/listen for:** Identifying sources of data that could provide evidence needed to answer questions about the impact or significance of meteor collisions across the history of our planet. (SEP: 1.2; CCC: 3.1; DCI: ESS1.C.2)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 10	**10.A** Plan an investigation in groups and as a class to produce data to serve as the basis for evidence regarding the relationship between the kinetic energy of the impactor and the size of the crater it produces and how changes in the mass and velocity of the impactor do not have equal effects on its kinetic energy. (SEP: 3.1; DCI: PS3.B.4; CCC: 1.5) **10.B.** Apply the correlation coefficient to analyze the relationship between changes in the mass and velocity of an impactor and the size of the crater it produces and use these ideas to refine an explanation about the changes in matter and energy within the meteor-Earth system. (SEP: 4.2, 4.5; DCI: PS3.B.4; CCC: 1.5, 5.2)	**10.A.1 When to check for understanding:** On day 1, when students are asked to design one protocol to change the velocity and one protocol to change the mass of the impactor **What to look/listen for in the moment** • Include how to change the independent variable (velocity or mass of the impactor), the variable that will be controlled (mass or velocity of the impactor), and the measurements that will be collected about the dependent variable (crater size). (SEP: 3.1; DCI: PS3.B.4; CCC: 1.5) **10.A.2 When to check for understanding:** At the end of day 1, after students have recorded the results of their investigations in their small groups **What to look/listen for in the moment** • Use *Lab Data Sheet* to record the data. (SEP: 3.1) • Include at least two trials for each height or mass tested. (SEP: 3.1) • The variation in the data lies within an acceptable margin. (SEP: 3.1) **10.B.1 When to check for understanding:** On day 2, when students use the correlation coefficient to analyze the results from the Crater Size Investigation **What to look/listen for in the moment** • These graphs help us see that increases in the velocity and mass of the impactor result in larger craters (larger volume). (SEP: 4.2; CCC: 1.5) • The velocity of the impactor has the strongest relationship with the crater size, as reflected by the coefficient of correlation. This means that the size of the crater is better explained by the velocity and/or kinetic energy of the impactor. (SEP: 4.2; DCI: PS3.B.4; CCC: 1.5) **10.B.2 When to check for understanding:** On day 2, students will revise their explanation for the changes in matter and energy in the meteor-Earth system. **What to look/listen for in the moment:** Look for the revised explanation to include the following elements: • Differences in the kinetic energy of a small and a large meteor due to their mass (SEP: 4.5; CCC: 1.5, 5.2) • Changes in the surface due to the kinetic energy of the meteors (SEP: 4.5, DCI: PS3.B.4; CCC: 1.5, 5.2) • Some of the energy is transferred to the surroundings as sound and heat. (SEP: 4.5; CCC: 5.2) • The initial kinetic energy of the large meteor results in more heat in the system upon surface impact, which vaporizes the meteor, while the kinetic energy of a small meteor does not result in enough heat to vaporize it. (SEP: 4.5; DCI: PS3.B.4; CCC: 5.2) • Matter from the meteor vaporizes, so it might disperse throughout the surroundings. Some matter from the surface is ejected out to the surroundings. Some matter on the surface is broken down and may be vaporized as well. (SEP: 4.5; CCC: 5.2)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 11	**11.A** Apply scientific ideas and principles related to changes in matter and energy to provide an explanation for why much of the matter that makes up the objects that enter Earth's atmosphere end up not leaving an impact on the surface. (SEP: 6.3; CCC: 3.1, 5.2; DCI: PS3.A.2, PS3.A.4)	**11.A.1 When to check for understanding:** In the individual explanation students construct for the question on **slide K** **What to look/listen for in the moment:** Students do the following: • Apply the ideas outlined in the assessment guidance box related to changes in matter and energy and any force interactions that would have caused these. (SEP: 6.3, DCI: PS3.A.2, PS3.A.4) • Accounting for where all the missing matter could have gone to in Earth's systems. (CCC: 5.2) **11.A.2 When to check for understanding:** In the whole class discussion of the two questions on **slide L** **What to look/listen for in the moment:** Students explain changes in the scale of the fragments reaching the planet's surface (smaller mass, slower speed) results in less kinetic energy and/or less momentum and therefore would result in no (or negligible) damage or effects. (PS3.A.2, CCC: 3.1)
Lesson 12	**12.A** Analyze empirical evidence to identify patterns in cratering on solar system objects without atmospheres that can support claims about the changes in cratering activity on Earth. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2)	**12.A When to check for understanding:** On day 1, while students discuss patterns observed in image data and their corresponding inferences as well as during the following Turn and Talk about how these connect to their models **What to look for/listen for in the moment:** Look for students to discuss the following ideas: • Connections between specific empirical observations from the data and patterns across the set of crater images (CCC: 1.5; DCI: ESS1.C.2) • The surface of planets and moons without an atmosphere is covered by craters of different sizes, from small to very large ones. (CCC: 1.5; DCI: ESS1.C.2) **12.A.2 When to check for understanding:** On day 2, when students analyze crater frequency data from the Moon **What to look for/listen for in the moment** • Use the graphs to identify patterns of the crater activity on the Moon throughout time, highlighting periods of increasing, decreasing, or relatively constant crater activity. (DCI: ESS1.C.2; CCC: 1.5) • The frequency of large meteors was much higher around 4.5 billion years ago and has been decreasing ever since. (DCI: ESS1.C.2; CCC: 1.5) • The frequency of small and medium-size meteors has fluctuated over the Moon's history. (DCI: ESS1.C.2; CCC: 1.5) **12.A.3 When to check for understanding:** Towards the end of day 2, when students write claims about the frequency of cratering activity on Earth **What to look/listen for in the moment** • The frequency of small meteors approaching Earth has changed over time, and it is currently higher than the frequency of medium-size and large meteors. The frequency of small craters on the Moon and the frequency of objects entering Earth's atmosphere support this claim. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2) • The frequency of large meteors hitting Earth was much higher 4.5 billion years ago. This is supported by the frequency of large craters on the Moon. (SEP: 4.1; CCC: 1.5; DCI: ESS1.C.2)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 13	**13.A** Use a small-scale model to illustrate how erosion, acting over long periods of time, can alter the evidence of cratering activity on Earth's surface. (SEP: 2.3; DCI: ESS1.C.2; CCC: 3.2) **13.B** Read scientific literature to determine how geological processes over long periods of time can help explain the stability of the Moon's surface as it compares to Earth's changing surface. (SEP:6.4, 8.1; DCI: ESS1.C.2; CCC: 3.2, 7.1)	**13.A When to check for understanding:** On day 1, when students use the physical model of erosion to test their ideas. **What to look/listen for in the moment** Look for students to do the following: • Use a physical model to illustrate the effect of erosion or other Earth processes on craters over time. (SEP: 2.3; DCI: ESS1.C.2) • Discuss the differences in the timescale between the physical model and the real Earth surface system. (CCC: 3.2) **When to check for understanding:** On day 2, when students complete their reading individually and record their ideas on their assigned handout **13.B.1 What to look/listen for in the moment** • Students annotate the reading and apply their understanding of Earth's processes to the timeline graph of Earth's cratering history. (SEP:8.1; DCI: ESS1.C.2; CCC: 3.2, 7.1) • Make a claim about the period of time (scale) over which a geologic process has altered the surface of Earth. (SEP:6.4; DCI: ESS1.C.2; CCC: 3.2, 7.1) **13.B.2 When to check for understanding:** At the end of day 2, when students write an explanation about the difference between the surfaces of the Moon and Earth **What to look/listen for in the moment** • Include information from the readings about how plate tectonics, erosion, weathering, glaciation, and accretion contribute to the change in Earth's surface at different scales. (SEP:8.1; DCI: ESS1.C.2; CCC: 3.2, 7.1) • Explain why the lack of these mechanisms on the Moon help preserve cratering evidence on its surface. (SEP:6.4; DCI: ESS1.C.2; CCC: 7.1) • Explain how different geologic processes on Earth have erased evidence of cratering activity. (SEP:6.4; DCI: ESS1.C.2; CCC: 7.1)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 14	**14.A** Read scientific literature to determine the central ideas and summarize the different changes in earth systems due to the Chicxulub meteor impac and their effects on different types of organisms and ecosystems across different spatial and temporal scales by paraphrasing them in simpler but still accurate terms. (SEP: 8.1, CCC: 2.4, DCI: ESS1.C.2) **14.B** Compare and evaluate competing arguments for different mechanisms for how energy was transferred and matter changed across different earth systems as a result of the formation of the Chicxulub crater. (SEP: 7.1, CCC: 5.2, DCI: PS3.A.2) **14.C** Develop and revise a model to provide a mechanistic account of how energy was transferred and/or matter was changed by the formation of the Chicxulub crater in such a way that it resulted in the extinction of certain types of organisms (change) and not others (stability) 65 million years ago. (SEP: 2.3, CCC: 5.2, 7.1, DCI: PS3.A.2, ESS2.A.3)	**14.A When to check for understanding:** Split students into group before having them read and annotate their assigned articles. Have students add their ideas to the fourth column of *Extinction Evidence Organizer*, and then report a summary to their group at two different points in the lesson • **(slide F)** • **(slide K)** **What to look/listen for:** See *Extinction Evidence Organizer Key*. **14.B When to check for understanding** 1. Students individually read and annotate at two different points in the unit. **(slides O and S)** 2. Students in small groups argue for (or against) a new mechanism that could help answer our question. **(slides P and T)** **What to look/listen for** 1. Underlining or highlighting parts of the text that provide a new idea for how energy transfers could have been affected through other earth systems (CCC: 5.2) 2. Arguing for (or against) a new mechanism related to our question (SEP: 7.1, DCI: PS3.A.2, ESS2.A.3) **14.C When to check for understanding:** After students complete their individual model **(slide Y)** **What to look/listen for:** See *Mass Extinction KEY*.
Lesson 15	**15.A** Revise an explanation based on valid and reliable evidence to answer Driving Question Board questions that involve explaining the stability and/or change in the motion of space objects, the frequency of meteor collisions, and Earth's surface. (SEP: 6.2; CCC: 5.2, 7.1; DCI: ESS1.B.1, ESS1.C.2, PS2.B.1, PS3.A.2)	**15.A When to check for understanding:** At the beginning of the lesson, when students revise the Driving Question Board **What to look for/listen for in the moment** • Look for students to use multiple sources of evidence to explain the motion of space objects, falling or orbiting, and their stability and change over time, using matter changes and interactions, forces acting on matter, and/or energy flow. (SEP: 6.2; CCC: 7.1; DCI: ESS1.B.1, PS2.B.1, PS3.A.2) • Listen for students to use multiple sources of evidence to explain how geologic processes, acting over a long time, may change early rock records on Earth. (SEP: 6.2; CCC: 5.2, 7.1; DCI: ESS1.C.2, PS3.A.2) **Transfer Task PE: HS-ESS1-6** Apply scientific reasoning and evidence from ancient earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history. (SEP: 6.4; DCI: ESS1.C.2, PS1.C.1, PS2.B.1; CCC:5.2, 7.1)

Lesson-Specific Teacher Materials

Lesson 1: Answer Key 1

Initial Consensus Models

First initial model of the Chelyabinsk event

Develop two models to explain our observations from the Chelyabinsk event.
Use pictures, symbols, and words to show what you think was happening to the rock
A) after the rock has entered Earth's atmosphere and
B) when a part of it (meteorite) hit Earth's surface.

Look/listen for these ideas in frame A:

- **Matter changes**
  - Pieces of the rock are changing by some combination of breaking off, melting, burning, or vaporizing.
  - There could be controversy on the path of the larger pieces of matter (straight or curved).
- **Energy**
  - The pieces of matter of the meteor and what is coming off of it are heating up (temperature increases).
  - These temperature increases are resulting in light radiating off the matter (of the rock).
  - There is uncertainty around whether the air too may be heating up around the rock.
  - Sound is produced and energy is transferred to the surroundings (as a shockwave) as it travels through the atmosphere and when it explodes.
- **Forces**
  - Gravity acts on the meteor.
  - The idea of air resistance (possibly as a type of friction) may come up, and it may raise controversy of whether this is force acting on the rock. The idea that it is pushing against the direction of motion of the rock may come up, but there may be some uncertainty around this.

Look/listen for these ideas in frame B:

- **Matter changes**
  - The solid ground (permanently) deforms (or is cratered) where some pieces hit.
  - Pieces of the ground might break up and/or be kicked up and/or pieces of rock might also be kicked up after the collision (e.g., bounce away from the impact site).
- **Energy**
  - Energy transfer may come up here, though it is less likely to be the main theme. If it comes up it may be in reference to ideas established in the *Electricity Unit* and to the pieces of rock or ground kicked up and/or to breaking bonds in anything this permanently deformed.
  - Sound is produced and energy is transferred to the surroundings (as a shockwave) as it travels through the atmosphere and when it explodes.
- **Forces**
  - Collision and contact forces act on the rock and the ground during the collision between them (equal and opposite). Gravity acts on any pieces of the matter (rock or ground or water) that are thrown back up into the air.

First initial model of space objects' motion

Use pictures, symbols, and words to show what you think is happening in outer space that helps explain

- why some objects remain in orbit.
- why some objects hit Earth.

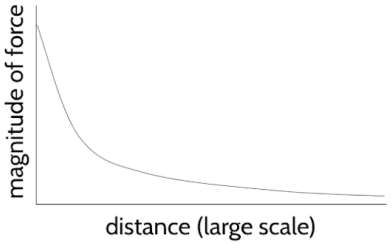
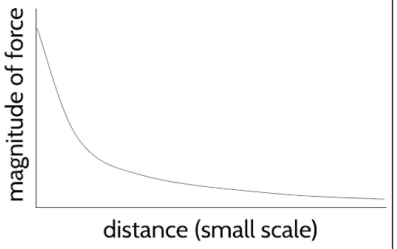
Look/listen for these ideas:

- **Matter changes**
  - The meteor was a single piece of matter.
  - There could be controversy around whether the rock was on a straight or curved path toward Earth.
  - That Earth was moving too, but it was following a curved path (its orbit)
  - Mention about the distance between Earth and orbiting object
- **Energy**
  - That the rock had KE
  - That Earth had KE (may or may not be mentioned)
- **Forces**
  - Gravity acts on the meteor, but there is likely to be controversy around where it starts acting on it.
  - That the direction that gravity acts on the rock is towards Earth
  - Mention of the magnitude of the force(s) acting on the orbiting object

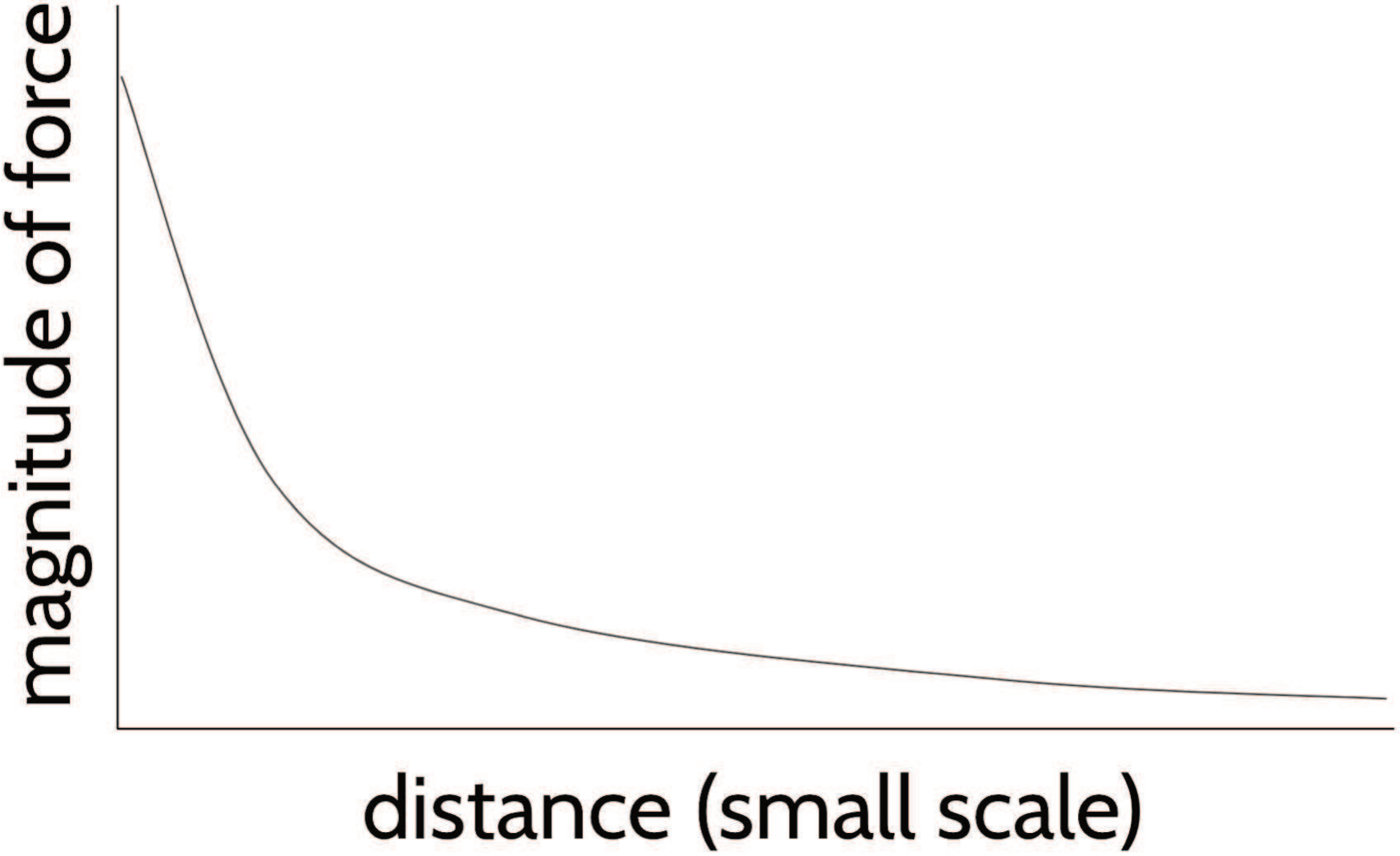
Lesson 2 Posters

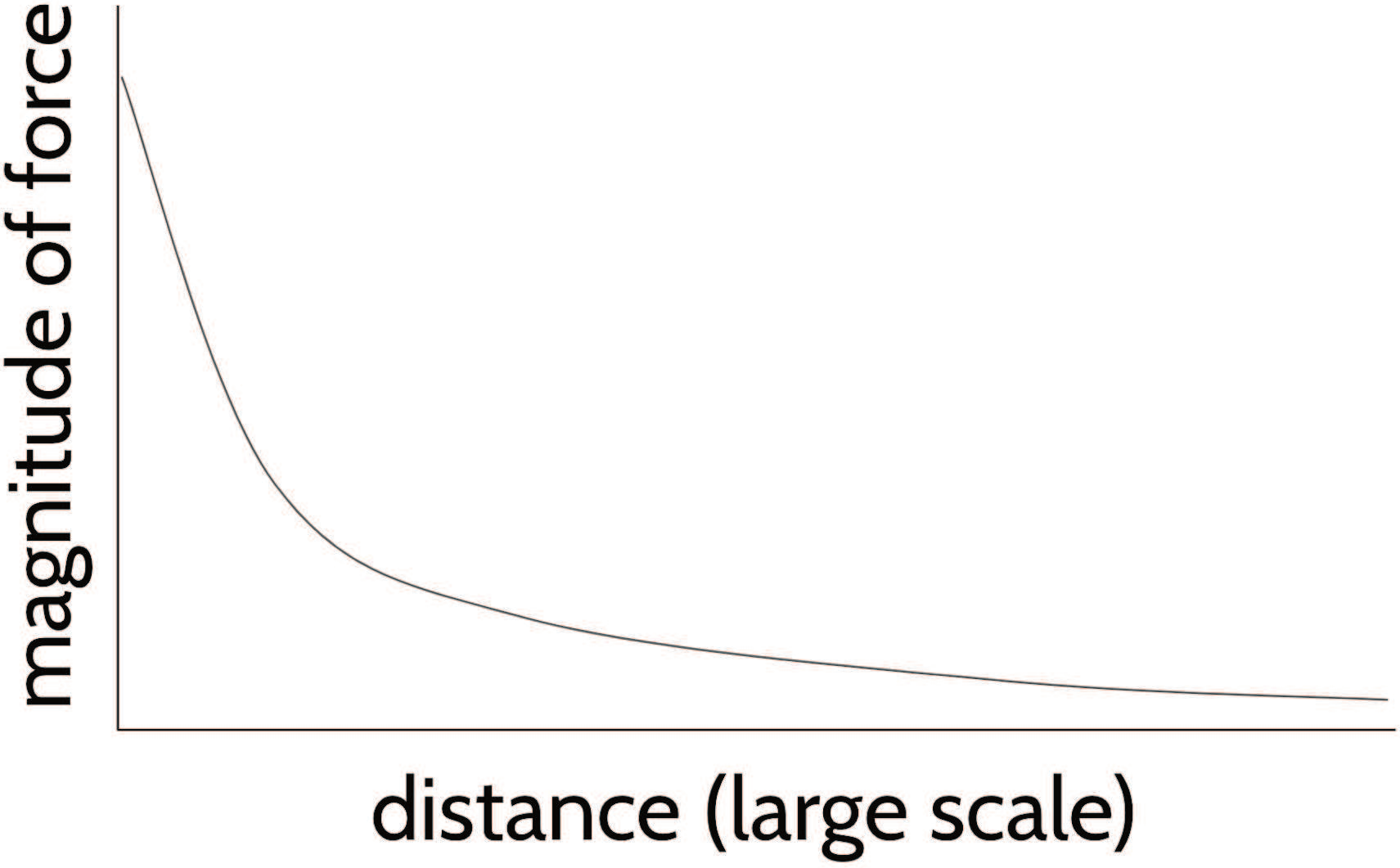
This is how the *Gravity-Magnetism Comparison* poster will look at the end of this lesson:

Gravity-Magnetism Comparison

	Gravitational	Magnetic
Direction of these forces on other matter (in the space where we are located)	Towards the center of Earth	Earth's magnetic north
Type(s) of matter it acts on	All matter	Magnets and some metals
What produces it?	All matter	Some magnets, changing electric fields, Earth's mantle
Magnitude of force vs. distance from Earth		

You can print or draw on half-sheet papers the following images:

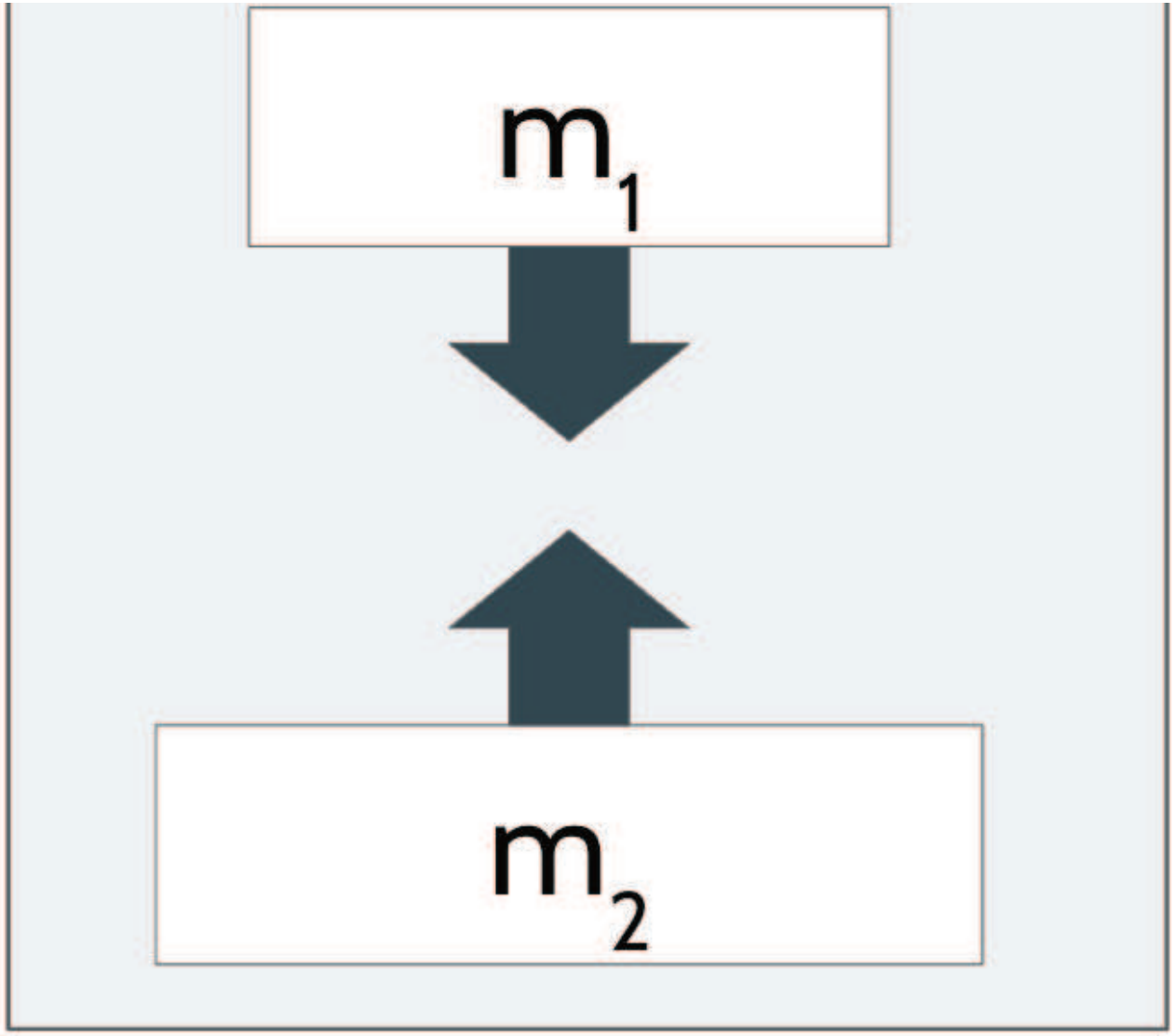



magnitude of force
distance (large scale)

This is how the *Newton's Third Law for Forces at a Distance* poster will look like at the end of this lesson:

Newton's Third Law for Forces at a Distance

When two pieces of matter (m_1 and m_2) interact through a field force like gravity, magnetism, or electricity, the forces between them are equal in magnitude and opposite in direction.


m_1
m_2

Lesson 2: Teacher Reference 2

Magnet Investigation Stations

Follow these directions to construct a Magnetic Force vs. Distance Investigation station. Each group will require one station, so calculate the number needed for your largest class. For each station, you will need the following materials:

- 2 neodymium magnets in the following groupings: 2 large magnets: 1A, 1B, 1C; 1 small and 1 large magnets: 2A, 2B, 2C, 3A, 3B, 3C (note that the B and C groups are optional depending on class size)
- 5 wooden cubes (1.26 x 1.26 x 1.26 in)
- 30 wood circles (1.5 x 1.5 x 0.12 in)
- 1 wood stick (1.0 x 12 x 0.5 in)
- transparent tape
- wood glue
- sticky putty
- 1 digital scale

Building the magnet beams

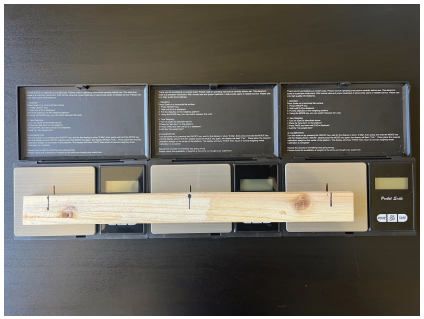
1. Place three digital scales next to each other as shown on the image. Then, use a permanent marker to mark the center of the stainless steel plate on each digital scale.



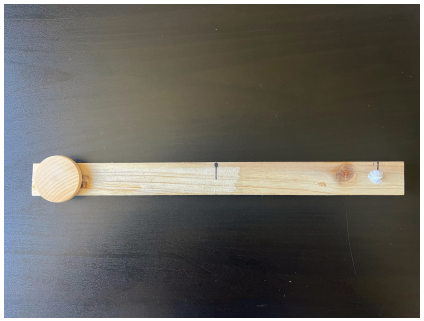
2. Draw a mark at the center of the 12-inch stick.



3. Position the stick so that the mark you made aligns with the mark on the stainless steel surface of the middle scale. Then, use the marks on the stainless steel surfaces of the side scales to draw two additional marks near each end of the stick that align with the marks on the side scales.



4. Use the marks at the ends of the stick to align and glue on 2 circles. Make sure the center of the wood circle aligns with the mark on the stick. Repeat this so each group's stick has two wood circles glued on a side.



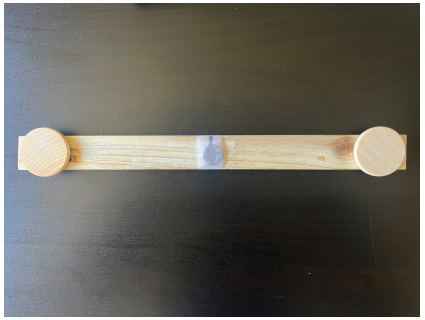
5. You need to define a specific direction to orient the magnets before gluing them to the wood to ensure that they produce attractive forces with the other magnet that will be used in the investigation. To do so, mark one side of a large magnet. Stack another large magnet on top of this one. This may cause it to flip and reorient as it stacks. This is good as it ensures that the same pole of the magnet is facing toward you as the first magnet. Mark the same side of this magnet. Repeat this until you have the stack of large magnets all marked on the same side. Once you are done labeling enough large magnets for all groups, stack and mark the small magnets in the same manner. Add the first small magnet on top of the marked face of the large magnet stack, allowing it to flip if necessary. Mark the upward-facing side of the small magnet. Stack and mark small magnets until there are enough for all groups.



6. Peel a small, marked magnet off the top of the stack and glue it to the center of a stick, with the marked side facing down against the wood, on the same side as the wood circles. Once the glue has dried, wrap a piece of tape around the magnet to secure it to the stick. This tape will help ensure that the magnet remains attached to the wood. Repeat this step until one third of the sticks have a small magnet mounted to each.

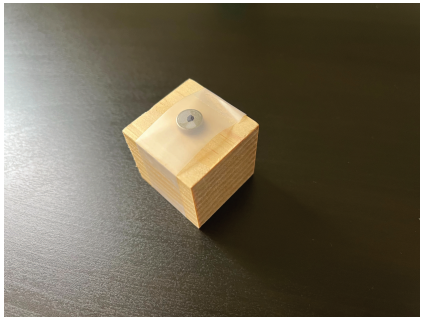


7. Peel a large, marked magnet off the bottom of the stack and glue it to the center of a stick, with the marked side facing down against the wood, on the same side as the chips. Once the glue has dried, wrap a piece of tape around the magnet to secure it to the stick. Repeat this step until two thirds of the sticks have a large magnet mounted to each.

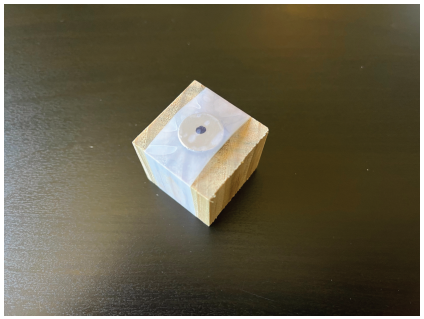


Building the magnet base

8. Peel a marked small magnet off the stack and glue it to the center of a side of the wood cube with the magnet's marked side facing up so it is visible when you attach it to the wood. Once the glue has dried, wrap a piece of tape around the magnet to secure it to the wood cube. This tape will help ensure that the magnet remains attached to the wood. Repeat this step until you have enough small-magnet bases for one third of the groups.

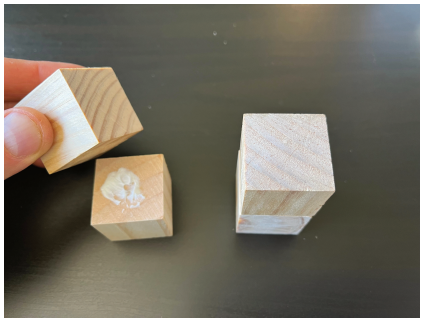


9. Peel a marked large magnet off the stack and glue it to the center of a side of the wood cube with the magnet's marked side facing up so it is visible when you attach it to the wood. Repeat this step until you have enough large-magnet bases for two thirds of the groups.

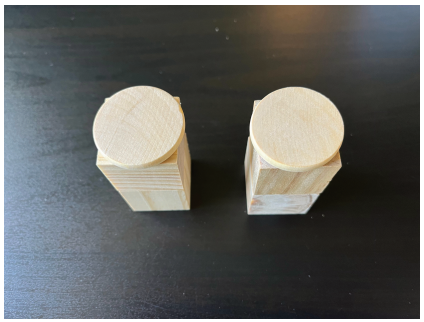


Building the beam support and labeling each station

10. Glue two wood cubes together (without magnets).



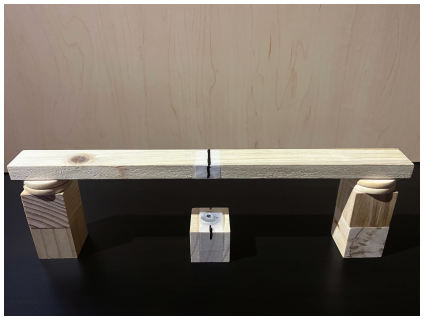
11. Orient the glued cubes so the longest side is vertical. Glue a circle chip to the center of the top face of each cube stack, so it looks like the image.



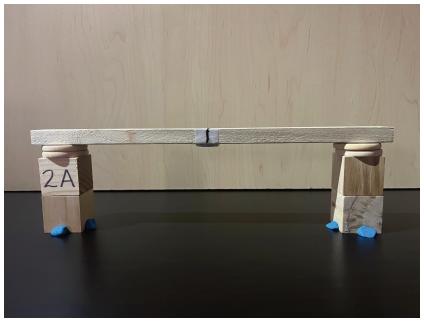
12. Repeat steps 10 and 11 to make enough supports to have 2 at each station. Label two supports for each station with one of these codes: 1A, 2A, 3A, 1B, 2B, 3B, 1C, 2C, 3C. Select and label for each station a beam and a base magnet cube according to the following assignments: Group 1A: large magnet on base and large magnet on beam Group 2A: large magnet on base and small magnet on beam Group 3A: small magnet on base and large magnet on beam Group 1B: large magnet on base and large magnet on beam(optional) Group 2B: large magnet on base and small magnet on beam(optional) Group 3B: small magnet on base and large magnet on beam(optional)



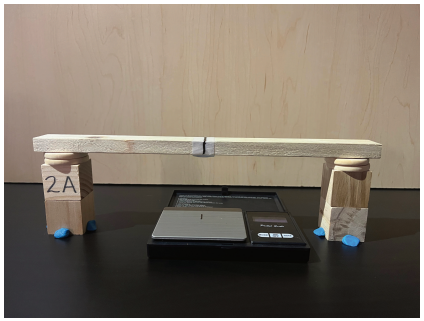
13. Mark each beam and base with the center location of each magnet so that the mark is visible along the side and on top of the beam and the base. This will allow students to more easily line up the magnets with each other.



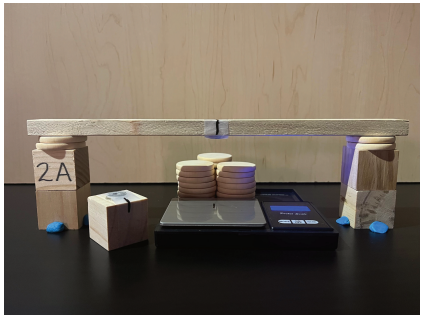
14. Set up the supports and assigned beam for each station so that the circle chips on the beam and both supports line up. Use sticky putty to secure the supports to the table top in these locations.



15. Slide a digital scale beneath the beam. Groups will only need one scale for this investigation.



16. Leave an additional 26 loose circle chips at each station (26 loose + 4 secured = 30 circle chips total per station).



Lesson 2: Teacher Reference 3

Alternate Live Demonstration

These are the directions for doing this demonstration live rather than using the video provided in the *Teacher Guide*: https://youtu.be/fBvELBBHH_4.

You will need the following materials:

- 2 beam supports (see *Magnet Investigation Stations*)
- 1 magnet base with small magnet
- 1 magnet bean with a large magnet
- 3 digital scales
- 3x3 sticky notes
- Permanent marker

1. Place a stand on each outer scale. Tare the scales with the stands on them. Tell students that this helps ensure that we cancel out the effects of the force of gravity from the masses on the scales.



2. Balance the beam with the large magnet on one of the stands and have a student report its weight. Record this on a sticky note.



3. Move the beam over so its circle chips are aligned with and resting on the circle chips on both stands. Have students report what each of the two scales under the stands now reports. Record these on a sticky note.



4. Ask students why the two values reported on each scale would appear to sum (add up) to the value reported when the beam was on a single scale. Students should say the weight is now distributed. Emphasize that the total downward force on the matter above the system can be measured by adding the two measurements from both scales together.

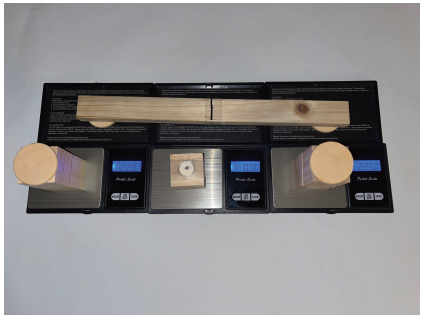
5. Zero both scales and emphasize that zeroing both now removes the contribution of the force of gravity on this beam from what the scales will register so that any changes in the numbers they display are due to additional forces. You may need to toggle the power on and off to zero out the force currently on the scale.



6. Remove the beam.



7. Set the base magnet cube with a small magnet on the scale. Emphasize that now the scale is registering a force from gravity acting downward on it. Point out that the value it is registering is positive.

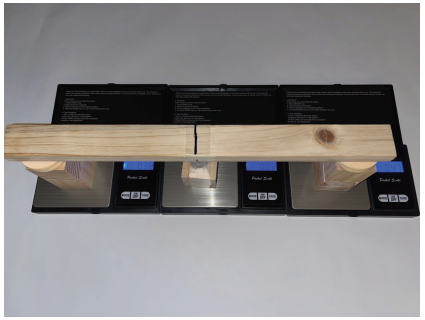


8. Zero the scale, emphasizing that this will take out (or remove) the contribution of that force on the entire cube and magnet.



9. Say, We are now going to measure the forces between each of these magnets when we bring them about 1 inch apart. To do that we will need to compare what we see reported on this middle scale to the two values reported on these other two scales.

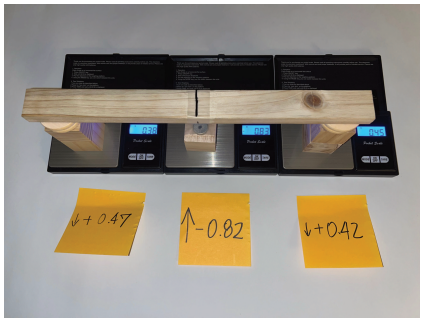
10. Move the beam over so its circle chips are aligned with and resting on the circle chips on both stands. Shift the cube on the middle scale so the mark on it is lined up with the one on the beam above it.



11. Ask students to read off the value of the middle scale and whether it is negative or positive. Students will report a negative value. Write this value on a sticky note and put it near the middle scale. Say, This indicates that the scale is detecting an upward force on it now. Let's see how that compares to the forces on the other two scales.



12. Ask students to report the two values from each of the scales under the beam supports and whether they are positive or negative. Students will report positive values. Write each of these values on half of a sticky note.



13. Establish that equal and opposite forces are acting on both magnets. Compare the values recorded on the stickies. Ask students what they notice about the magnitude of these three force values. The sum of the second two magnitudes (approximately) equals the magnitude of the first force. If you add up the second measurement of two forces, they would cancel out the first force.

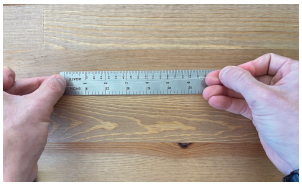
Lesson 2: Teacher Reference 4

Making Impactors

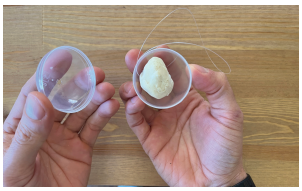
Weigh the two capsule halves plus the clay, making sure the total mass is 20 grams or 40 grams.



Use the nylon string to create a loop that is approximately 6 inches long. Make a knot where the ends meet.



Place the end with the knot and the remaining nylon string inside the two capsule halves, along with the clay.



Bring the capsule halves together until you hear a click and then pull the nylon string taught.



Lesson 2: Answer Key 1

Key: Calculating Forces

Universal Law of gravitation

$$F_g = G\left(\frac{m_1 * m_2}{r^2}\right)$$

Values for *G* for different units of measure used

$6.67 * 10^{-11} \frac{N * m^2}{kg^2}$	$6.67 * 10^{-17} \frac{N * km^2}{kg^2}$	$6.67 * 10^{-5} \frac{N * m^2}{g^2}$

Use the information in the table to calculate the force of gravity exerted between Earth and the space object assigned to you.

Space object	Mass	Distance from center of Earth	Force of gravity between Earth and space object
International Space Station (in orbit)	$4.45 * 10^5$ kg	$6.8 * 10^3$ km	$3.8 * 10^6$ N
Vanguard 1 (in orbit)	1.46 kg	Closest: $7.0 * 10^3$ km	$1.2 * 10^1$ N
		Farthest: $1.0 * 10^4$ km	$5.8 * 10^0$ N
Mir space station (collided with Earth)	$1.30 * 10^5$ kg	Closest: $6.7 * 10^3$ km	$1.2 * 10^6$ N
		Farthest: $6.8 * 10^3$ km	$1.1 * 10^6$ N
Skylab (collided with Earth)	$7.50 * 10^4$ kg	$6.8 * 10^3$ km	$6.4 * 10^5$ N
* The mass of Earth is 5.97×10^{24} kg.			

Show how to use the equation to predict the amount of force for your assigned condition based on the table above. Document in the following table each of the steps for setting up the equation, substituting known values, and performing the correct order of operations using this equation.

Space object in orbit you are calculating for:	Space object that collided with Earth that you are calculating for:

Force of gravity between International Space Station and Earth

Given:

$m_1 = 4.45 * 10^5$ kg

$m_2 = 5.97 * 10^{24}$ kg

$r = 6.8 * 10^3$ km

$$F_g = \frac{(6.67 * 10^{-17}\ N*km^2/kg^2) * (4.45 * 10^5\ kg) * (5.97 * 10^{24}\ kg)}{(6.8 * 10^3\ km)^2}$$

$$F_g = \frac{1.77 * 10^{14}\ N*km}{4.62 * 10^7\ km^2}$$

$F_g = 3.8 * 10^6$ N

Force of gravity between Vanguard 1 and Earth (closest to Earth)

Given:

$m_1 = 1.46$ kg

$m_2 = 5.97 * 10^{24}$ kg

$r = 7.0 * 10^3$ km

$$F_g = \frac{(6.67 * 10^{-17}\ N*km^2/kg^2) * (1.46\ *kg) * (5.97 * 10^{24}\ kg)}{(7.0 * 10^3\ km)^2}$$

$$F_g = \frac{5.79 * 10^8\ N*km^2}{4.90 * 10^7\ km^2}$$

$F_g = 1.2 * 10^1$ N

Force of gravity between Vanguard 1 and Earth (farthest to Earth)

Given:

$m_1 = 1.46$ kg

$m_2 = 5.97 * 10^{24}$ kg

$r = 1.0 * 10^4$ km

$$F_g = \frac{(6.67 * 10^{-17}\ N*km^2/kg^2) * (1.46\ *kg) * (5.97 * 10^{24}\ kg)}{(1.0 * 10^4\ km)^2}$$

$$F_g = \frac{5.79 * 10^8\ N*km^2}{1.0 * 10^8\ km^2}$$

$F_g = 5.8 * 10^0$ N

Force of gravity between Mir space station and Earth (closest to Earth)

Given:

$m_1 = 1.30 * 10^5$ kg

$m_2 = 5.97 * 10^{24}$ kg

$r = 6.7 * 10^3$ km

$$F_g = \frac{(6.67 * 10^{-17}\ N*km^2/kg^2) * (1.30 * 10^5\ kg) * (5.97 * 10^{24}\ kg)}{(6.7 * 10^3\ km)^2}$$

$$F_g = \frac{5.16 * 10^{13}\ N*km^2}{4.49 * 10^7\ km^2}$$

$F_g = 1.2 * 10^6$ N

Force of gravity between Mir space station and Earth (farthest to Earth)

Given:

$m_1 = 1.30 * 10^5$ kg

$m_2 = 5.97 * 10^{24}$ kg

$r = 6.8 * 10^3$ km

$$F_g = \frac{(6.67 * 10^{-17}\ N*km^2/kg^2) * (1.30 * 10^5\ kg) * (5.97 * 10^{24}\ kg)}{(6.8 * 10^3\ km)^2}$$

$$F_g = \frac{5.16 * 10^{13}\ N*km^2}{4.62 * 10^7\ km^2}$$

$F_g = 1.1 * 10^6$ N

Force of gravity between Skylab and Earth

Given:

$m_1 = 7.50 * 10^4$ kg

$m_2 = 5.97 * 10^{24}$ kg

$r = 6.8 * 10^3$ km

$$F_g = \frac{(6.67 * 10^{-17}\ N*km^2/kg^2) * (7.50 * 10^4\ kg) * (5.97 * 10^{24}\ kg)}{(6.8 * 10^3\ km)^2}$$

$$F_g = \frac{2.98 * 10^{13}\ N*km^2}{4.62 * 10^7\ km^2}$$

$F_g = 6.4 * 10^6$ N

Lesson 2: Answer Key 2

Exit Ticket Key

Lesson-level performance expectation being assessed

2.A Use simple limit cases and mathematical representations to describe patterns in the change of magnitudes of magnetic and gravitational forces on two objects caused by changes in their distances from each other. (SEP: 5.2, 5.4; CCC: 1.4; DCI: PS2.B.1, PS2.B.2)

3-D elements addressed in this assessment		Q 1	Q 2	Q 3	Q 4	Q 5	Q 6
SEPs	**5.2 Using Mathematics and Computational Thinking** Use mathematical, ~~computational, and/or algorithmic~~ representations of phenomena ~~or design solutions~~ to describe ~~and/or support~~ claims and/or explanations.	X	X			X	
CCCs	**1.4 Patterns:** Mathematical representations are needed to identify some patterns.					X	X
DCIs	**PS2.B.1 Types of Interactions:** Newton's law of universal gravitation ~~and Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic forces~~ between distant objects. (HS-PS2-4)	X	X	X			
	PS2.B.2 Types of Interactions: Forces at a distance are explained by fields (gravitational, ~~electrical, and magnetic~~) permeating space ~~that can transfer energy through space. Magnets or electrical currents cause magnetic fields; electrical charges or changing magnetic fields cause electrical fields.~~ (HS-PS2-4), (HS-PS2-5)			X			

Question 1

The International Space Station (ISS) is only 409 km (about 254 miles) above Earth. This sounds like a lot, but since Earth is 6,371 km (3,959 miles) in radius, the astronauts there are only 6% farther away from the center of Earth than we are!

The force of gravity on a 70-kg astronaut on Earth is 700 N. Which is the best estimate for the force of gravity this astronaut experiences from Earth when they are on the ISS?

- 700 N
- **620 N**
- 720 N
- Close to 0 N

What to look for in response
The correct answer is: **620 N**

Students should determine that since the ISS is at some distance from Earth's surface, it should have a gravitational force on it less than 700 N. However, because the ISS is relatively close to Earth, the drop off should not be particularly great. This can be determined mathematically by using the universal law of gravitation.

What to do: Encourage students to enter values into the equation for gravitational force and then attempt to sketch a proportional image of Earth to see how close the ISS really is to Earth.

Question 2

If the ISS were moved to a distance of 384,400 km from Earth (the same distance between Earth and the Moon), what force would the same astronaut experience from Earth's gravitational pull?

- 720 N
- 620 N
- 10 N
- Close to 0 N

What to look for in response
The correct answer is: **Close to 0 N**

Students should reason that increasing the distance almost a thousand times follows the pattern established in question 1: that the force will be significantly decreased because squaring 1,000 results in 1,000,000, a tiny number.

What to do: Encourage students to calculate and graph question 2 as compared to question 1 so they can visualize how drastically the force falls off at greater distances.

Question 3
Use what you know about gravitational fields to briefly explain why your answers to 1 and 2 are different.
What to look for in response Earth's gravitational field is much stronger close to the planet but gets much weaker farther away as attraction between an object and Earth weakens. **What to do:** Remind students of the connections between gravitational fields and forces.

Question 4
Have you ever felt heavier or lighter than your actual weight, perhaps in an elevator going up or down? What was happening that caused that feeling?
This prompt is intended to help students think about why their work in Lesson 2 will be important. This question should only be a completion grade.

Question 5
Which types of space objects would we expect to experience a larger gravitational pull from Earth? • Small objects that are near Earth • **Large objects that are near Earth** • Small objects that are far away from Earth • Large objects that are far away from Earth
What to look for in response The correct answer is: **Large objects that are near Earth** Large objects near Earth experience a much stronger gravitational pull toward Earth, so they are more likely to hit the planet. **What to do:** Have students examine the equation for gravitational force and test how changing the mass and distance generally impact the force and therefore the potential damage.

Question 6
How did mathematical representations, such as graphs and equations, over the last few periods help you identify patterns that help make sense of gravity acting across space?
What to look for in response **Note: These could be different for each student.** • Students should discuss particular ways in which they used mathematics to identify and make sense of patterns throughout the lesson. • Students should say how a particular mathematical activity or tool helped them figure out something about gravity, for example, how strong it is at different distances. **What to do** If students are struggling to articulate how they used mathematical thinking in their sensemaking, discuss particular ways as a class. These could be • describing patterns in how force and distance between two magnets compare for different sizes of magnets, which helped us make a claim about how a force at a distance can change as objects move apart or • comparing patterns in magnetic fields to those in gravitational fields, which helped us understand how the pattern in gravitational fields is similar to that in magnetic fields.

Lesson 3: Teacher Reference 1

Circular Motion Setup

The circular motion apparatus is relatively easy to make, although it can be time consuming for students to adjust in the middle of an investigation. For this reason we recommend premaking these apparatuses, as described below.

General safety protocols for demonstrations and hands-on activities:

- Wear sanitized safety glasses with side shields or indirectly vented chemical splash goggles during the setup, hands-on, and takedown segments of the activities.
- Ensure all students wear sanitized safety glasses with side shields or indirectly vented chemical splash goggles during the duration of the investigation.
- Secure loose clothing, wear closed-toe shoes, and tie back long hair.
- Provide students with hand sanitizer wipes to use at the completion of the activities.
- Describe the procedures for disposal of materials and cleaning up the work space. .
- Make sure there are no fragile items in the activity zone, especially in the area where the orbiting object is being swung.
- Use caution when working with glass or plastic - sharp ends can cut/puncture skin.
- Wash hands with soap and water or use hand sanitizer wipes immediately after completing this activity.
- Review the safety protocol shown on *Investigating Circular Motion* and **slide K** with the class.

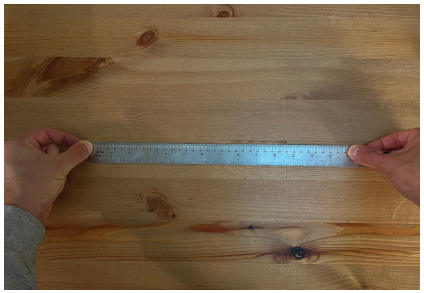
Building the Circular Motion setup
Materials:

- 3 feet of Nylon fishing line
- 1 plastic capsule
- 1 carabiner
- 2 washers
- permanent marker
- plastic tube
- Tape

Take the fishing line and tie a knot, leaving at least 3 inches of string.



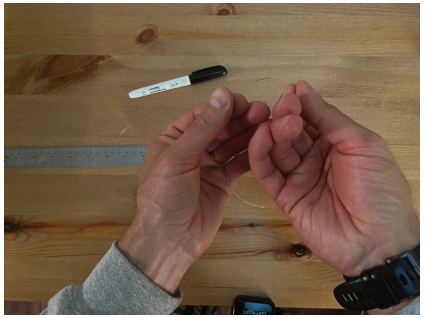
Starting from the knot, measure a piece of string whose length equals the length of the tube plus the radius of the orbiting object. In this picture, the radius used was 20 cm and the length of the tube was 15 cm. Make a mark with a permanent marker at that length.



Make a mark with a permanent marker at that length.

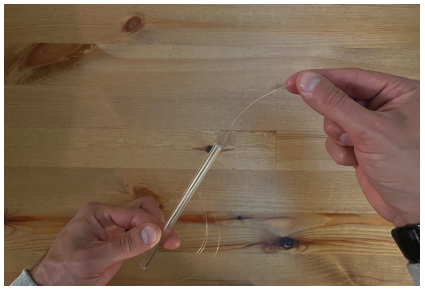


Make sure the mark is easily visible, as students will use it to ensure the radius is constant during their investigation.



Cut the string so the total length from end to end is around 3 feet.

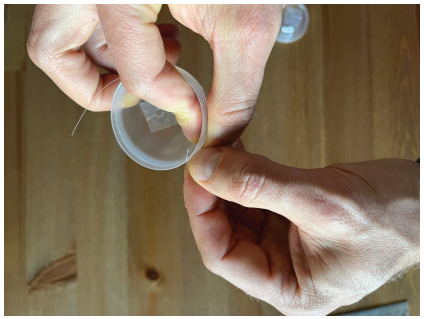
Take the end with the knot close to it and pass the fishing line through the tube.



Take both plastic capsules and place a small piece of tape blocking the hole in each capsule. The purpose of this tape is to block the airflow through it.



Place the 3 inches or so of string inside one of the capsules, making sure the knot is also inside it.



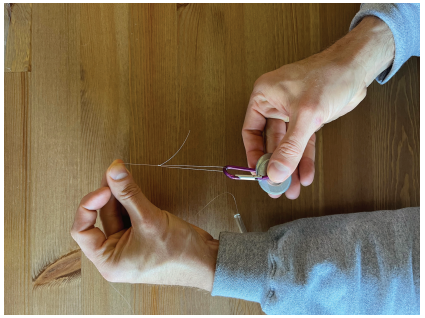
Bring both capsules together until you hear a click sound, making sure the 3 inch end is inside the capsules. This will represent the orbiting object. Lightly tug on orbiting objects to ensure that they are properly attached.



Make a loop on one end of the string and tie a knot on it.



Hang the carabiner with two washers on this loop.



Make an additional setup for each class you have. You will use it during a class demonstration, where it will require cutting the string and thus, rendering it unusable.

Operation

Start circular motion by swinging the orbiting object around slowly, then speeding up until the motion is smooth. Ideally, the marker should hover just below the tube. Ideally, students should swing the orbiting object without too much additional input once it is moving, just a subtle turn of the hand.

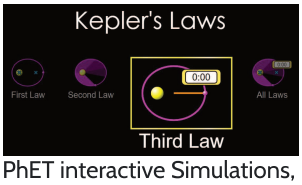
The person swinging the orbiting object is best placed to count the number of swings, as they receive both visual and haptic feedback from the device, so we recommend that the student who is doing the swinging count 20 swings. Meanwhile, a second student keeps time. The first student should tap their foot as a signal to begin the timer, then tap their foot again as a signal to end the timer at 20 swings.

Lesson 3: Answer Key 1

Kepler's 3rdLaw Key

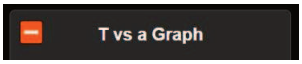
Set up the simulator:
Go to the following link: https://www.openscied.org/simulation/keplers-laws/

Select the "Third Law" screen.



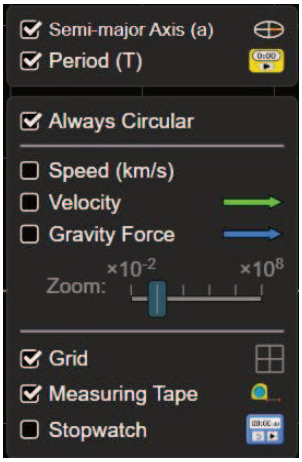
PhET interactive Simulations, University of Colorado Boulder

Minimize the "T vs a Graph" panel (we will use it later).



PhET interactive Simulations, University of Colorado Boulder

In the menu on the right side of the screen, turn on the following options by checking the boxes: Semi-major Axis (a) Period (T) Always Circular Grid Measuring Tape Make sure all other options are unchecked.



PhET interactive Simulations, University of Colorado Boulder

Push the play button at the bottom of the screen to make the planet move in its orbit.



PhET interactive Simulations, University of Colorado Boulder

Part 1: Explore the simulation, using the default orbit created by these settings.

a. What happens when you push the yellow button on the Period tool?
Answers may vary. Accept any answers that describe a measurement of time for the object to travel around the Sun once.

b. Based on this behavior, how would you define the period of an orbit?

The period of an orbit is the amount of time it takes, in years, for the orbiting object to travel around the Sun once and return to its starting point.

c. Take multiple period measurements of the orbit. Record your observations in the data table.

Trial	Label the starting point.	Period, T (years)
Trial 1	Orbit diagrams will depend on the starting point defined by the student. They do not affect the length of the period.	2.83
Trial 2		2.83
Trial 3		2.83

d. Use the Measuring Tape tool to find the length of a. What is this distance? What does it mean?
2.00 AU. This is the radius of the orbit, or the distance between the object and the Sun as it travels around in a circular path.

e. The units on the tape measure are AU, which stands for "astronomical unit." Why do you think we use a special unit to measure distances in the solar system, instead of something like meters or kilometers?
We use AU because the distances in the solar system are so large, if we measured them in meters or kilometers we would need values in the hundreds of thousands (and greater). The units in AU allow us to describe distances with smaller unit quantities and are easier to compare from planet to planet (or object to object) within our solar system.

Part 2: Collect data comparing orbits of planets in our solar system.

You can use the dropdown menu in the "Target Orbit" panel to help you recreate the orbits of Venus and Earth.

a. Use the tools in the simulation to complete the data table:

	Period, T (years)	Radius, a (AU)	Calculate T/a (years/AU)
Default orbit	2.83	2.00	1.41
Earth	1.00	1.00	1.00
Venus	0.59	0.72	0.82

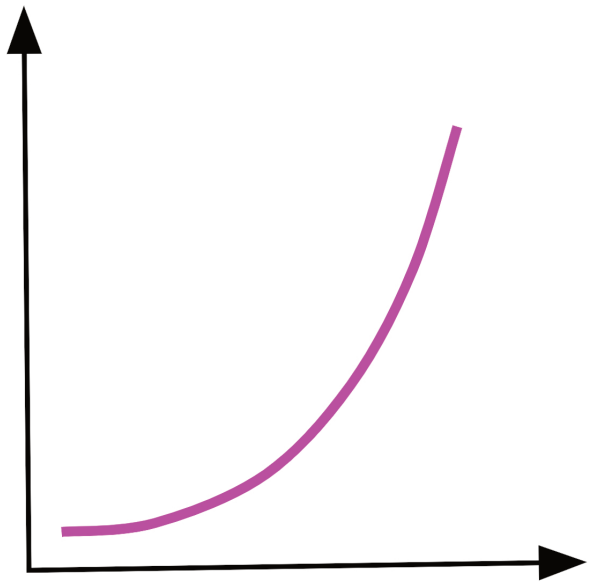
Small variations in these data are acceptable due to the difficulty in positioning the planet precisely on top of the target orbit.

b. What do you notice about the relationship between period, T, and radius, a?
There is a positive correlation between T and a. When one increases, the other does as well.

Part 3: Examine the mathematical relationship between period and radius.

Click the "+" button on the "T vs a Graph" panel to open the graph.

a. Sketch the shape the graph of T/a makes:



b. Describe the effect of a change in radius, a, on the period, T. What type of mathematical relationship is this? Choose one.

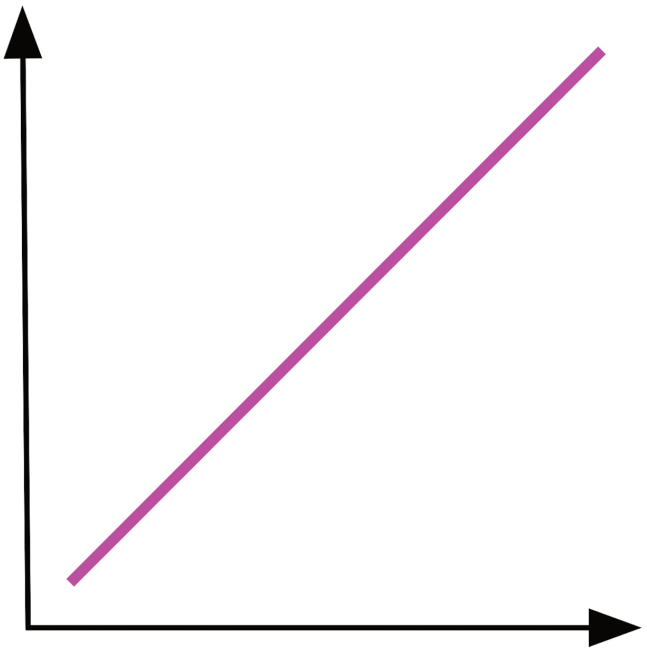
- Linear
- Exponential
- It is quadratic.
- There is no clear relationship.

Justify your choice based on the graph.
For objects in our solar system, T increases faster than a. This is why T/a is greater at larger distances from the Sun. The shape of the graph shows that there is exponential growth, because the line is curving upwards.

c. Use the options on each axis to change the exponent on each variable. Find the combination of exponents that results in a constant ratio for all orbits in our solar system:

$$\frac{T^{2}}{a^{3}} = 1.00$$

d. Sketch the shape of the graph with these exponents:



e. Scientists refer to the relationship between the radius and period that you identified in **questions c** and **d** as Kepler's third law. What does this law tell us about the motion of planets around the Sun?

It tells us that the farther the planet is from the Sun, the longer it takes it to orbit the Sun.

f. Suppose NASA discovers a new asteroid at a distance of 3.5 AU from the Sun. Use the relationship between T and a that you just discovered to determine how long it would take that asteroid to complete one orbit, in Earth years.

$T(\text{years})^2 / a(\text{AU})^3 = 1.00\ \text{years}^2/\text{AU}^3$

$T(\text{years})^2 = a(\text{AU})^3\ \text{years}^2/\text{AU}^3$

$T^2 = 3.5^3$

T = 3.5^(3/2)

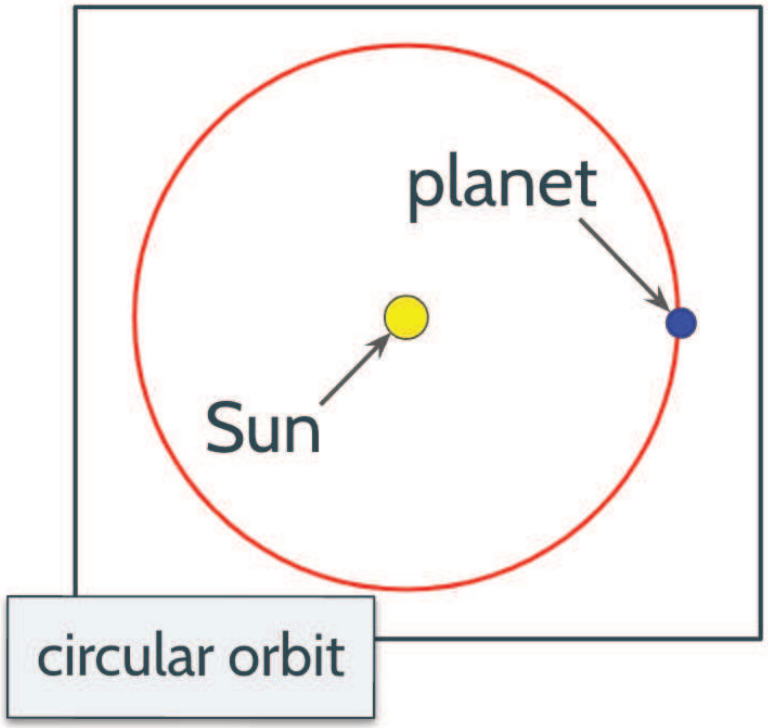
T = 6.5 years

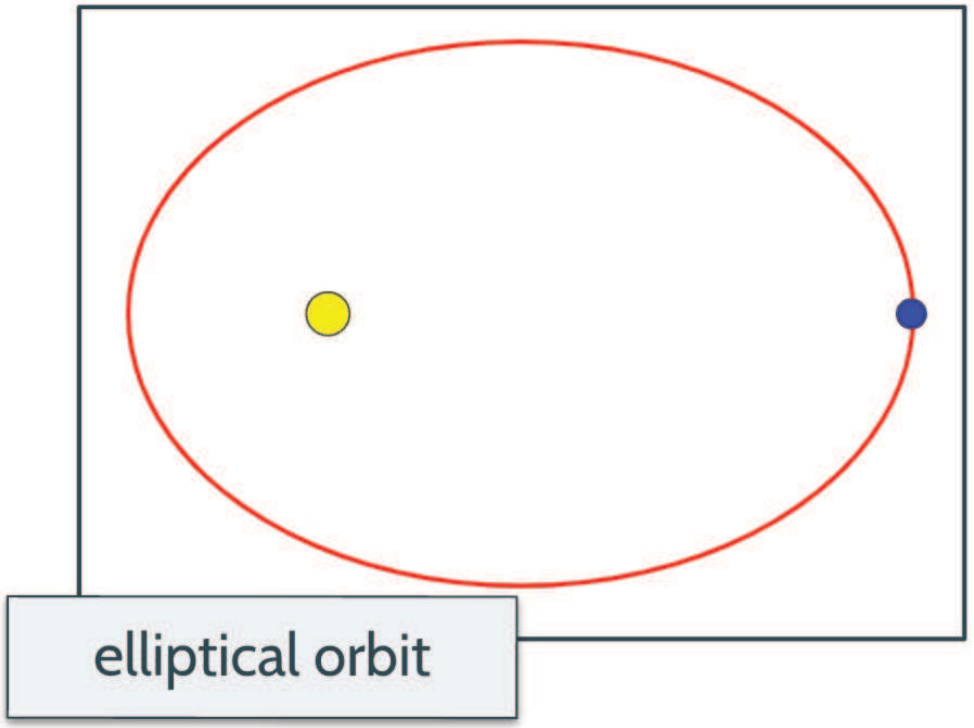
During the mid-unit transfer task, in Lesson 7, students will use similar sensemaking to explain the changes in the orbit of a space object based on data about its period of revolution and semimajor axis (radius). If students are struggling with this last question, consider having them practice using additional examples with varying periods of revolution and radii.

Lesson 4: Answer Key 1

Orbital Shapes Key

Part 1: Identifying noticings about circular and elliptical orbits.



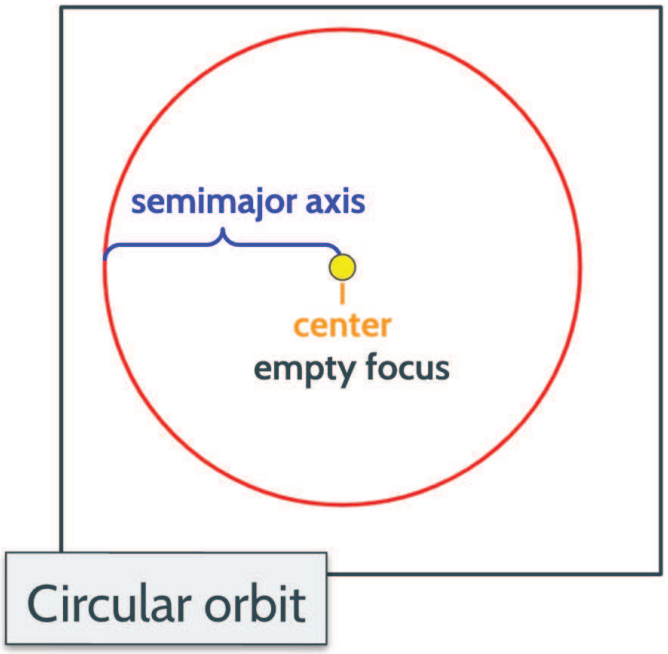


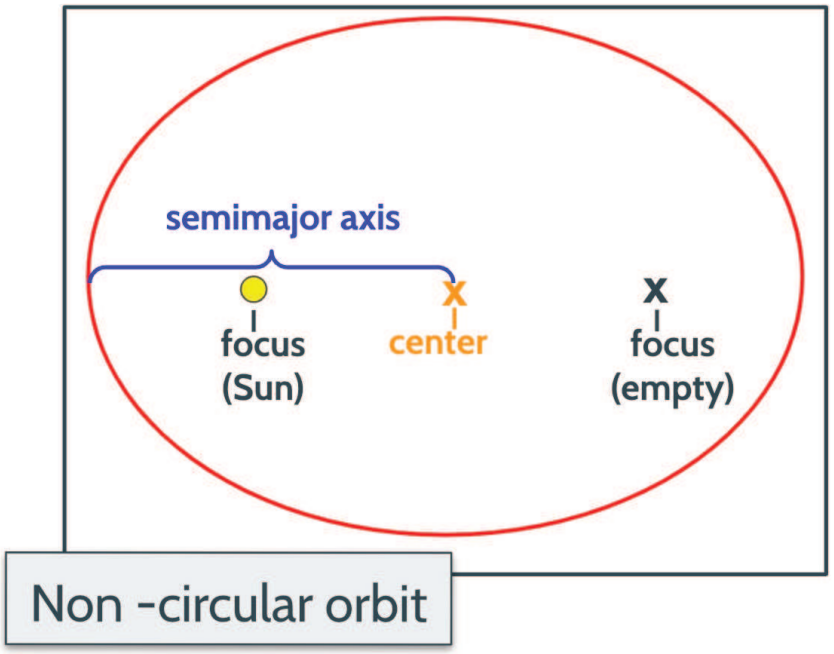
What specific things do you notice are different about these orbits?	If you had to describe what was different about these orbits using quantities, what would you need to measure?

Part 2: Describe orbital shapes.

Scientists use the following terms to describe the orbital paths of space objects:

- **Semimajor axis:** The semimajor axis of an elliptical orbit is like the long radius of the ellipse. In an elliptical orbit, the semimajor axis is half of the longest width.
- **Empty focus (foci):** Think of the empty focus points in an elliptical orbit as two special spots inside the ellipse. In an elliptical orbit, the Sun is located at one of the two foci while the other focus remains empty. In a circular orbit, they are at the center of the circle.
- **Center:** The center of an elliptical orbit is like the middle point of the oval path. It is the same distance away from both foci, meaning it is in the middle between the Sun and the empty focus. In a circular orbit, the more-massive object, such as the Sun, is located in the center.
- **Eccentricity**: Eccentricity is a measure that describes the amount of deviation an orbit has from being circular. The closer the eccentricity is to 1, the less circular the orbit is, and the closer it is to 0, the more circular it is.





Part 3: Model orbit shapes.

You and your partner should have the following materials	
• 2 pushpins • 3 loops of string of various lengths • pencil • calculator	• piece of butcher paper • cardboard sheet • ruler • eraser

Your task is to use these materials to construct physical models of orbits for different objects.

1. **Circular orbit:** Use the following ideas and steps to help you build a circular orbit model.

        - Use one pushpin, the pencil, and one loop of string to construct a shape that looks like a circular orbit.
        - Identify and plot the location of the central body (e.g., Sun).
    - On your constructed orbit, label the following:
        - the point that represents the central body
        - the orbital path
        - the radius (or semimajor axis) of the orbit
        - any additional information or annotations you would like
        - Calculate the eccentricity ratio for this orbit, using centimeters for measurements and the following equation:

$$\text{eccentricity} = \frac{\text{distance between foci}}{2 * (\text{length of semimajor axis})}$$

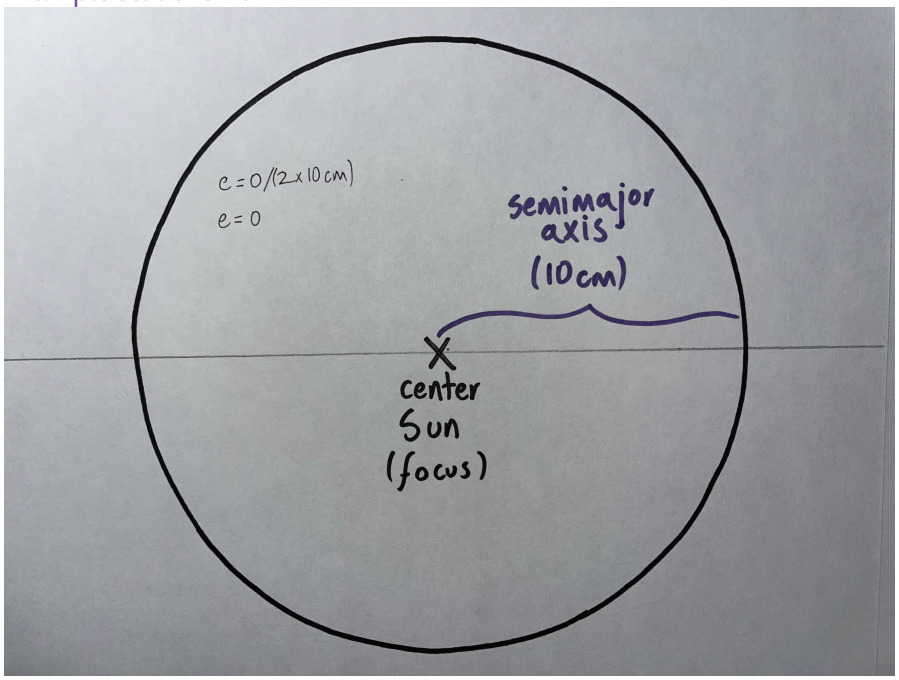
        - What is the distance between foci? (Hint: when there is only one focus, what is the distance from it to itself?): 0
        - What is the length of the semimajor axis? 10 cm, 15 cm, or 21 cm
        - What is the eccentricity of your orbit : 0
        - Label the eccentricity of the orbit on your drawing

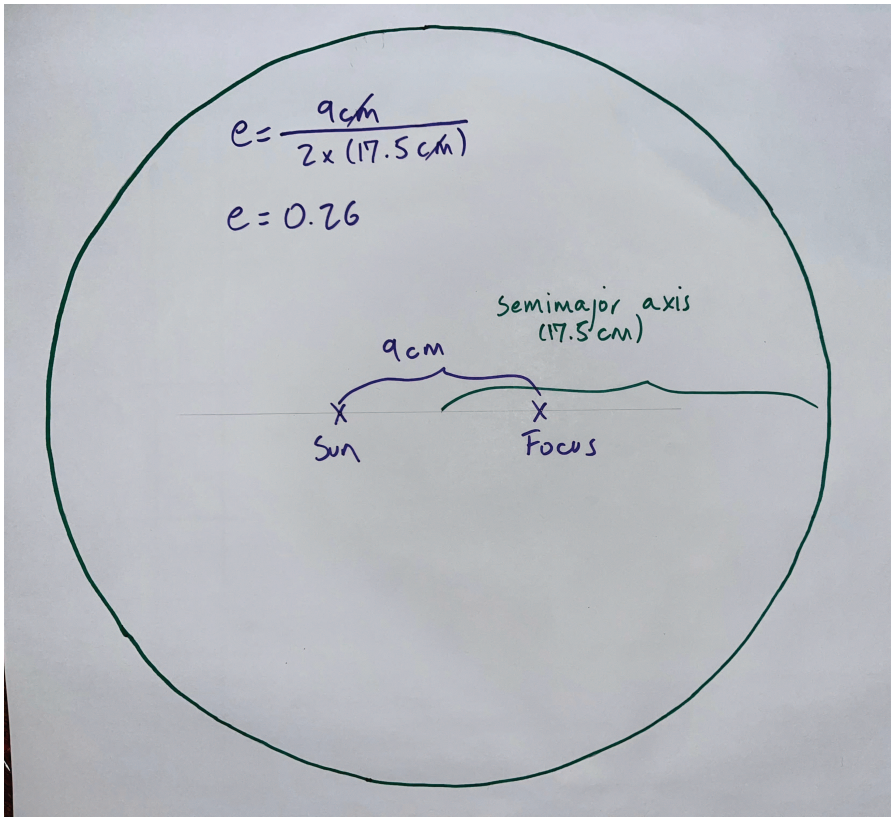
2. **Elliptical orbit:** Decide on three different distances between the foci that you will each use to construct your elliptical orbit models. For example, one student could use a distance of 10 cm between the foci, another 15 cm, and the third 18 cm. On the opposite side of your paper, stick two push-pins into the paper separated by the distance your group assigned to you. Use your materials to construct a shape that looks more like an elliptical orbit. Test your thinking out with your finger in place of the pencil until you create the shape you want to record.
    - Use two pushpins and one loop of string to construct a shape that looks like an elliptical orbit.
    - Things to consider
        - the size of the orbit
        - the overall shape of the orbit
    - On your constructed orbit, label the following:
        - the point that represents the Sun
        - the orbital path
        - the semimajor axis of the orbit
        - the second focus of the orbit
        - any additional information or annotations you would like
        - Calculate the eccentricity ratio for this orbit, using centimeters for measurements and the following equation:

$$\text{eccentricity} = \frac{\text{distance between foci}}{2 * (\text{length of semimajor axis})}$$

- What is the distance between foci? (Hint: when there is only one focus, what is the distance from it to itself?): 9 cm
- What is the length of the semimajor axis? 17.5 cm
- What is the eccentricity of your orbit? 0.26
- Label the eccentricity of the orbit on your drawing

Example student work





3. Use drawings and/or descriptions to compare the two orbital shapes.

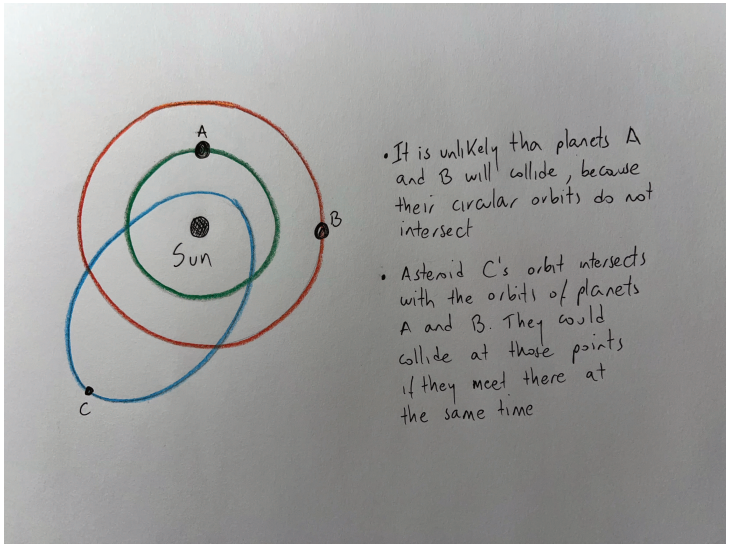
	Planet's Orbit	Comet's Orbit
Shape of orbital path	Circular - the planet is always the same distance from the Sun, which is at the center.	Stretched out (elliptical), where the distance across changes.

Location of foci	The foci are both in the Sun at the center with zero distance between them, and/or there is only one focus.	The foci are near the orbital path, one is on the Sun and the other is out in empty space, far from the Sun.
Location of fun	At the center, where the foci are.	At one of the foci, which is far to one side of the ellipse. Not in the center.
Eccentricity	*Distance between foci = 0 cm* *Semimajor axis (radius) = 10 cm* *Eccentricity = 0/(2*10 cm) = 0*	Distance between foci = 9 cm Semimajor axis = 17.5 cm Eccentricity = 9 cm/(2 * 17.5 cm) = 0.26

STOP once you finish this part. You will complete Part 4 later in the lesson!

Part 4: Develop a model

1. Use words and drawings to show how the shapes, or eccentricities, of the orbits of objects in our solar system influence the likelihood of those objects colliding.

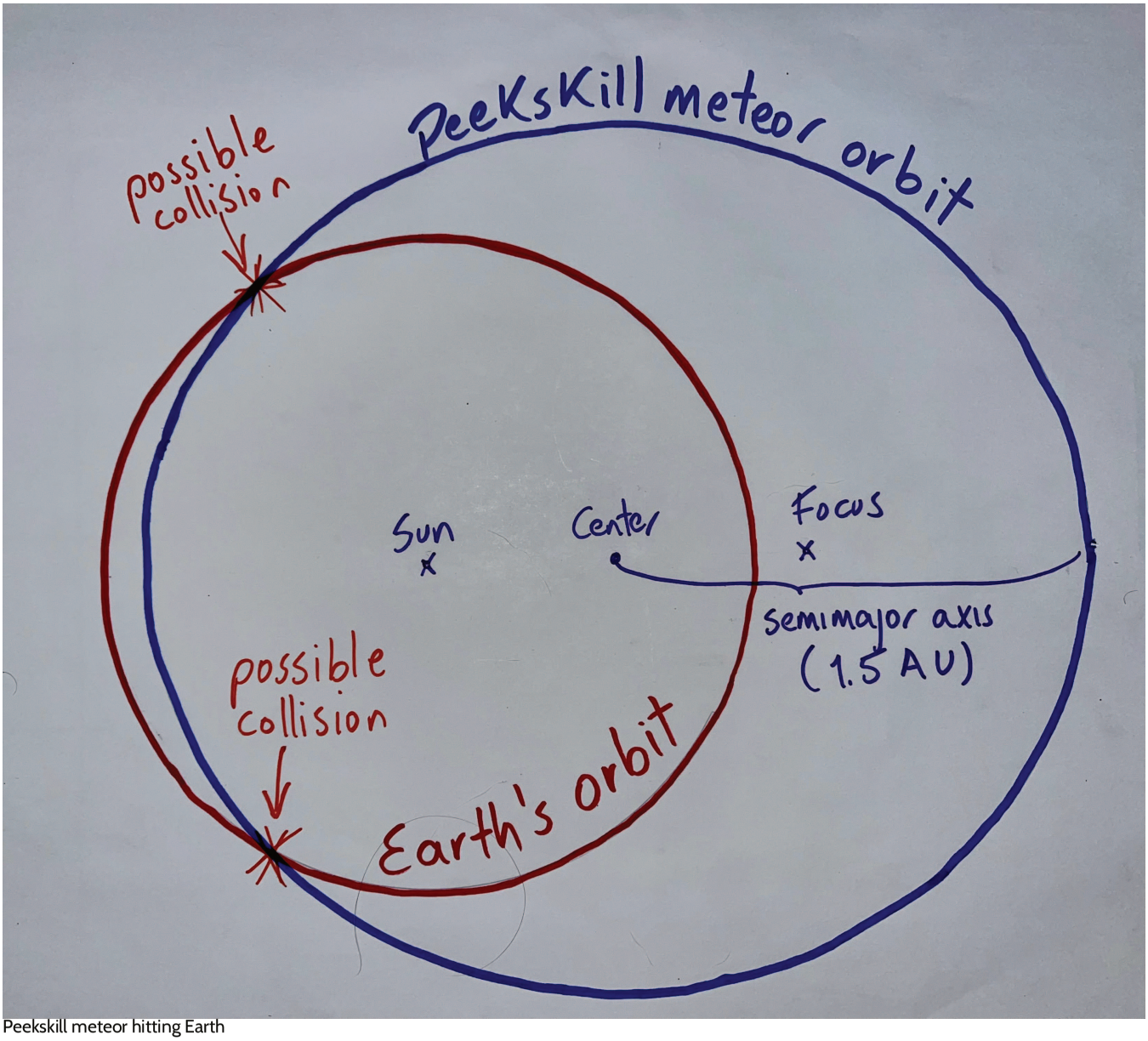


2. What additional information would you need to create a model that predicts with high accuracy the potential of a collision between a comet and Earth?

I would need to know the exact position of the objects over time. That will help me determine if they will meet at the intersection points.

Their orbital period can also help me determine how fast they move, which can help make better predictions too.

Example Collision Model



Peekskill meteor hitting Earth

This model cannot explain exactly where Earth and the Peekskill meteor collided, as there are two points where their orbits intersected. If it occurred at either point, the model cannot specify.

Pendulum Demonstration Protocol

Prepare materials:

- chart paper titled “How can we use fields to help explain where the energy transfers occur in the system when an object gains and loses distance?”
- chart paper titled “Pendulum model”
- chart paper titled “Orbit model”. On this paper, draw the orbit shape from *Energy Transfer Investigation*
- markers
- capsule with weight of 20-80 g
- string of length of 50 cm
- M-E-F poster

Make the pendulum:

- Tie a knot at one end of the string. A square knot works well.
- Put the end of the string with the knot into the open capsule and then close the capsule on the string so it is now a ball.

In general, you just need a simple pendulum that can rock back and forth. You can also use the gif on Slide Q.

Introduce the pendulum model: Say, *We decided it's difficult to investigate where energy is stored and transferred for orbiting space objects for a variety of valid reasons. In science we often use physical models to represent scenarios we cannot necessarily investigate ourselves.* Hold up your pendulum and get it oscillating and say, *This is a pendulum; notice how it goes back and forth. We can use this to understand the energy of orbits. Let's build our energy transfer model as we make sense of the flow of energy for our pendulum so we can apply it to orbits.* Provide each student with a copy of *Energy Transfer Investigation*.	

Make connections to orbits. Present **slide P**. As the pendulum oscillates, use the slide prompts to facilitate a discussion about the connections between the pendulum and orbits:

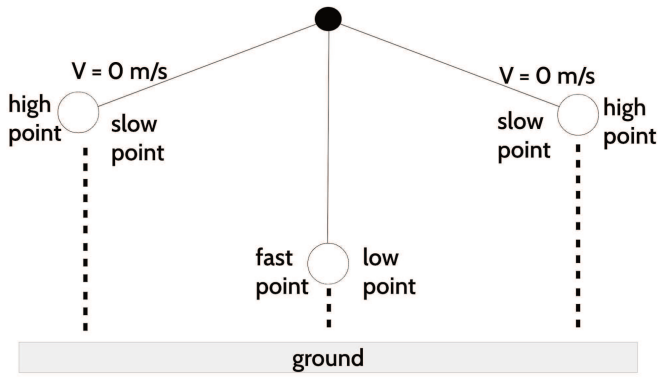
- *What are the similarities between the motion of an orbiting object and of a pendulum?*
- *What are the differences?*
- *What distances are changing in both?*

Look for the following ideas:

- There is a height involved.
- The objects repeat their motion consistently.
- The pendulum is on the Earth while orbital motion is in space
- The height or distance is changing on both

Connect the speed of the pendulum to orbits. Present **slide Q**. Use the slow-motion gif of the pendulum swinging. Say, *Let's think about the speed and kinetic energy of the pendulum and connect it to orbits. What do you notice about this pendulum's kinetic energy?* Students are likely to say that there are slow points with low kinetic energy at the highest heights and a fast point with high kinetic energy at the lowest height.

Say, *Right, there are low and high kinetic energy points.* Using student feedback, identify and draw those low and high points on the "Pendulum model" poster. See the image for guidance.



High and low points

Connect the speed of the pendulum to orbits: Present **slide R.** Use the slow-motion gif of the pendulum swinging. Say, *Let's think about the speed and kinetic energy of the pendulum and connect it to orbits.*

Point at a slow point and ask, *At those slow points, what do you think slowed the pendulum down?* Students are likely to say that gravity slowed it down.

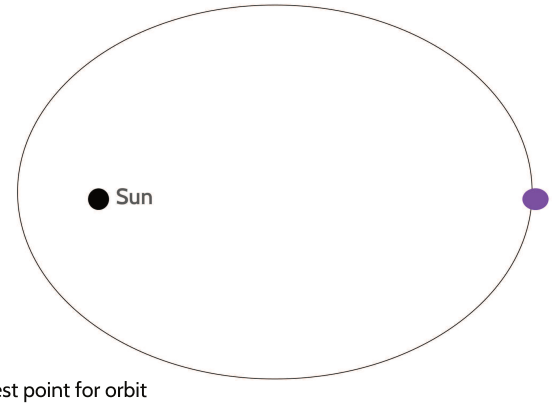
Follow up by asking, *What do you notice about the pendulum's position at those slow points?* Students are likely to say that it is at the highest heights.

Follow up by saying, *Let's try to connect this to orbits. Is there a point on our orbit where the asteroid is at its slowest and has its lowest kinetic energy?*

Look for the following idea:

- Yes, when it is furthest from the Sun.

Draw and label this point on the "Orbit model" poster and have students label on their handout for stage 1 the location of the asteroid where it is moving the slowest along its orbit.



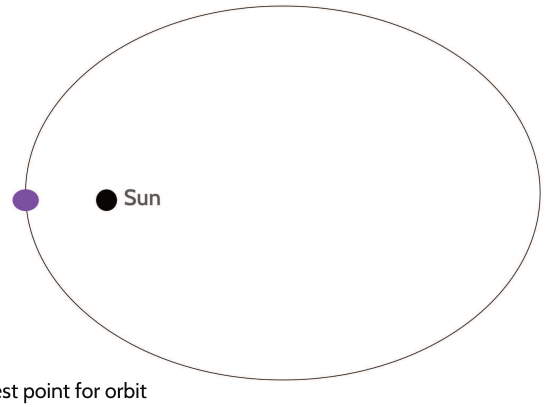
Slowest point for orbit

Point at the identified fastest point on the pendulum drawing. Say, *We identified this point as the fastest point of the pendulum motion and also its lowest distance from Earth. Is there a point in orbital motion when the asteroid is moving the fastest?*

Look for the following idea:

- When the asteroid is closest to the Sun.

Draw and label this point on the "Orbit model" poster and have students label on their handout for stage 2 the location of the asteroid where it is moving the fastest along its orbit.



Fastest point for orbit

Hold the pendulum at a distance that is in between the lowest and highest height, as shown in the image, or point at your drawing in the spaces between the fastest and slowest points. Ask students:

- *What is going on in these sections*?

Look for the following ideas:

- The pendulum is falling on one side while gaining height on the other.
- The pendulum is speeding up on one side while slowing down on the other.

Say, *Right, we know that as the pendulum falls it speeds up, but when it goes up, we can see it slow down. What is happening to the kinetic energy at these points if it can be speeding up or slowing down?* Students are likely to say that it can be gaining kinetic energy or losing kinetic energy.

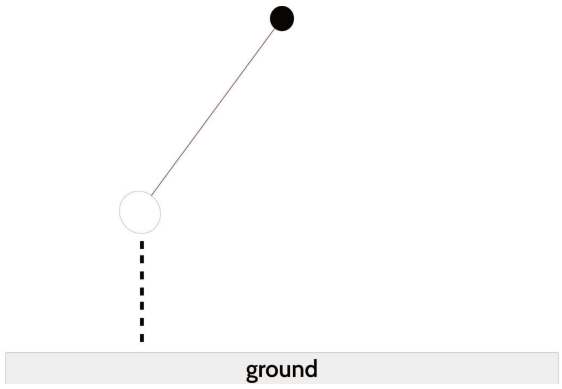
Connect their thinking to orbits by asking:

- *Are there any points in orbital motion when the asteroid might be gaining kinetic energy or losing kinetic energy?*

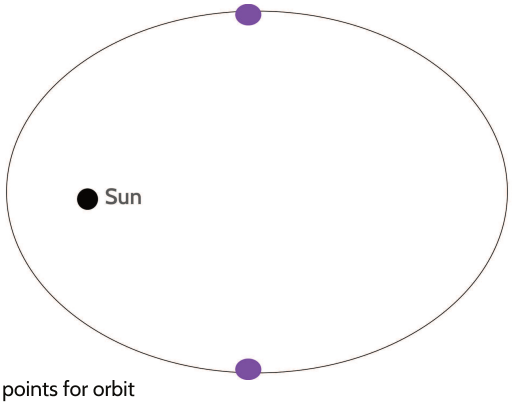
Look for the following idea:

- The halfway points between the furthest point from and the closest point to the Sun.

Draw and label these points on the "Orbit model" poster and have students label on their handout for stage 3 the locations of the asteroid where it is experiencing the same motion as the pendulum. Emphasize that they should label two points where one point is where the asteroid is gaining kinetic energy and another point where the asteroid is losing kinetic energy.



Hold here



Middle points for orbit

Develop an energy transfer/field model. Present **slide S.** Set up the energy transfer model**.** Say, *Because the connections are pretty strong between the pendulum and orbital motion, our understanding of the pendulum's energy will be able to be applied to orbital motion. Let's set the basis for our energy transfer model.*

Ask students, *What are the two masses that are interacting to produce gravitational forces on this pendulum?* Students should identify Earth and the pendulum. Say, *Let's call the pendulum object 1 so we can generalize our model to other scenarios.* Add these to the model as m_1 and m_2 for addition #1.

Follow up by asking, *What do we know about the gravitational forces between the two objects?* Students should say that the forces are equal and opposite.

Say, *Let's put a dotted box around them to indicate they are both part of the same closed system that we are considering. We can say that it is a closed system because we know that matter does not transfer in or out of the system.* Add a dashed-line box around object 1 and Earth as addition #2.

Grab and hold the pendulum still at the highest point. Say, *At this point the pendulum is still for a moment when it turns around and starts going back down. Does the pendulum have kinetic energy at this point? Why or why not?*

Look for the following ideas:

- Yes.
- No, because there's no motion.

Students are likely to say yes but can't justify why they think the pendulum has kinetic energy at that point. If this happens, prompt them with this question:

- *Typically, how do we see energy in an object?*

Look for the following idea:

- Motion shows energy.

Let the pendulum drop and swing down. Ask students, *Is there energy in the system now? What evidence do you have?*
Students are likely to say that the pendulum started moving and sped up.

Ask, *What transferred energy into the pendulum that caused it to move?* Students will identify the gravitational field.

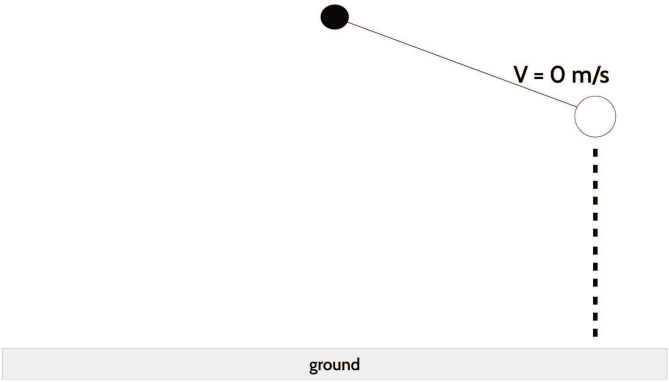
Reference the energy and force legs of the M-E-F poster**.** Point to where it says "unbalanced forces can transfer energy". Say, *Right, we know*

Additions #1 & #2

How can we use fields to help explain where the energy transfers occur in the system when an object gains or loses distance?



PhET interactive Simulations, University of Colorado Boulder



Hold here

that the gravitational field is the only meaningful force that can transfer energy to the pendulum here. Connect this force to orbits by asking students, *What force is transferring energy to the asteroid and making it move in an orbit?* Students should say that it is also the gravitational field.	

Say, *Scientists consider it helpful to think of the field that exists in the space between the two objects as a third part of this system since it can be produced by the interaction of both objects and it can act on both objects.* Add a box labeled "gravitational field between m_1 and m_2" to the system as addition #3.

Say, *Let's think about when the field transfers energy into the object and the gravitational force gets stronger. Is it when the distance decreases or increases?* Students should say:

- When the distance decreases.

Follow up by asking, *What changes in the object do we see as distance decreases and energy transfers to it?* Students should say:

- The object speeds up.

Ask, *How much does the distance affect how much energy is transferred? What will change its kinetic energy more, bigger changes in distance or smaller changes in distance?* Students will say that big distance changes will lead to more energy being transferred.

Add in addition #4 with an energy arrow, change in distance, and change in motion. As you do, say, *We can draw a big arrow to show that the gravitational field is transferring a lot of energy to the object because we have a big change in the speed of the object.*

Connect these ideas to orbital motion. Point to the image of the orbit on the "Orbit model" poster.. *If the asteroid is moving counterclockwise, where along the orbit is the energy being transferred into the asteroid?* Students should say:

- The long section where the asteroid is moving towards the Sun.

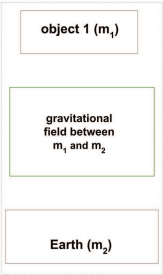
What evidence do you see that shows that energy is being transferred into the asteroid? Students should say that the asteroid speeds up.

Say, *We know that energy transfers from the gravitational field to the pendulum. Is energy also transferring from the gravitational field to Earth?* Students are going to say yes because the gravitational field goes both ways.

If students are struggling to answer this question, remind them that the gravitational field is in between both objects and goes

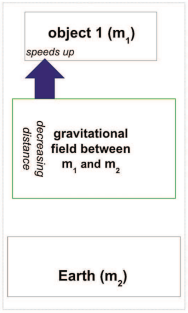
Addition #3

How can we use fields to help explain where the energy transfers occur in the system when an object gains or loses distance?



Addition #4

How can we use fields to help explain where the energy transfers occur in the system when an object gains or loses distance?



equally to both objects.

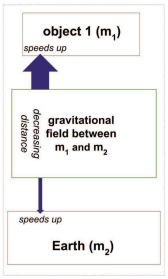
Follow up with, *Do we see big changes in motion for Earth when the distance between the pendulum and Earth decreases?* Students are likely to say no.

Add in addition #5 with a small energy arrow and change in motion. As you do, say, *We can draw a small-sized energy arrow to show that we are transferring a small amount of energy to Earth. We know this because we don't see big changes in motion or distance for it.*

Say, *We have actually seen this type of effect before where we have equal energy and equally strong forces acting on two objects. In our Vehicle Collisions Unit we saw that the less-massed car experienced a greater change in motion while the more-massed one saw little to no changes in its motion.*

Addition #5

How can we use fields to help explain where the energy transfers occur in the system when an object gains or loses distance?



Say, *We have covered the part when the pendulum loses distance, but we have not developed ideas about the going-up portion of the pendulum swing when it gains distance.*

Again, raise the pendulum and then let it swing back and forth a couple of times. Hold the pendulum at its lowest distance and point out that after this point, the pendulum starts to gain distance and eventually reaches the maximum distance where it comes to a stop. Say, *Earlier we decided that after this point the pendulum is losing kinetic energy. Where is the kinetic energy being transferred into?* Students should say:

- It is transferring into the gravitational field.

Follow up with, *What evidence did we have that it was losing kinetic energy?* Students will say that it was slowing down.
Say, *Right, this point is actually the fastest point of the pendulum motion. After this point, the object starts to gain distance from Earth and slows down to a stop. Let's add our ideas to our model.*

Add in addition #6 with an arrow, change in motion, and change in distance.

Connect these ideas to orbital motion by asking students: *Where can we see the asteroid gaining distance from the Sun and transferring its energy into the gravitational field?* Students are likely to say that it is near the point where the asteroid is closest to the Sun.

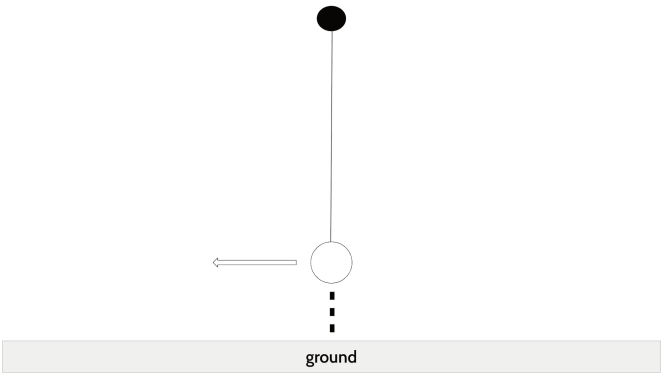
Now connect their energy and motion thinking to the energy and motion of Earth as it gets further away from the pendulum by asking students:

- *What happens to the energy and motion of Earth as it gets further away from the pendulum?*

Students should say that Earth slows down because its kinetic energy is being transferred out.

Follow up by asking, *Does it slow down a lot?* Students will say no.

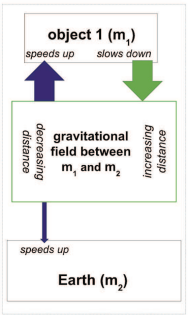
Add in addition #7 with the arrows and changes in motion, saying, *Again we can draw a small energy arrow to show that the gravitational field is transferring a small amount of energy out of Earth because we can see small changes in its motion.*



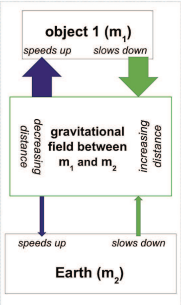
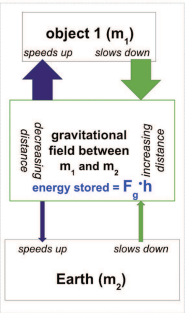
Hold here

Addition #6

How can we use fields to help explain where the energy transfers occur in the system when an object gains or loses distance?



Addition #7

Say, *We can see now that as the pendulum swings back and forth, and as the asteroid goes around its orbit, energy is transferring into and out of the gravitational field. Thinking about the amount of energy that is transferred in and out of the field requires us to keep track of the distance the pendulum falls and rises and when the pendulum speeds up and slows down.* Point out that our energy transfer model for our pendulum shows the flow of energy as it moves. Ask students, *What would we have to change about our model so that we could apply it to orbital motion?* Students are likely to say that it works as is and we would only have to change Earth to be the Sun.	*How can we use fields to help explain where the energy transfers occur in the system when an object gains or loses distance?* 
Introduce stored energy equation. Present **slide T**. Say, *The amount of energy stored in the field relative to Earth's surface can actually be calculated by simply multiplying the height of the object times the force of gravity on it. For Earth the force of gravity is just mass times the gravitational acceleration of 9.81m/s^2, which is known as just g. The force of gravity is that equation because distance changes are not significant enough, but for an asteroid it is a bit more complicated because the force of gravity changes significantly as its distance changes from the Sun.* Add in addition #8 with the stored energy equation to the center.	Addition #8 *How can we use fields to help explain where the energy transfers occur in the system when an object gains or loses distance?* 

Lesson 5: Teacher Reference 2

Extension Opportunity

Extension opportunity description

In this extension opportunity, students will calculate the total amount of energy in the Sun-asteroid system to further prove that energy is conserved, that the Sun-asteroid system is closed, and that energy transfers between the gravitational field and the objects.

Who might benefit from this extension opportunity?

This extension opportunity is recommended as a differentiation option for students who have demonstrated either prior mastery or high interest in the related science and engineering practices it entails. It is not recommended as a required extension for all students. This is because the extension involves developing mathematical models from experimental data.

Here is an option to consider that may better support the required mathematical modeling:

- Offer this after students complete *Energy Transfer Investigation*.

What practices will be needed for the first part of this opportunity?

Students will need to engage in these elements of "developing and using models" and "using mathematics and computational thinking" for the conceptual understanding of the mathematics work:

- 2.3 Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.
- 5.2 Use mathematical, computational, and/or algorithmic representations of phenomena or design solutions to describe and/or support claims and/or explanations.

Students will need to engage in these elements of "energy and matter" with understanding the flow of energy:

- 5.1 The total amount of energy and matter in closed systems is conserved.
- 5.3 Energy cannot be created or destroyed--it only moves between one place and another place, between objects and/or fields, or between systems.

How can I introduce the extension opportunity?

Identifying the total energy of each system
Have students start by

- calculating the total energy of the pendulum and the asteroid by adding up the stored energy with the kinetic energy for each stage.
- identifying patterns in the total energy for the pendulum and asteroid.

Students will find that the total energy of the pendulum system is constant through each stage, but that is not true for the asteroid system. Have students brainstorm ideas as to why the calculated total energy of the asteroid system is not constant. Suggest to them that the stored energy for orbital motion is inherently negative.

Explain to students that scientists often consider the starting point of stored energy to be at infinite separation and that at that point the stored energy is zero because the gravitational force becomes negligible. As an object starts to get closer to the central mass, the number becomes more negative (a bigger negative number) because the object is becoming more bound to its orbit. So when an object goes around its orbit, its stored energy can become more negative or less negative.

This counterintuitive idea highlights how gravity and energy works in connection.

Recalculating total energy

Have students

- calculate the total energy of the asteroid system but with a negative stored energy.

Students will find that the total energy is consistently a constant negative value. Question the students to think about how we can have a negative total energy.

Lesson 5: Answer Key 1

Orbital Energy Key

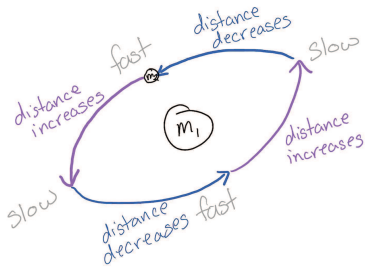
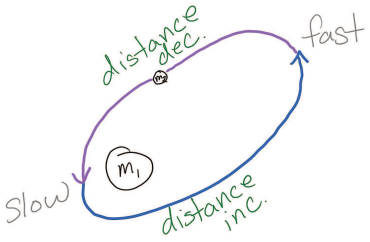
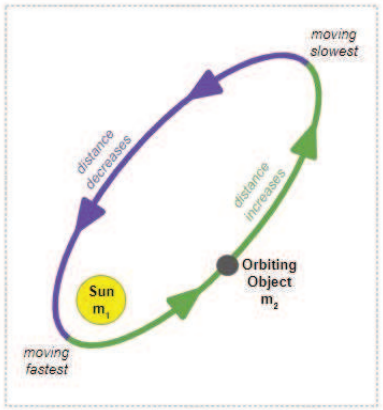
LLPE being assessed: 5.A Develop an energy transfer model that illustrates how energy flows and is conserved within an elliptical orbital system between the orbiting object, the Sun, and the gravitational field. (SEP: 2.3; CCC: 5.1, 5.3; DCI: ESS1.B.1, PS2.B.1, PS3.A.2, PS3.B.2)

3-D elements addressed in this assessment		Q1	Q2	Q3	Q4	Q5
SEPs	**Developing and Using Models:** Develop, ~~revise,~~ and/or use a model based on evidence to illustrate and/or predict the relationships ~~between systems or~~ between components of a system.	X	X	X	X	X
CCCs	**Energy and Matter: Flows, Cycles, and Conservation:** The total amount of energy and matter in closed systems is conserved.					
	Energy and Matter: Flows, Cycles, and Conservation: Energy cannot be created or destroyed—only moves ~~between one place and another place,~~ between objects and/or fields~~, or between systems~~.		X	X		
DCIs	**ESS1.B.1** Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. (HS-ESS1-4)	X	X	X	X	X
	PS2.B.1 Newton's law of universal gravitation ~~and Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic~~ forces between distant objects. (HS-PS2-4)		X	X		X
	PS3.A.2 At the macroscopic scale, energy manifests itself in multiple ways, such as in motion,~~ sound, light, and thermal energy~~. (HS-PS3-2) ~~(HS-PS3-3)~~		X	X		X
	PS3.B.2 Energy cannot be created or destroyed, but it can be transported from one place to another~~ and transferred between systems~~. (HS-PS3-1),~~(HS-PS3-4)~~		X	X		X

1. Annotate and create a model for an object orbiting the Sun with a high eccentricity.
    a. Draw and label a potential location for the sun that would result in an orbit of high eccentricity.
    b. Color code and label the orbit path to show when the orbiting object is moving closer to the Sun and show the direction of its motion on the orbit path.
    c. Color code and label the orbit path to show when the orbiting object is getting farther from the Sun and show the direction of motion on the orbit path.
    d. Label the point along the orbit path where the object will be moving the fastest (highest kinetic energy).
    e. Label the point along the orbit path where the object will be moving the slowest (lowest kinetic energy).

Rubric for question 1

	Foundational pieces	Linked understanding	Organized understanding
3-D elements	Look for • A model or drawing of an elliptical orbit path around the Sun. (SEP, 2.3; ESS1.B.1, PS3.A.2) • The model describes the speed of the orbiting object at multiple points. (SEP, 2.3; PS3.A.2) • The model describes the changes in distance at multiple points. (SEP, 2.3; ESS1.B.1)	Look for • A model or drawing of an elliptical orbit path and the Sun located at one of the foci. (SEP, 2.3; ESS1.B.1) • The model describes the speed of the orbiting object as faster at one end of the orbit and slower at the other (but not necessarily yet in the correct places). (SEP, 2.3; PS3.A.2) • The model describes the distance as increasing on one side of the orbit path and decreasing on the other (but not necessarily yet in the correct places). (SEP, 2.3; ESS1.B.1)	Look for • Responses that reflect organized understanding draw on elements from all three dimensions. However, as this is the first moment of assessment, we are not assessing students on CCC: 5.1, 5.3, in regards to energy, energy transfer, and energy conservation. The remaining assessment moments will ask students to use these crosscutting concepts.

Example		 	*N/A*
Feedback/ what to do	*Linking* Invite students to revisit their models from Lesson 4. What shape are highly eccentric orbits, and are they like circles or more squished? Where is the Sun always located for orbits?	*Organizing* Ask students to use the model to show where energy is being transferred from and to the orbiting object.	*N/A*

2. Where does energy transfer to when the orbiting object slows down (its kinetic decreases)? (CCC: 5.3; PS3.B.2)

Into space
Back to the Sun

3. Where does energy transfer from when the orbiting object speeds up (its kinetic energy increases)? (CCC: 5.3; PS3.B.2)

It comes from the gravitational force from the Sun.

4. Describe using words, drawings, and symbols what is happening to the direction and magnitude of the force of gravity on both the Sun and the object as the object moves along its path. (PS2.B.1)

The force of gravity between the Sun and the object would be stronger when they are closer together and weaker when they are farther away.
The force on each object always points towards the other object (Sun or orbiting object).
The forces are always equal to each other, even as they change magnitude throughout the orbit cycle.

5. How could these forces be playing a role in transferring energy to and from the asteroid to explain our changes in kinetic energy? (PS2.B.1, PS3.B.2)

When the object is moving towards the Sun, the force is pulling it in and speeding it up. This would explain the increase in kinetic energy.
When the object is moving away from the Sun, the force is pulling it back and slowing it down. This would explain the decrease in kinetic energy.

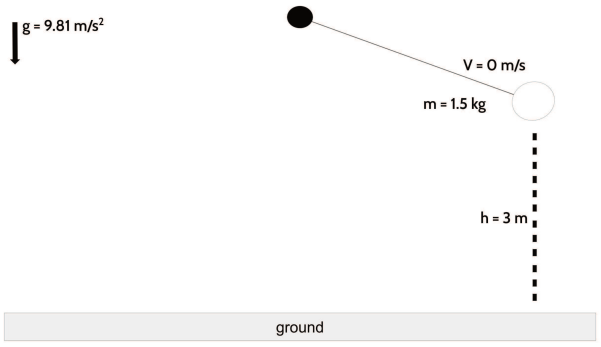
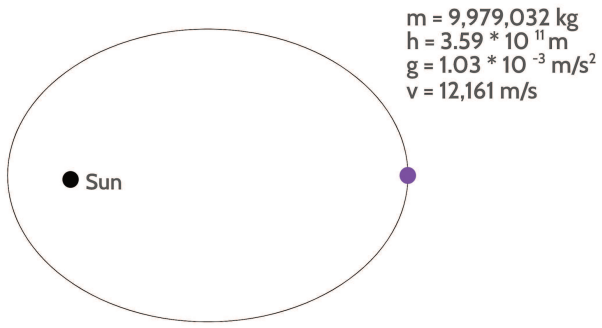
Lesson 5: Answer Key 2

Energy Transfer Investigation KEY

Types of Energy:

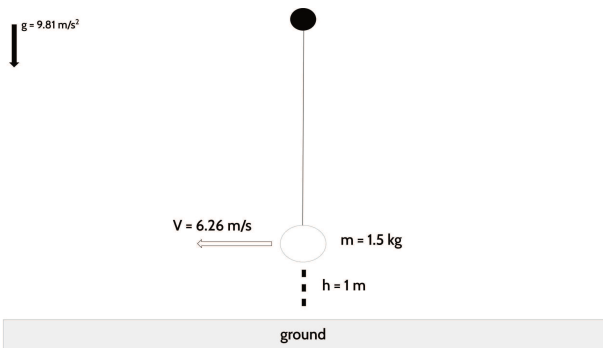
- **Kinetic Energy:** The energy of motion. It is the energy that an object or particle possesses due to its movement. The faster an object moves, the more kinetic energy it has.
  - Equation: ½ mv^2
- **Stored Energy in gravitational Fields:** The energy an object possesses due to its position or configuration. It's the stored energy waiting to be transferred. Stored energy comes from the object's interaction with a force field (like gravity) or its internal configuration.
  - Equation: mgh
- **Change in Energy:** The amount of energy that transfers between the field and the asteroid when the object moves between stages.
  - Equation for change in Stored Energy: $SE_2 - SE_1$
  - Equation for change in Kinetic Energy: $KE_2 - KE_1$

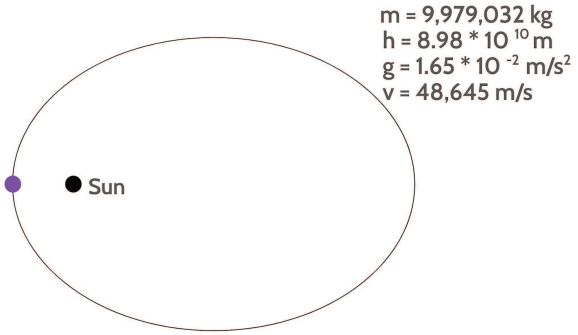
1. Use the organizers and data below to investigate the energy of the pendulum and orbit. (SEP: 2.3, 5.2, DCI: PS3.B.2)

Pendulum	Asteroid Orbit
Stage 1: Label the point along the orbit that represents the pendulum position	
	
Energy Perspective: Calculate the amount of Stored Energy and Kinetic Energy at this stage	
SE: 44.145 J KE: 0 J	SE = 3.69×10^{15} J KE = 7.38×10^{14} J

Pendulum	Asteroid Orbit

Stage 2:
Label the point along the orbit that represents the pendulum position





Energy Perspective:
Calculate the amount of Stored Energy and Kinetic Energy at this stage

SE: 14.715 J
KE: 29.39 J

SE = 1.475×10^{16} J
KE = 1.181×10^{16} J

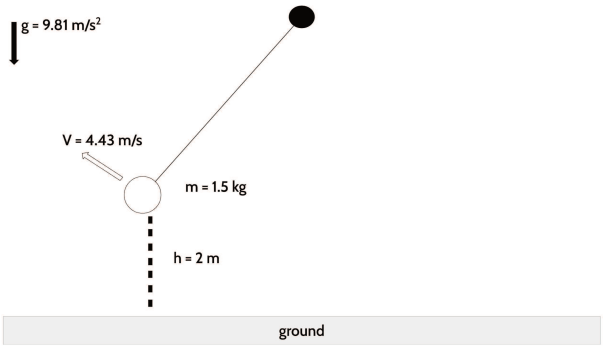
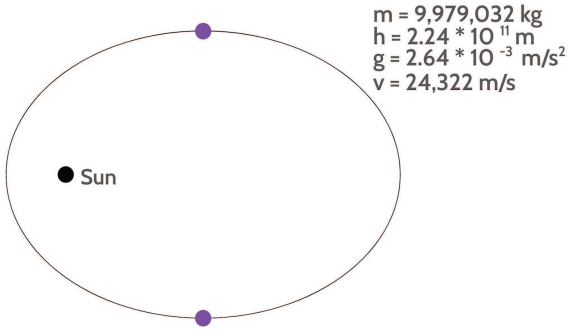
Changes in Energy:
Calculate the change in Stored Energy and Kinetic Energy between Stages 1 and 2

ΔSE = -29.43 J
ΔKE = 29.43 J
Note: Students might get slightly different values due to rounding errors.

ΔSE = 1.106×10^{16} J
ΔKE = 1.106×10^{16} J
Note: Students might get slightly different values due to rounding errors.

Pendulum	Asteroid Orbit

Stage 3:
Label the point along the orbit that represents the pendulum position

	
Energy Perspective: Calculate the amount of Stored Energy and Kinetic Energy at this stage	
SE: 29.43 J KE: 14.72 J	SE = 5.901×10^{15} J KE = 2.952×10^{15} J
Changes in Energy: Calculate the change in Stored Energy and Kinetic Energy between Stages 2 and 3	
ΔSE = 14.715 J ΔKE = -14.715 J Note: Students might get slightly different values due to rounding errors.	ΔSE = -8.889×10^{15} J ΔKE = -8.858×10^{15} J Note: Students might get slightly different values due to rounding errors.

During the mid-unit transfer task, students will use the kinetic energy equation to calculate the amount of energy of an object at the moment of collision with another object. Consider providing additional practice questions at the end of this lesson where students need to calculate the kinetic energy of orbiting objects with varying velocities and masses.

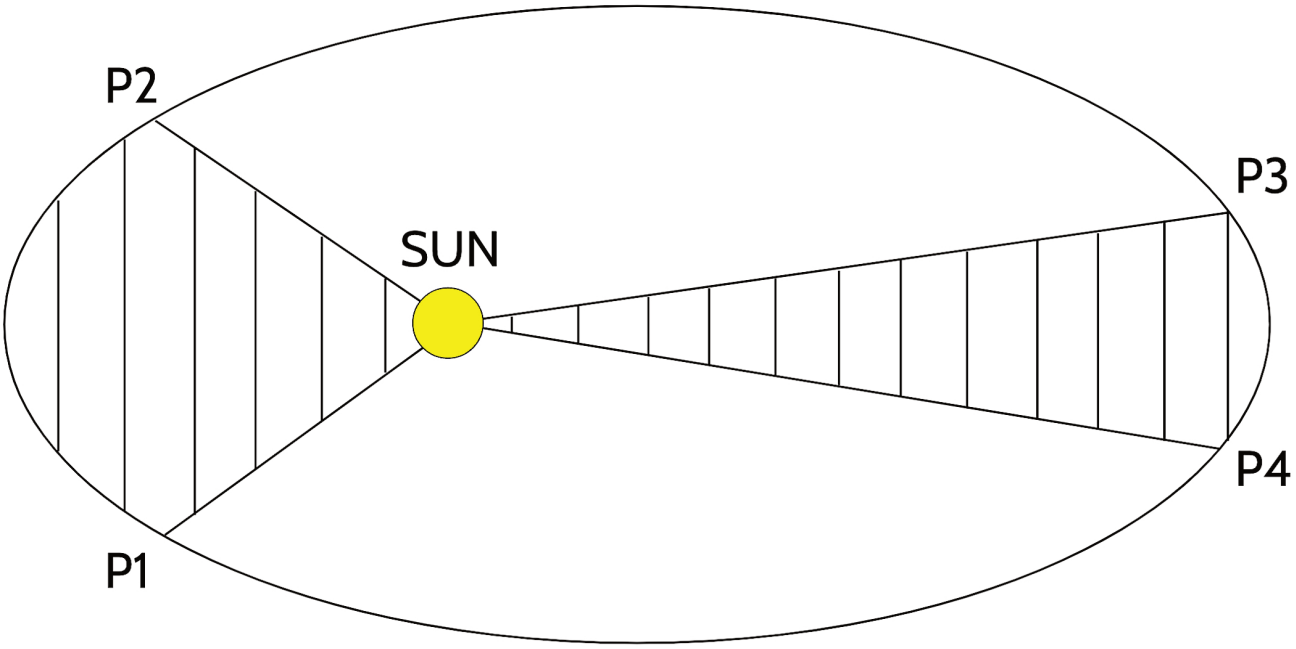
2. In closed systems, energy is conserved (energy is not transferring out or into the system, but transferred within parts of the system). Do we have evidence to suggest the Sun-Asteroid is a closed system? Explain using words, drawings, and/or symbols. (SEP: 2.3, 5.2, CCC: 5.1, DCI: PS3.B.2, PS3.A.2)

-
- We do not have evidence that this is a closed system.
- While energy transfer occurs between the asteroid and the gravitational field, the total energy is not conserved between stages. The changes in stored energy (SE) and kinetic energy (KE) do not cancel out, suggesting that external forces are acting on the asteroid. These could include gravitational influences from other objects or other forces affecting its motion.

- Since energy is not staying within just the asteroid and the gravitational field, this system is not fully closed.

During the mid-unit transfer task, students will consider how a gravity tractor can transfer energy to an asteroid to change its orbit. See how students describe energy transfer between the object and the gravitational field. If students only mention the values of kinetic energy and energy stored in fields, provide feedback that prompts them to describe whether and how energy is transferred in the system.

3. Kepler's Second Law predicts that an orbiting object will go through equal areas in equal lengths of time as shown in the image below. Use your findings and words/images/drawings to show how the orbiting object will go through those sections in equal times even though one section has a longer length than the other. (SEP: 2.3, 5.2, DCI: ESS1.B.1, PS3.A.2)



- During the P2 to P1 section, the object is moving fast with high kinetic energy.
- During the P3 to P4 section, the object is moving slowly with low kinetic energy.
- This will result in equal time.

4. How does this model about energy and changes in energy help us predict where and when an object will be along its orbital path and how does this help us assess risk of collision? (SEP: 2.3, 5.2, DCI: ESS1.B.1, PS3.B.2)

- We can use it to predict how fast an object will be going at certain heights or where it will be on the path.
- We can use it to determine the severity of a collision based on where the object is along its path.

Lesson 7: Answer Key 1

Key: Changing Asteroid Orbits

Performance expectation being assessed

HS-PS2-4 Use mathematical representations of Newton's Law of Gravitation ~~and Coulomb's Law~~ to describe and predict the gravitational ~~and electrostatic~~ forces between objects**.** [Clarification Statement: Emphasis is on both quantitative and conceptual descriptions of gravitational ~~and electric fields~~.] [*Assessment Boundary: Assessment is limited to systems with two objects.*]

In addition to the SEP, CCC, and DCI associated with this PE, this assessment also addresses one additional crosscutting concept and two additional DCI elements, described below:

3-D elements addressed in this assessment		Q1	Q2	Q3	Q4a	Q4b	Q5
SEPs	**Using Mathematics and Computational Thinking:** Use mathematical, computational, and/or algorithmic representations of phenomena ~~or design solutions~~ to describe and/or support claims and/or explanations.	X	X		X		X
	Developing and Using Models: Develop, ~~revise,~~ and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.				X		X
CCCs	**Patterns:** Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena.		X	X	X		
	Scale, Proportion, and Quantity: Algebraic thinking is used ~~to examine scientific data and~~ predict the effect of a change in one variable on another.	X				X	X
DCIs	**PS2.B.1** Newton's law of universal gravitation ~~and Coulomb's law~~ provide the mathematical models to describe and predict the effects of gravitational ~~and electrostatic forces~~ between distant objects. (HS-PS2-4)	X	X		X		
	PS2.B.2 Forces at a distance are explained by fields (gravitational, ~~electric, and magnetic~~) permeating space that can transfer energy through space. ~~Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields.~~ (HS-PS2-4),(HS-PS2-5)		X		X		
	ESS1.B.1 Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. (HS-ESS1-4)			X	X		
	PS3.B.2 Energy ~~cannot be created or destroyed, but it~~ can be transported from one place to another and transferred between systems. (HS-PS3-1),(HS-PS3-4)			X			X

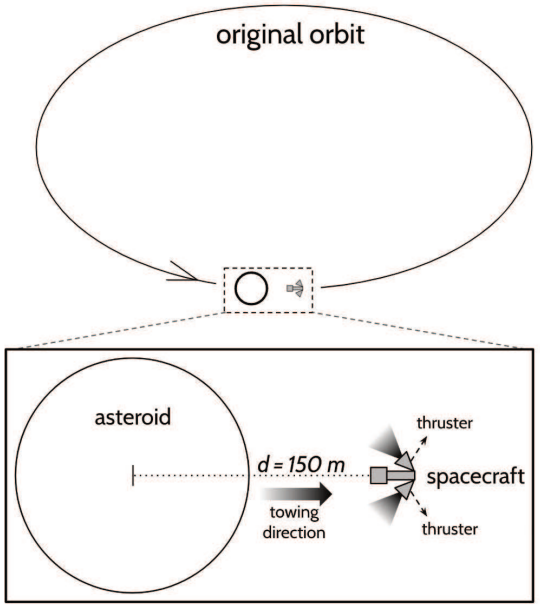
In this unit, we have been learning about various meteors and asteroids that have collided with Earth. While some, such as the Chelyabinsk meteor, cause only minor damage, others have had more serious impacts. So, what happens if we spot a big asteroid heading our way? Well, NASA and other space agencies worldwide are actively working on ideas to divert asteroids that could pose a serious danger to life on Earth. Let's explore two of these strategies:

Strategy 1: Gravity tractor

In this strategy, a spacecraft is sent toward an asteroid. Once there, the spacecraft positions itself in front of the asteroid and hovers there. Instead of physically touching the asteroid, the spacecraft uses the pull of gravity like a towline to move the asteroid. The spaceship has thrusters that push outward, preventing it from hitting the surface of the asteroid. To power these thrusters, the spacecraft is equipped with technology that turns solar energy into electricity, ensuring there is enough energy to change the asteroid's path.

With this strategy, scientists believe that a 20,000-kilogram ($2 * 10^4$ kg) gravity tractor can change the orbit of an asteroid of 8 billion kilograms (8,000,000,000 kg = $8 * 10^9$ kg) if it moves in front of and about 150 meters (m) away from the asteroid.

Question 1: Use the equation below and the information provided to calculate the force of gravity between the asteroid and the spacecraft. Show the steps you follow to find the value for F_g.



$$F_g = G\left(\frac{m_1 * m_2}{r^2}\right) \text{ where } G = \frac{6.67 * 10^{-11}\,N * m^2}{kg^2}$$

Given:

$m_1 = 2 * 10^4$ kg

$m_2 = 8 * 10^9$ kg

r = 150 m

$$F_g = \frac{(6.67 * 10^{-11}\ Nm^2/kg^2) * (2 * 10^4\ kg) * (8 * 10^9\ kg)}{(150\ m)^2}$$

$$F_g = \frac{(1.07 * 10^4\ Nm)}{225 * 10^2\ m^2}$$

$F_g = 4.75 * 10^{-1}$ N = 0.475 N

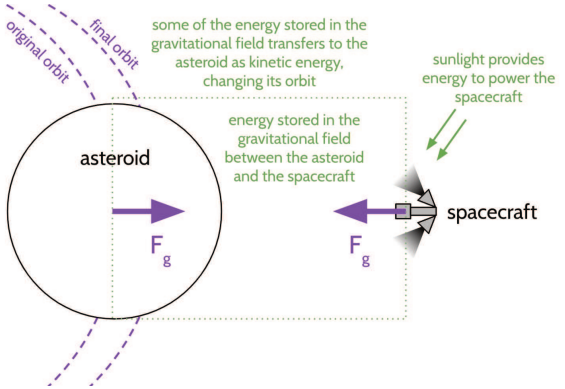
Question 2: Scientists estimate that a gravity tractor, like the one described above, needs to move in front of the asteroid for one year to shift the asteroid into an orbit that does not pose a threat to Earth. Which timescale will be best at showing whether the strategy is successfully moving the asteroid's orbit?

A. Observe the motion of the asteroid over one day.
B. Observe the motion of the asteroid over one week.
C. Observe the motion of the asteroid over several weeks.
D. Observe the motion of the asteroid over several months.

Use your results from question 1 to support your answer:

Look for students to choose C or D. The force between the spacecraft and the asteroid is very small (0.475 N), causing minimal changes in the motion of the asteroid that would be hard to observe within the span of one day or one week.

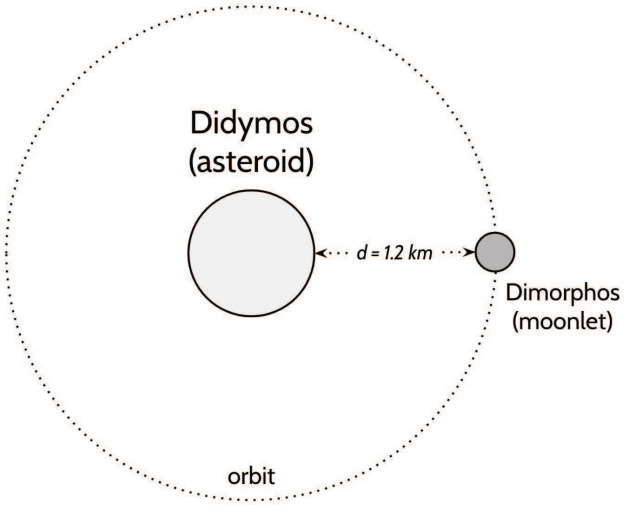
Question 3: According to this strategy, the gravity tractor can change the motion of an asteroid. As we have seen in this and other units, changes in motion are related to energy transfer in the system. Use the image and words to explain how the energy from the gravity tractor transfers to the asteroid without touching it:



Look for students to track how energy transfers in the system. An energy flow explanation should include the following steps:
+1 The spacecraft uses sunlight as its energy source, converting this solar energy into electricity to power its thrusters (optional).
+1 These thrusters serve to keep the distance (150 m) between the spacecraft and the asteroid.
+1 The distance between both objects results in gravitational fields, and some of the energy from the spacecraft is transferred into these gravitational fields.
+1 The energy transferred in the gravitational fields is then transferred to the asteroid as kinetic energy, causing changes in its motion.

Strategy 2: DART

NASA has been working on a project called the Double Asteroid Redirection Test (DART) to see how much we can change the path of an asteroid by hitting it with a spacecraft. In November 2021, NASA launched a small spacecraft, roughly the size of a vending machine, toward a rock named Dimorphos. Dimorphos is about the same size and weight as the Great Pyramid of Giza and moves in a **circular orbit** around an asteroid called Didymos, which is much larger and massive. These smaller rocks, like Dimorphos, are called *moonlets* because they orbit an asteroid instead of a planet.



About a year after the spacecraft was launched, it successfully crashed with the moonlet Dimorphos in the opposite direction of its motion. Before the DART, NASA knew that the moonlet had a **period of revolution (T_i)** of 11.92 hours and its orbit had a **semimajor axis (a_i)** of around 1.2 km (0.75 mi). With this information, NASA scientists set a goal: if the moonlet's orbit period changed by 73 seconds or more, the mission would be considered a success. Recent observations reveal that the moonlet's orbital period shifted from 11.92 hours (before the crash) to 11.38 hours (after the crash), indicating that the mission achieved its intended outcome.

Question 4: Scientists predicted a minimum change of 73 seconds in the moonlet's revolution period, yet the **observed period (T_f)** after the DART was nearly 30 minutes shorter at 11.38 hours. Let's explain what this means for the motion of the moonlet and the success of this mission.

a. **Compare time and spatial scales:** How large of an impact will the observed change in time have on the shape of the orbit? Make an initial prediction and explain your reasoning. No calculations required for now!

Accept all predictions, but look for students to compare 30 minutes to 11.92 hours, as this will show them using mathematical and algebraic thinking to consider the significance of this change in the overall shape of the orbit.

Let's test your prediction using the relationship between the period of revolution and the semimajor axis we found in this unit:

Before the crash	After the crash
$\frac{T_i^2}{a_i^3}$	$\frac{T_f^2}{a_f^3}$

Use this space to show your reasoning (*note: If you are uncertain about how to use this relationship but believe you can describe the change in the shape of the orbit using words and/or drawings, use this space to show your reasoning.*):

Given:

Initial period of revolution = T_i = 11.92 h

Initial semimajor axis a_i = 1.2 km

Final period of revolution = T_f = 11.38 h

Final semimajor axis = a_f

$$\frac{(11.38\text{h})^2}{(a_f)^3} = \frac{(11.92\text{h})^2}{(1.2\text{ km})^3}$$

$$a_f = \sqrt[3]{(1.57\text{ km}^3)}$$

$$a_f = 1.16\text{ km}$$

Accept students' written explanations about the shape of the observed orbit in terms of the semimajor axis (or radius, or distance between objects) and the significance of this scale difference. For example: The final period of revolution got shorter. This means that its velocity is higher. We learned that the velocity of the object depends on the force of gravity acting on it, so higher velocities are related to a larger force of gravity. Gravity increases when the distance between both objects decreases, so this means the orbit has a shorter semimajor axis. Because the period of revolution got shorter by 30 minutes instead of a few seconds, the observed orbit had a semimajor axis/radius/distance a lot smaller than expected.

These types of explanations suggest students are using the mathematical reasoning expected with Kepler's laws and Newton's law of universal gravitation, integrating different variables in the system.

How to modify instruction: Encourage students to use drawings and/or mathematical symbols in their explanations to provide additional evidence about students' use of SEP2 and SEP5 and their ideas about ESS1.B.1.

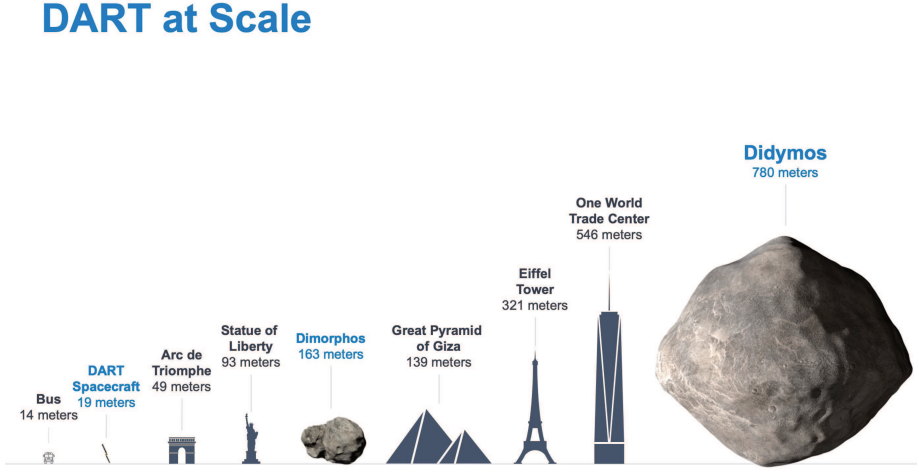
b. This is an example of making predictions and then comparing patterns in the system at one scale (time differences) to patterns at a different scale (size differences). What are other systems where you would expect to observe different patterns when observed at various scales?

Accept all answers. Some possible answers include the following:

- Looking at magnetic forces (small scale) to explain gravitational forces (large scale)
- Looking at forces acting on small pieces (foam - small scale) to explain the forces acting on tectonic plates (large scale)
- Looking at electricity (small scale) to explain the blackouts in Texas (large scale)

Question 5: The spacecraft crashed into Dimorphos at roughly 6,258 m/s (13,999 mph). Compared with Dimorphos, which has a mass of about 5 billion kilograms (5,000,000,000 kg = $5 * 10^9$ kg), the DART spacecraft weighed just 550 kilograms ($5.5 * 10^2$ kg) at the time of impact. So how did such a light spacecraft affect the orbit of a relatively massive asteroid?

Use an energy transfer perspective and the equation below to support your answer:



Adapted from: NASA / Johns Hopkins APL

$$\text{kinetic energy} = \frac{m * v^2}{2}$$

Rubric for question 5

	Foundational pieces	Linked understanding	Organized understanding
3-D elements	**Look for:** Students include ideas about energy transfer in the system. (PS3.B.2)	**Look for:** Students use algebraic thinking to include the role of mass and velocity in their energy transfer explanations. (DCI: PS3.B.2; CCC: 5)	**Look for:** Students use algebraic thinking to include the role of mass and velocity in their energy transfer explanations. (DCI: PS3.B.2; CCC: 5) **AND** Students use the mathematical model of kinetic energy to calculate the energy of the spacecraft at the moment of collision to generate and use their answer to support their explanation. (SEP: 2.3; DCI: PS3.B.2)
Example	The spacecraft transferred a lot of energy to the moonlet during the collision.	The spacecraft was small but going super fast, so it had enough kinetic energy to transfer to the moonlet and change its orbit.	Given: $m = 5.5 * 10^2$ kg $v = 6{,}258$ m/s $KE = \frac{5.5 * 10^2 \text{ kg} * (6{,}258 \text{ m/s})^2}{2}$ $KE = 10{,}769{,}705{,}100$ J This is a lot of energy! Even though the spacecraft was small, due to its velocity it had a lot of kinetic energy. When it transferred to the moonlet, it caused its orbit to change.

Feedback	*Linking* Encourage students to use ideas about the mass and the energy of the spacecraft to elaborate their answer.	*Organizing* Encourage students to be more accurate in their explanations by using the equation.	*Extending* Challenge students by asking them about what happened with the energy of the spacecraft once it crashed with the moonlet. While the original question is not targeting that part of this DCI element, this extension opportunity will provide evidence about students' ideas about energy conservation in the system.

How to modify instruction: Have a couple of computers in a designated area that students can use. One computer can have access to https://youtu.be/czB61D6qwoc?si=-_iv-yVanrHupGeO, while the second computer can have access to https://www.openscied.org/simulation/keplers-laws/. Let students decide which simulation can help them clarify their ideas. These models might help students explore the relationships among distance, velocity, mass, and gravity, which can help them include these variables during this assessment moment.

Lesson 10: Teacher Reference 1

Preparing Crater Lab

General safety protocols for demonstrations and hands-on activities:

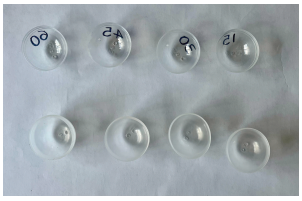
- Wear sanitized safety glasses with side shields or indirectly vented chemical splash goggles during the setup, hands-on, and takedown segments of the activities.
- Ensure all students wear sanitized safety glasses with side shields or indirectly vented chemical splash goggles during the duration of the investigation.
- Secure loose clothing, wear closed-toe shoes, and tie back long hair.
- Provide students with hand sanitizer wipes to use at the completion of the activities.
- Describe the procedures for disposal of materials and cleaning up the work space. .
- Make sure there are no fragile items in the activity zone, especially in the area where the orbiting object is being swung.
- Use caution when working with glass or plastic - sharp ends can cut/puncture skin.
- Wash hands with soap and water or use hand sanitizer wipes immediately after completing this activity.
- Review the safety protocol shown on *Lab Data Sheet* and **slide K** with the class.

Creating the impactor

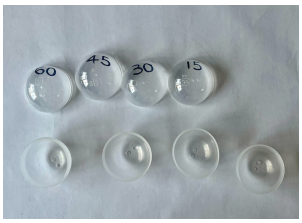
Materials

- small capsule
- large capsule
- nylon string (fishing line)
- nonhardening modeling clay, such as Plastilina
- permanent marker

Label the mass of each impactor using a permanent marker. Write the mass value from right to left on the inner side of the capsule.



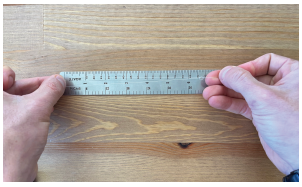
When you flip the capsule, the number should be legible.



Place a piece of tape inside each capsule to block the hole. This will prevent flour from getting inside the impactor during the investigation.



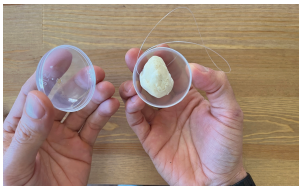
Use the nylon string to create a loop that is approximately 6 inches long. Make a knot where the ends meet.



Weigh the two capsule halves plus the clay, adjusting the clay amount until you reach the desired mass (15, 30, 45, or 60 grams).



Place the nylon string end with the knot inside the two capsule halves, along with the clay.



Bring the capsule halves together until you hear a click and then pull the nylon string taught. The impactor is ready.

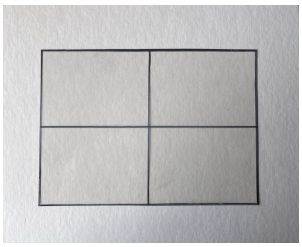


Creating the crater measuring tool

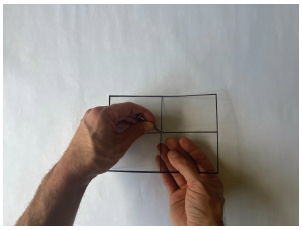
Materials

- 5” x 7” 0.04 thick acrylic sheet
- printout of tool image on last page of this document
- fine-tip permanent marker
- 12” ruler
- pushpin
- pointy object, like a nail
- wood skewer

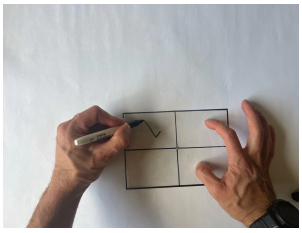
Use a ruler, permanent marker, and the printout to draw two perpendicular lines in the middle of the clear sheet. Draw the edges of the sheet as well.



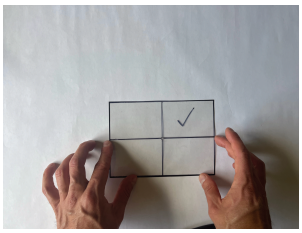
Flip the clear sheet, so the side with the permanent marker is in contact with the surface. Use a pushpin to make a small hole at the intersection. Use a nail or a larger object to expand the hole, but not larger than 3 mm in diameter.



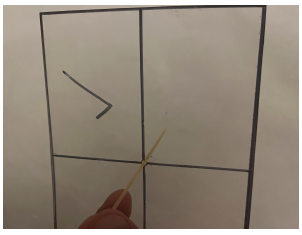
Flip the clear sheet again, and draw a check mark flipped horizontally. This check mark should be on the same side as the one with the perpendicular lines.



When you flip the sheet again, the check mark should be in its regular position. This checkmark will indicate to students they are placing the ruler in the right direction.



4. Use a wood skewer to make sure it can go through the hole without getting stuck. The crater measuring tool ruler is ready.



Creating a lab setup for each group

Materials

- 15.7-cup plastic container
- butcher paper (or newspaper)
- 6” wooden skewer
- impactor (15-g, 30-g, 45-g, or 60-g)
- 6” ruler
- 1 kg of flour
- 80 g cocoa powder
- salt shaker
- measuring tape, metal, retractable
- 12” ruler
- permanent marker
- jumbo craft stick

Each group will require a 15.7-cup plastic container fill with flour to the top



Lift the container and tap it three times against the table.



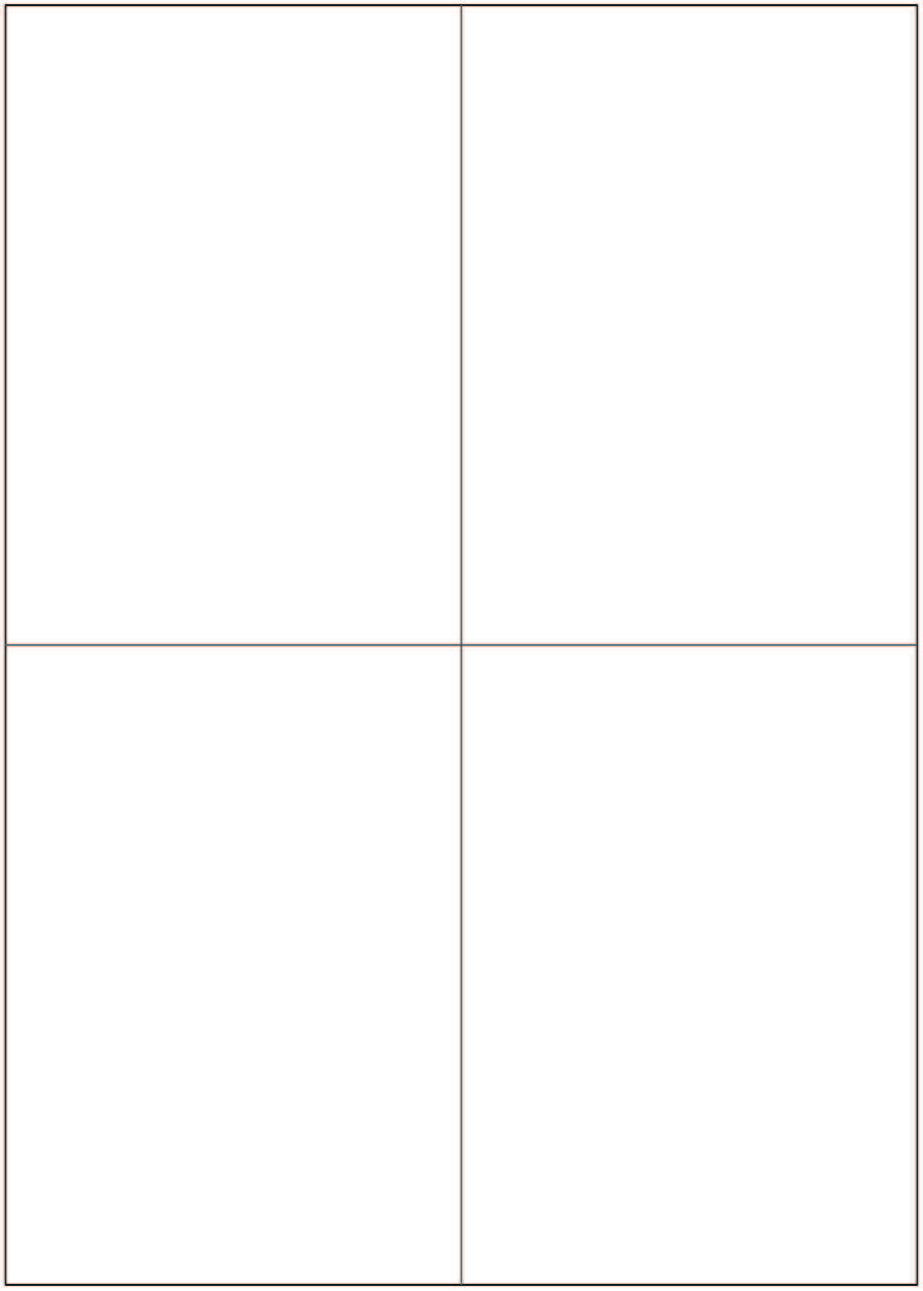
Use the ruler to remove the excess of flour and create a flat surface. The flour container is ready.



Additionally, include in each lab setup the following materials: butcher paper (to place the container on top of it and make cleaning easier), measuring tape, a jumbo craft stick, a couple wooden skewers, 6” ruler, a 30-g impactor, and a 15-g, 45-g, or 60-g impactor, shaker filled with 80 grams of cocoa powder.



Printout for crater measuring tool



Building Stream Table

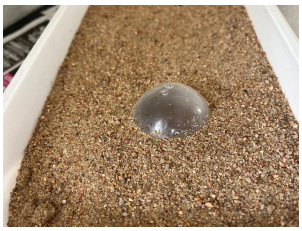
For each stream table, you will need the following materials:

- Plastic paint tray (4" W x 8" L)
- Approximately 2.5 kg of sand
- 2-3 plastic spheres (the same used to make the impactors in Lesson 2 and Lesson 10).
- Water

Drill ¼-inch holes, separated by half an inch, at the lower end of the paint tray. Fill the paint tray with enough sand until you are about 1/2 inch from the edge.



Bury the sphere half way in the sand. Bury more than 1 sphere in order to create more than one crater.



Sprinkle some water around the spheres, to compact the sand.

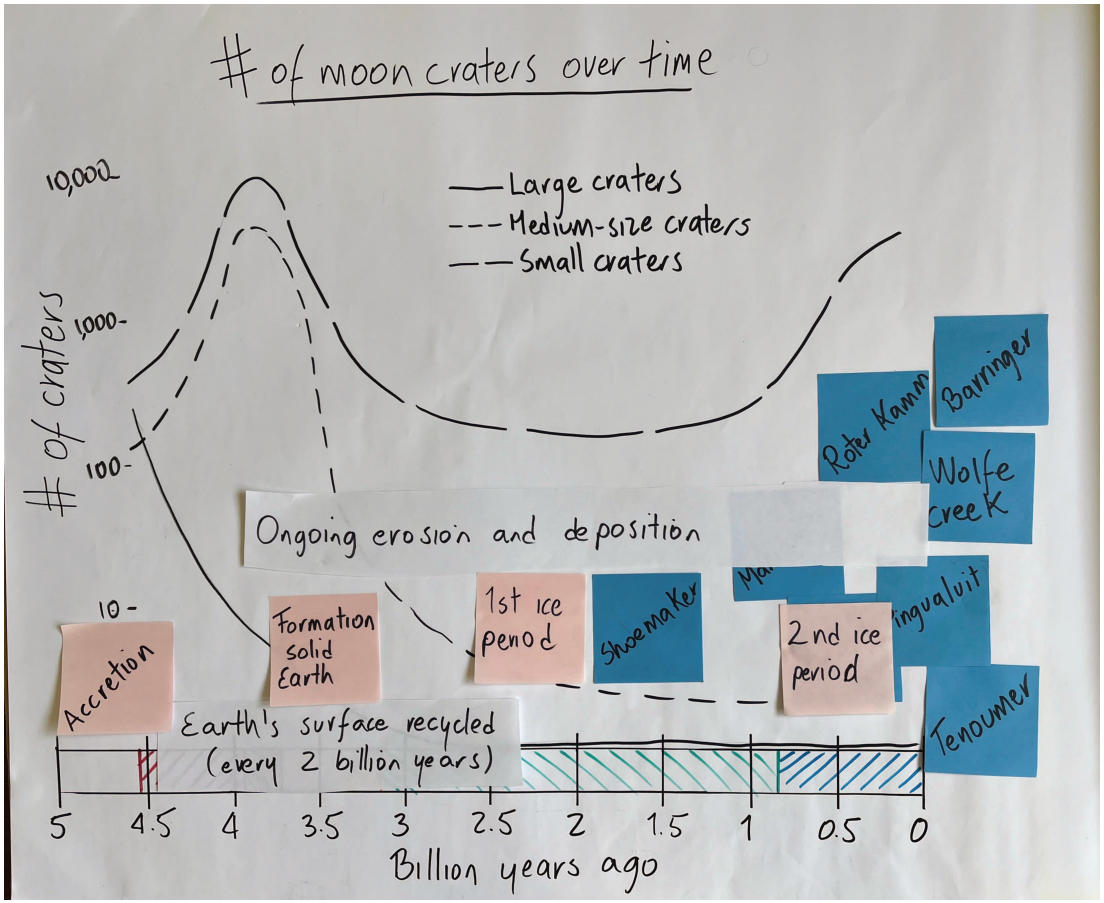


Remove the spheres from the sand.



Lesson 13: Teacher Reference 2

Example Student Timeline



Lesson 13: Answer Key 1

Progress Tracker KEY

Coding Key

Create a color and symbol coding system and key. Include colors for tracking each of the M-E-F perspectives, new questions, and other categories you think will help keep things organized. You can add additional colors or symbols as needed. This is your tool to track your sensemaking. Your coding system does not have to be the same as those of other students, and you can be as creative as you would like.

Color / Symbol	Meaning	Color / Symbol	Meaning	Color / Symbol	Meaning
Red	Changes in matter				
Green	Changes in energy				
Purple	Changes in forces				

Lesson #	What did you figure out?	Which lenses did you use to figure this out?	How did using these lenses help you figure this out?
3	A space object must have the right velocity in order to orbit a star or planet. If it is moving too fast, it will continue into space. If it is moving too slow, it will fall toward the star or planet because **the force of gravity** will pull it towards the star or planet. The distance between an orbiting object and the main object determines how fast it orbits (period of revolution). The relationship (T^2/a^3) of orbital period (T) to radius (a) is constant for the objects orbiting the same space object.	☒ **Change over time or space** ☐ **Thinking at/across different scales** ☐ **Changes in energy/matter in the system** ☒ **Patterns in the data/system**	We looked at changes in the motion of objects over time and space. This lens helped us find that the larger the distance between an orbiting object and the object it orbits, the more time it takes this object to complete a revolution. We also used patterns to identify the relationship between the orbital period and the radius. This consistent pattern means that if you know how long it takes for one object to orbit a planet or star and how far away it is, you can use that to figure out the same for any other object orbiting the same body. It shows that objects further away take longer to orbit, but in a predictable way.

Lesson #	What did you figure out?	Which lenses did you use to figure this out?	How did using these lenses help you figure this out?
4	Planets move in almost circular orbits, while other space objects, like asteroids and comets, move in elliptical orbits. Planets are not likely to collide with each other because their orbits don't intersect. However, planets can collide with space objects if their orbit paths cross. Orbits are elliptical in shape with the Sun at one of the focus points. We can determine the shape of the orbit by knowing the closest and farthest distance of the object to the Sun.	☒ Change over time or space ☐ Thinking at/across different scales ☐ Changes in energy/matter in the system ☒ Patterns in the data/system	By looking at the shapes of the orbits of space objects, we can understand why some of them collide. These shapes help us predict if two objects might be at risk of collision. However, these predictions are not always accurate because they don't tell us when the objects will be at the same point in space.

Lesson #	What did you figure out?	Which lenses did you use to figure this out?	How did using these lenses help you figure this out?
12	There are a lot of craters on planets and moons without an atmosphere, which means there have been a lot of collisions with space objects. The craters show that sometimes there were more impacts and other times fewer impacts. Some craters, like the ones on the Moon, are really old, so we know that collisions between space objects have been happening for a very long time.	☒ Change over time or space ☐ Thinking at/across different scales ☐ Changes in energy/matter in the system ☒ Patterns in the data/system	We looked at how often meteors hit moons and planets without an atmosphere over time. This helped us see that the number of small, medium, and large meteor impacts has changed over time. It also made us think about whether Earth's atmosphere is affecting the evidence of meteor impacts we see on our planet.

Lesson #	What did you figure out?	Which lenses did you use to figure this out?	How did using these lenses help you figure this out?
13	Most visible craters on Earth are from the last 650 million years, even though Earth is 4.5 billion years old. Earth's craters are not as clear as the ones on the Moon. Plate tectonics, erosion, weathering, glaciation, and accretion have all shaped Earth's landforms throughout its history. These processes help explain why we don't see many old craters on Earth.	☒ **Change over time or space** ☒ **Thinking at/across different scales** ☐ **Changes in energy/matter in the system** ☐ **Patterns in the data/system**	By comparing craters on Earth and the Moon over millions of years, we found that Earth shows very little evidence of meteor impacts older than 650 million years. Understanding how Earth's processes work over time and how they change the surface helped us explain why our planet looks so different from the Moon.

Lesson 14: Answer Key 1

Extinction Evidence Organizer Key

Lesson Question: Student-generated questions may vary slightly but are key to the navigation into the rest of the lesson and should be a variation of the following question: How can a meteor impact cause the extinction of some organisms but not others?

Source of information	What lens(es) are we trying to use when we gather information from this source?	What scale(s) of effects does this help explain in earth systems?	How does this inform our explanation about how a meteor impact can cause the extinction of some organisms but not others?
Source #1 (day 1)	☒ Matter changes ☐ Energy transfers ☐ Force interactions	☐ short-term effects (hours or days) ☒ longer-term effects (years or centuries)	**Chicxulub #1: K-Pg** layer • There is a layer of material (K-Pg boundary) that deposited all around Earth 65 million years ago. It is a material that went through a phase change and is rarely found naturally on Earth. • Dinosaur fossils are present below but not above the K-Pg boundary, indicating their disappearance (extinction) around that time. • Other types of organisms went extinct as well at that time, but others did not.

Sources #2-5 (day 2)	☒ Matter changes ☐ Energy transfers ☐ Force interactions	☒ short-term effects (hours or days) ☒ longer-term effects (years or centuries)	**Chicxulub #2: Seafloor** • **Impactor size**: Although diminished due to erosion and other natural processes, there is evidence of a hole creating a 1800-foot (549-m) tall peak-ring mountain range along the crater's edge. We call this the Chicxulub crater. • **Deformation:** The resulting force of the impact caused the crust at that location to deform, rebound, and permanently deform in a rebounded shape. • **Ejecta composition:** Some of the plate material and most of the matter that made up the meteor would have been ejected farther away. • **Sedimentation:** Sedimentation preserved the structure of the crater and may have preserved where the ejecta landed. **Chicxulub #3: Cenotes** • **Fractures:** The Chicxulub impact caused fractures in the limestone around the rim of the crater that led to the formation of the cenotes in a ring pattern along the edge of the crater. NASA found that the cenotes along the north and northwest of the Yucatán Peninsula formed along the edge of the Chicxulub crater. • **Impactor size and speed:** Samples from rocks show that cenotes at the Chicxulub crater rim were formed by cracks in limestone bedrocks as a result of an impactor collision. Such significant changes in Earth's crust are a result of an impactor that was at least 1×10^{15} kg, as it was traveling at least 20 km/s. • **Historical importance:** Cenotes are freshwater-filled, natural caverns that have surface openings. They provided fresh water to people living in the Yucatán and also held spiritual importance to the Mayans. • **Ejecta state change:** Some of the matter that made up the crust and the meteor would have been ejected back outward (either as hot liquid rock or vapor). **Chicxulub #4: Iridium** • **K-Pg boundary:** Iridium concentrations found in a sedimentary rock layer (K-Pg boundary) that is 65-66 million years old, all around Earth, match those typically found in meteors but not naturally found on Earth. • **Atmospheric interaction:** Simulations show that a meteor this size would have lost little mass from air friction, which also would not have slowed it down. It would have sped up as it moved through the atmosphere (due to gravity).

			• **Ejecta trajectory:** Some of the plate material, water, and the matter that made up the asteroid would have been ejected so high up it would have gone into space and then reentered the atmosphere all over Earth a bit later. **Chicxulub #5: Sediment** • **Iridium source:** Iridium concentrations found in a sedimentary rock layer (K-Pg boundary) that is 65-66 million years old suggest it is from a meteor. • **Plate material:** Plate material (glass spheres and shocked quartz) are also found in this layer all around the world. The former were heated to liquid and then cooled as they fell to Earth. The latter is from a sudden pulse of high-magnitude forces on the solid matter. • **Ejecta composition:** A higher concentration of spheres as well as larger-sized spheres are found at sites closer to the crater (e.g., North America) compared to sites farther away. • **Meteor trajectory:** The oblong shape of the crater and the distribution pattern of these spheres suggests that the meteor that formed it hit Earth's surface at a shallow angle on a path to the northwest.
Source #6 (day 3)	☒ Matter changes ☒ Energy transfers ☐ Force interactions	☐ short-term effects (hours or days) ☒ longer-term effects (years or centuries)	Despite the ways the Chicxulub impactor shifted Earth's systems, some species survived due to their adaptability. • Organisms that could quickly adapt to rapid climatic changes, such as temperature fluctuations and altered precipitation patterns, were more likely to survive. • Marine organisms that could tolerate changes in ocean chemistry, such as acidification and anoxia, had a better chance of surviving. • Species that could inhabit a variety of environments or migrate to more favorable areas had a survival advantage. • Organisms with diverse diets or the ability to find alternative food sources were less likely to face extinction when their primary food sources became scarce. • Species with physiological traits that allowed them to withstand harsh conditions, such as extreme heat or toxic environments, were more likely to endure environmental disruptions.

Name: _____Date: _____

Lesson 14: Answer Key 1

Alternate Mechanisms

Evidence from the K-Pg Layer

1. **Global layer:** There is a layer of material (K-Pg boundary) found in hundreds of sites throughout Earth that dates back to 65 million years ago.
2. **High prevalence of iridium:** Iridium concentrations found in a sedimentary rock layer (K-Pg boundary) that is 65-66 million years old, all around Earth, match those typically found in meteors but not naturally found on Earth.
3. **Mass dinosaur extinction:** Dinosaur fossils are present below but not above the K-Pg boundary, indicating their disappearance (extinction) around that time.
4. **Tiny glass spheres:** The tiny glass spheres in this layer are formed when surface rock is melted in the impact, ejected into the air as a spray of small, heated droplets, and then quickly cooled and crystallized (resolidified) as they fall back down to Earth.
5. **Shocked quartz and fractured limestone:** Shocked quartz in this layer is formed when quartz crystals undergo a sudden pulse of high-magnitude forces (great pressure). This produces identifiable microfractures in the crystals. The shocked quartz was found near fractures in the limestone bedrock where the rim of the Chicxulub impact crater formed.

Alternate mechanism	Which source of evidence from the K-Pg layer supports this alternate claim?
Mechanism A: Global wildfires	• **Mechanism A:** The ejecta from the Chicxulub impactor transferred a significant amount of thermal radiation to Earth upon reentry into the atmosphere. This affected Earth's biosphere, resulting in global wildfires. Evidence in K-Pg layer • The initial impactor collison may explain the shocked quartz and high levels of iridium. In addition, the impactor ejecta may explain the evidence of the glass spheres formed by an intense heating and subsequent cooling process. • Dinosaurs would likely not survive the global wildfires and thermal radiation caused by the reentry of ejecta. The high heat radiation and mass wildfires would result in the mass elimination of all living plants that supply oxygen on Earth. • The initial impactor collision would have created the shocked quartz. • The reentry of heated ejecta.
Mechanism B: Stratospheric soot	• **Mechanism B:** The stratospheric soot (ejecta) released from the Chicxulub crater impacted all of Earth's systems when the soot aerosols spread across Earth's atmosphere, cooling the planet and limiting photosynthesis in global oceans. Evidence in K-Pg layer • The massive stratospheric soot would have changed Earth's climate, blocking primary producers from sunlight and resulting in the cessation of photosynthesis. This would have affected all organisms that rely on a stable climate or oxygen supply, such as dinosaurs.

Alternate mechanism	Which source of evidence from the K-Pg layer supports this alternate claim?
Mechanism C: Global tsunami	• **Mechanism C:** The Chicxulub impactor produced a global tsunami 30,000 times more energetic than a modern day tsunami--subsequently impacting the world's oceans (Earth's hydrosphere). Evidence in K-Pg layer • Global tsunamis would make land inhabitable for dinosaurs or other organisms that relied on plants for food and oxygen. • This theory is less probable because it is highly unlikely that tsunamis would flood or eradicate large terrestrial areas. • How would global tsunamis explain the death of marine organisms during the end-cretaceous period?
Mechanism D: Global volcanic eruptions	• Mechanism D: The Chicxulub impactor generated ground motion through to Earth's mantle sufficient to trigger volcanic eruptions worldwide and significant changes to all of Earth's systems. Evidence in K-Pg layer • Massive volcanic eruptions may have led to Earth being inhabitable for terrestrial species like dinosaurs. These eruptions may have eliminated healthy ecosystems that dinosaurs and other organisms relied on for food. These eruptions may have killed living organisms by releasing harmful particles into the air, such as volcanic gas and ash. • Global volcanic eruptions would explain why there is global evidence of a melted layer of rock in the K-Pg layer. • How likely is it that volcanoes erupted in every single ecosystem where dinosaurs existed? How would mass volcanic eruptions explain the death of marine organisms during the end-cretaceous period?

Compare and evaluate the alternate mechanisms. Compare and evaluate at least two alternate mechanisms. Which alternate mechanism is most probable? Support your thinking with evidence from the K-Pg layer.

Look for students to do the following:

- Compare two alternate mechanisms.
- Discuss how one mechanism is more probable than the other or how both are probable.
- Use multiple pieces of evidence from the K-Pg layer as support for their thinking. See examples of this aligned evidence in the key above.
- Students may also claim that multiple mechanisms may have occurred together.

Lesson 14: Answer Key 2

Mass Extinction KEY

Building towards 14.C Develop a model to provide a mechanistic account of how energy was transferred and/or matter was changed from the formation of the Chicxulub crater in such a way that it resulted in the extinction of certain types of organisms (change) and not others (stability) 65 million years ago. (SEP: 2.4, CCC: 5.2, 7.1, DCI: PS3.A.2, ESS2.A.3)

In student models and their responses to the sticky questions left for their models, look for the following:

Parts and interactions (SEP: 2.4)

- *The meteor, the atmosphere, and interactions between them (e.g. meteor moving through the air, collisions between meteor and air particles) before the impact*
- *The meteor, the crust, and ejecta and the interactions between them*
- *Other earth systems and the interactions across them after the impact*

Cause and effect relationships

These should include at least two of the matter-related ideas listed below and two ideas from force interactions and/or energy transfers. (CCC: 5.2, DCI: PS3.A.2)

Matter changes	Force interactions	Energy transfers
*A. **Mass and speed:** The impactor had a lot of mass (1 x 10^{15} kg) and was moving fast upon impact (20 km/s).* *B. **Deformation:** The meteor burrowed deep into Earth's crust (many km). The crust at the impact site deformed and partially rebounded.* *C. **State change:** Most of the meteor and some of the matter that made up the crust vaporized or melted upon impact and then cooled and solidified later.* *D. **Ejecta:** The matter that made up the meteor and some plate material was ejected farther away or into space before falling back to Earth. Some of the impactor's matter was distributed all over Earth.*	*E. **Gravity** pulled the meteor toward Earth as well as the ejected matter.* *F. **Contact forces during impact:** The elastic behavior of the crust pushed back during the collision and ejected a lot of matter back out.* *G. **Air resistance and friction** had a smaller effect on the impactor than it does for smaller meteors (little mass loss and did not slow it down).*	*Same as C.* *H. **Air resistance and friction heated the** surface of the object moving through the atmosphere as well as the air around it.* *I. **To other earth systems:** The meteor would have had a huge amount of kinetic energy (2 x 10^{23} J) right before impact. Some of this energy would have been transferred to the air, ocean, and crust.*

Representation of at least one mechanism from the list of three below

Tsunamis is mechanism C, but it is not listed here, as it alone would not account for world-wide patterns of extinction. If students include this mechanism as well as one of the other three, that is fine. For the other mechanism(s) that students include, look for the use of at least three ideas related to matter changes and energy transfers that are connected together in a chain of cause and effect across multiple earth systems that would explain what happened across those different earth systems. (SEP: 6.2, CCC: 5.2, DCI: PS3.A.2, ESS2.A.3)

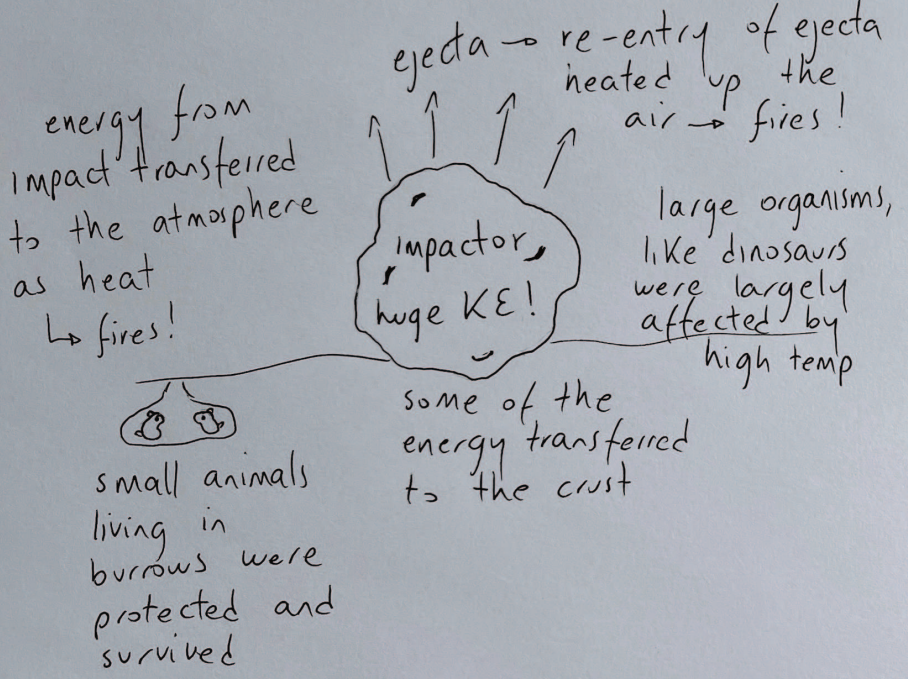
Mechanism	Earth systems represented	Matter changes	Energy transfers
A: Thermal radiation from ejecta reentry	*Atmosphere, space, and biosphere on the surface (ocean optional)*	*Same as D* *Same as H, but on every piece of ejecta*	*Same as H* *Heat transfer to the surface. This might be interpreted by students to be superhot ejecta falling to the surface and/or IR radiation coming off the ejecta.* *Ignition of biological material (fires)*
B: Global cooling from light-absorbing soot in atmosphere	*Atmosphere and biosphere on the surface (ocean optional)*	*Burning or combustion of crude oil in deposits at the crater site* *Same as D* *Small pieces of soot suspended in the highest layers of the atmosphere for months*	*Light from the Sun is absorbed and/or reflected by the soot particles. Less light reaches Earth's surface.*
D. Increased volcanic eruptions (ash effects)	*Atmosphere and biosphere on the surface and geosphere below (crust and mantle)*	*Ash ejected into the upper layer of the atmosphere (same as soot)*	*Seismic waves transfer energy through Earth's mantle from the impact site to the other side of the globe.* *Light from the Sun is absorbed and/or reflected by the ash. Less light reaches Earth's surface.*

Representing how these changes would account for why some types of organisms would survive but others would go extinct.

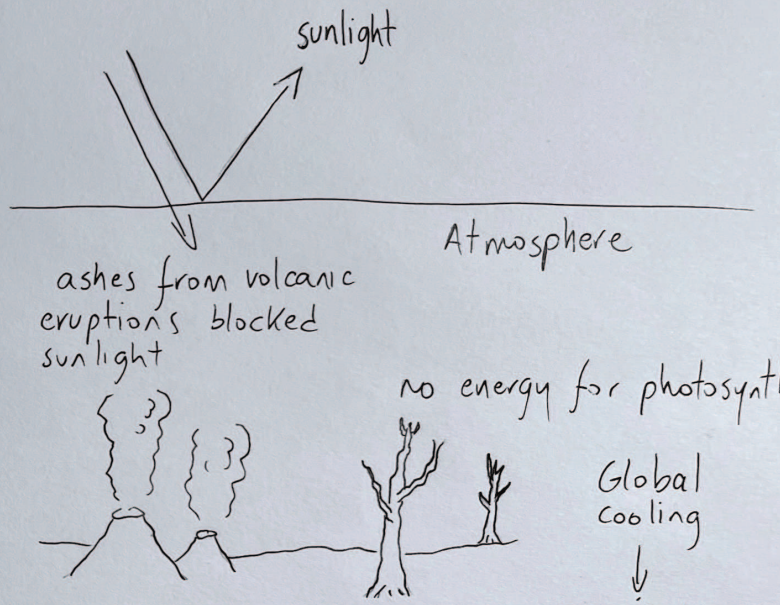
Any one of these should explain how the flow of matter (e.g., related to food or water) or changes in energy transfer (e.g., related to protection from IR radiation, photosynthesis) could lead to differential chances of survival in different environments, climates, and spheres. (SEP: 6.2, CCC: 3.1, 7.1, DCI: PS3.A.2, ESS2.A.3). See sample model below.

- *Decreased light levels led to less food for months or years for all food chains relying on photosynthesis. This led to the extinction of most herbivores and organisms that consume primarily herbivores.*
- *Organisms that could eat other things could survive on dead organisms until enough plants grew back—months or years later. These organisms that survived were also the ones that needed less food.*
- *Organisms that lived in well-insulated shelters or habitats (dens, living underground, deeper in the ocean) were shielded from the short-term, very elevated temperatures (oven temperatures) in the atmosphere due to ejecta reentry that occurred over a few hours or days.*

During the impact



After the impact



Lesson 15: Answer Key 1

Moon Formation KEY

Performance expectation being assessed: HS-ESS1-6 Apply scientific reasoning and evidence from ancient earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history. [Clarification Statement: *Emphasis is on using available evidence within the solar system to reconstruct the early history of Earth, which formed along with the rest of the solar system 4.6 billion years ago. Examples of evidence include the absolute ages of ancient materials (obtained by radiometric dating of meteorites, moon rocks, and Earth's oldest minerals), the sizes and compositions of solar system objects, and the impact cratering record of planetary surfaces.*]

In addition to the SEP, CCC, and DCIs associated with this PE, this assessment also addresses one additional scientific and engineering practice, one crosscutting concept, and one additional DCI element, described below:

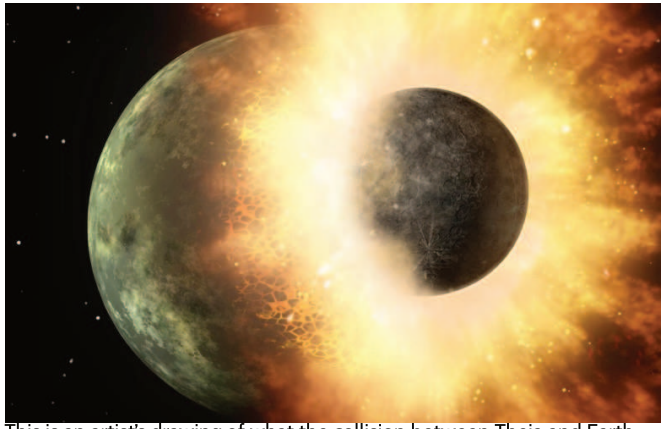
3-D elements addressed in this assessment		Q1	Q2	Q3	Q4
SEPs	**Constructing Explanations and Designing Solutions:** Apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.	x	x	x	x
	Analyzing and Interpreting Data: Evaluate the impact of new data on a working explanation and/or model of a proposed process or system.				x
CCCs	**Stability and Change:** Much of science deals with constructing explanations of how things change and how they remain stable.			x	
	Energy and Matter: Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system.	x	x		x
DCIs	**ESS1.C.2:** Although active geologic processes, such as plate tectonics and erosion, have destroyed or altered most of the very early rock record on Earth, other objects in the solar system, such as lunar rocks, asteroids, and meteorites, have changed little over billions of years. Studying these objects can provide information about Earth's formation and early history.			x	x
	PS1.C.1 Nuclear Processes: ~~Spontaneous radioactive decays follow a characteristic exponential decay law.~~ Nuclear lifetimes allow radiometric dating to be used to determine the ages of rocks and other materials. (secondary)				x
	PS2.B.1. Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects. (HS-PS2-4)		x		

Our solar system was formed about 4.5 billion years ago. Today, it is dominated by 8 large planets traveling around the Sun in nearly concentric orbits. But when the solar system was young, it was a chaotic place. There were probably many objects the size of planets, moving around and not always in orbits that did not overlap. Sometimes, these objects crashed into each other.

Scientists believe that a collision between two of these early objects is responsible for the formation of Earth's Moon. Scientists theorize that another planet, called Theia, formed very close to the young Earth. Theia was about the size of the planet Mars and would have had similar composition to the other rocky planets. About 100 million years after the solar system began to form, Theia crashed into Earth when their orbits intersected. This idea is known as the Giant Impact hypothesis.

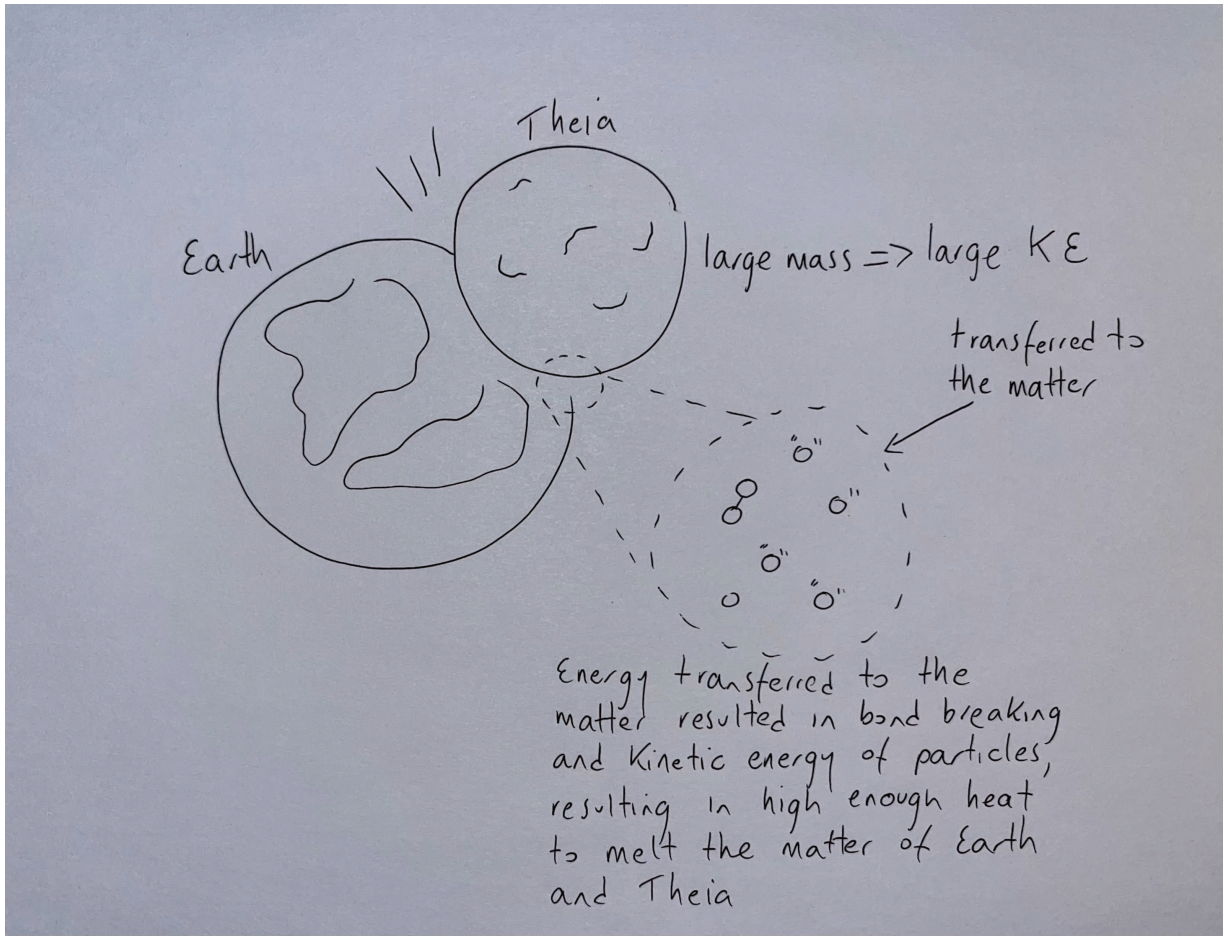
Much of science deals with constructing explanations of how things change and how they remain stable. Let's use some of the ideas we developed during this unit to explain how the sudden collision of Theia and early Earth could have led to the stable system we see today.

Question 1. Models of the impact between Theia and Earth result in Theia being destroyed and Earth melting into liquid rock. Use M-E-F thinking to explain why the models might produce this result (use a combination of words, drawings, and symbols).



This is an artist's drawing of what the collision between Theia and Earth might have looked like. NASA/JPL-Caltech

+1 Theia had a lot of kinetic energy due to its large mass.
+1 This large kinetic energy transferred to the matter in the Earth-Theia system.
+1 The energy transferred to the matter resulted in bond breaking and kinetic energy of particles, turning into heat.
+1 Heat from this collision was high enough to melt the matter in the Earth-Theia system.
The following model represents the same ideas:



Models suggest that only the smaller planet, Theia, was destroyed. A large amount of vaporized mantle material from both Earth and Theia was "splashed", or ejected, into space. Much of this ejected material fell back to Earth, but a lot remained in orbit and eventually clumped together. Scientists do not yet know exactly how long this process took, but over a relatively short time, the clumps came together and formed the Moon.

Question 2. Use what you have figured out about orbits and orbital forces to explain why, when Theia smashed into Earth, the matter that splashed out turned into a moon that orbited Earth. Use a combination of words, drawings, and symbols in your explanation.



This is a computer-generated model of material from both Earth and Theia "splashing" into space. NASA

+1 Compared to the matter that fell back to Earth, the velocity of the matter that became the Moon was large enough to remain in orbit.
+1 The gravity between the clumps of matter made them come towards each other to form the Moon.

Question 3. Scientists use computer models to make inferences about the formation of the Moon, but we do not have very much direct evidence of the hypothesized impact with Theia. Use words, drawings, and/or symbols to describe how Earth's processes over time might explain why it is so hard to find evidence of this impact.

This was a very old event in Earth's history. It is possible that plate tectonics could have erased some of the evidence of this impact on our planet. As the matter in the surface gets moved inside to the mantle and melted, any evidence of old cratering activity is erased.

Assuming the collision left a crater on the surface or matter of Theia on the surface, erosion by water and/or wind could have gradually erased evidence of the crater.

Question 4. When astronauts visited the Moon during the Apollo missions in the 1960s and 1970s, they collected rocks from the Moon and brought them back to Earth for analysis. Given the great challenges of collecting these samples, astronauts only grabbed samples from a few spots on the Moon and none from its deeper layers. This table shows the results that scientists have obtained from analyzing the composition of soil and rock samples from the Moon and Earth:

Composition of Moon Samples					
Study	**CaO (%)**	**FeO (%)**	**MgO (%)**	**Al_2O_3 (%)**	**SiO_2 (%)**
Ringwood (1979)	3.7	14.1	32.9	4.2	45.1

Taylor (1982)	4.6	13.1	32.3	6.1	43.9
Wänke and Dreibus (1986)	3.8	13.1	32.6	4.6	45.9
O'Neill (1991)	3.3	12.4	35.1	3.9	44.6
Kuskov and Kronrod (1998)	4.3	11.7	29.6	5.9	48.5
Warren (2005)	3.0	9.1	35.6	3.8	46.2
Composition of Earth Samples					
McDonough and Sun (1995)	3.6	8.2	38.2	4.5	45.5

As a comparison, these are the results from the composition of soil and rock samples from Mars.

Composition of Mars Samples					
Study	**CaO (%)**	**FeO (%)**	**MgO (%)**	**Al_2O_3 (%)**	**SiO_2 (%)**
Khan and Connolly (2008)	2.2	17.0	33.0	2.2	44.0
Sanloup et al. (1999)	2.0	17.7	27.3	2.5	47.5

Radiometric data of the soil and rock samples from the Moon suggest it is 4.53 billion years old. The best estimate for the total age of Earth and the solar system, based on radiometric data, is 4.54 billion years old.

Explain how the results from radiometric data and composition support the Giant Impact hypothesis, using any combination of words, drawings, or symbols.

Rubric for question 4

	Foundational Pieces	Linked Understanding	Organized Understanding
3-D elements	**Look for:** Students include evidence from the composition of the Moon and Earth to assess the Giant Impact hypothesis. (PS3.B.2)	**Look for:** Students use the data about radiometric dating *and* the composition of the Moon and Earth to assess the extent to which the evidence supports the Giant Impact hypothesis.	**Look for:** Students use the data about radiometric dating and the composition of the Moon, Earth, and Mars to assess the extent to which the evidence supports the Giant Impact hypothesis. **AND** Use ideas about the flow of matter in the system to connect the evidence with their explanation. (SEP: 2.3; DCI: PS3.B.2;
Example	The compositions of the Moon and Earth are very similar. This means that it is possible that the Moon was once part of our planet.	When Theia collided with Earth, the Moon came into existence shortly afterward. Radiometric data tell us that Earth is older than the Moon, which supports this idea. The fact that the Moon and Earth share similar compositions backs up this idea too, as the collision would have caused them to end up with similar stuff.	When Theia collided with Earth, their materials got all mixed up, and the Moon came into existence shortly afterward. Radiometric data tell us that Earth is older than the Moon, which supports this idea. The fact that the Moon and Earth share similar compositions backs up this idea too, as the collision would have caused them to end up with similar stuff. To put it in perspective, Mars has a somewhat different composition, so the resemblance between Earth and the Moon supports the Giant Impact hypothesis. The minor differences in the compositions of Earth and the Moon might be due to the material from Theia, which, like Mars, likely had a slightly different makeup than Earth.

Feedback	*Linking* Encourage students to include data from radiometric dating in their analysis as well. As you walk around the classroom, skim through student responses. Ask students who show this type of response:: • *Do the radiometric data support the Giant Impact hypothesis? Why or why not?* • *What do you think happened to the matter of Earth, Theia, and the Moon?*	*Organizing* Encourage students to add ideas about the changes in matter in the system that could help explain the results observed. Ask students who show this type of response: • *What do you think happened to the matter of Earth, Theia, and the Moon?* • *What do the data about the composition of Mars' samples suggest about the similarities and differences in matter composition between Earth and the Moon?*	*Extending* Ask students who show this type of response: • *Where on Earth could we find evidence of this collision?* • *What evidence would provide additional support to this hypothesis?* • *What evidence could cast doubt on this hypothesis?*

How to modify instruction: Many studies suggest that feedback is most helpful when it's given right away, rather than waiting for days or weeks. However, as this is the last task of the unit, students are unlikely to have enough time left to apply this feedback. If this is the case, make sure you walk around the room and elicit student ideas using the suggested prompts to provide immediate feedback that students can apply during this task.