

PHYSICS

Energy, Forces, &
Earth's Crust

**How do forces in
Earth's interior
determine what
will happen to the
surface we see?**



HIGH SCHOOL SCIENCE



TEACHER EDITION



How do forces in Earth's interior determine what will happen to the surface we see?

Energy, Forces, & Earth's Crust: Afar

OpenSciEd Unit P.2





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UNIT OVERVIEW

How do forces in Earth's interior determine what will happen to the surface we see?

This unit is anchored by a crack in Earth's crust that appeared in the Afar region in 2005. Earthquakes and a volcanic eruption also occurred around this time. Students read about the Afar event and about other earthquakes that occur in North America. Students look for similarities and differences in these earthquake events, prompting students to model the events that occurred before, during, and after the crack was discovered. In Lesson Set 1 (Lessons 1-8) students figure out that changes in the structure of matter involve unbalanced forces and energy transfer, using this idea to explain earthquakes and volcanoes at plate boundaries. Students then investigate the structure and dynamics of Earth's interior using tomography and modeling, including radioactivity, to explain the unbalanced forces driving changes in Earth's crust. In Lesson Set 2 (Lessons 9-13) Students investigate the ages of rocks to understand the history and future of the Afar region. Students use a simulation to figure out the interactions happening at tectonic plate boundaries, and investigate the nature of the relationship between mass and forces on the movement of tectonic plates to explain the past, present, and potential future of the Afar region. Students apply these ideas in a final transfer task to explain why the Midcontinent Rift, a rift similar to the rift in the Afar region, failed to create an ocean in the middle of North America 1.1 billion years ago.

Throughout the unit, students will do the following:

Developing and using models and constructing explanations and designing solutions

- Use a representation of spatial and temporal scales to investigate stability and change in Earth's systems, and the relationships between phenomena.
- Develop and use free-body diagrams to understand how unbalanced forces are related to energy transfer and matter transformations at different scales.
- Use a computer simulation to model the role of fields in matter transformations due to external forces.
- Develop and use a model of the relationships between energy, matter, and forces that will be a sensemaking tool throughout the rest of the course.
- Develop a model and analyze video to identify, model, and revise ideas about the relationship between forces, matter, and energy that drive the thermal convection cycle within the mantle.
- Construct a cause-and-effect model to explain how radioactive decay results in the release of enough heat to drive convection in the solid rock of Earth's mantle.
- Use mathematical thinking to determine the age of rocks from Afar and use that information to explain the history and future of tectonic activity around the world over large timescales.
- Use a simulation to investigate how plates interact at divergent and convergent plate boundaries.
- Model the forces of gravity and friction to explain ridge push and slab pull.

Building Toward NGSS Performance Expectations

HS-ESS1-5:

Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks.

HS-ESS2-1:

Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.

HS-ESS2-3:

Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection.

HS-PS1-8:

Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay.

UNIT STORYLINE

Unit Question: How do forces in Earth's interior determine what will happen to the surface we see?

How students will engage with each of the phenomena



Lesson Set 1: How does land stretch and when/why does it break?

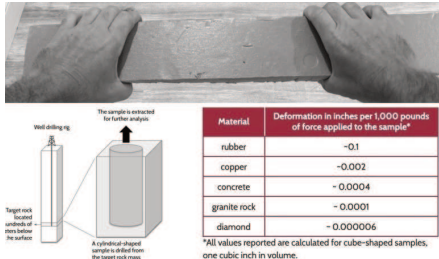
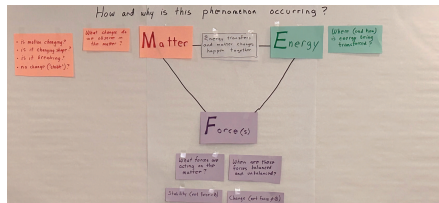
Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
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LESSON 1 Lesson Set 1 2.5 days What is happening in the Afar region? Anchoring Phenomenon	<i>A series of changes in Earth's crust over short and long timescales reveal puzzling patterns of earthquakes and cracks in Ethiopia, Africa, and similar patterns in North America.</i>	We explore a StoryMap about a series of events that left a giant crack in Earth's crust in the Afar region. We connect to prior earthquake experiences and earthquakes near us. We read about selected earthquakes and compare them with the events in Afar. We develop an initial model for before, during, and after the events. We develop questions for the Driving Question Board and ideas for investigations. We figure out: - A crack opened up in the Afar region in 2005. A volcanic eruption and an earthquake also occurred. - Earthquakes seem connected to faults, and most, but not all, happen along plate boundaries. - Earthquakes happen underground and can cause cracking/moving of Earth's surface. - There are similarities and differences between the earthquake cases and Afar events.	
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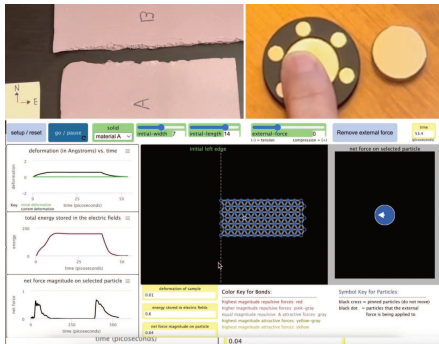
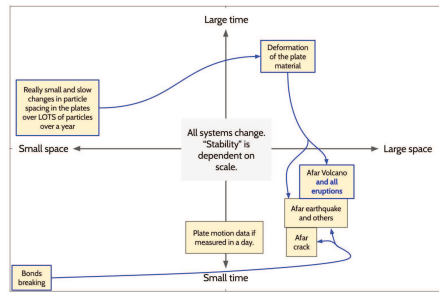
Navigation to Next Lesson: We have explored multiple cases of earthquakes causing cracks in the ground. We wonder what could be causing the ground to shake and break.

LESSON 2 Lesson Set 1 3 days What allows a system to remain stable when forces are acting on it, and what causes it to suddenly change? Investigation	<i>Earth's plates show variation in their motion over the course of a year. Some combinations of contact forces on a piece of foam keep it stationary, and others do not.</i>	We analyze plate motion data. We develop a model of force interactions between plates. We investigate the conditions that result in stability and change in motion of an object when multiple forces act on it. We use free-body diagrams to explain and predict how the magnitude of the forces applied at different scales impact the stability and changes in the matter within the system. We figure out: - Stability is dependent on scale. - The net force is the sum of all the forces acting on an object; it is zero when the forces are balanced along every axis. - Forces at different scales can help explain why matter remains in a stable state and why its motion changes.	
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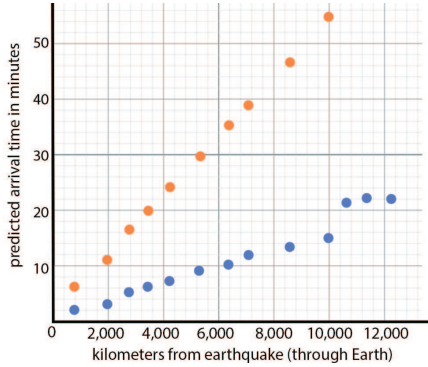
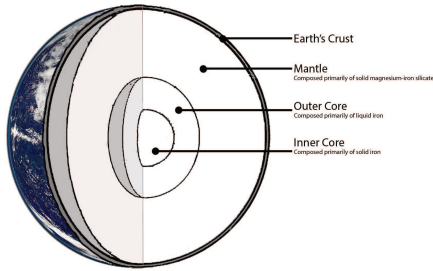
Navigation to Next Lesson: We have identified the net force of contact forces as a contributing factor in explaining the stability and changes within both matter and Earth's systems. We wonder about the changes in matter when external forces on an object continue to increase.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it												
LESSON 3 Lesson Set 1 1 day What happens to the matter and energy in a system when the magnitude of balanced forces on it increases? Investigation 	 <table border="1"> <thead> <tr> <th>Material</th><th>Deformation in inches per 1,000 pounds of force applied to the sample*</th></tr> </thead> <tbody> <tr> <td>rubber</td><td>~0.1</td></tr> <tr> <td>copper</td><td>~0.002</td></tr> <tr> <td>concrete</td><td>~0.0004</td></tr> <tr> <td>granite rock</td><td>~0.0001</td></tr> <tr> <td>diamond</td><td>~0.000006</td></tr> </tbody> </table> *All values reported are calculated for cube-shaped samples, one cubic inch in volume. <i>Foam changes shape when we push or pull on it. Rock samples often change shape after they are extracted from the surrounding bedrock. Compression machines measure deformation as external forces are applied to a sample.</i>	Material	Deformation in inches per 1,000 pounds of force applied to the sample*	rubber	~0.1	copper	~0.002	concrete	~0.0004	granite rock	~0.0001	diamond	~0.000006	We explore changes in a piece of foam as higher-magnitude forces are applied to it. We develop a model relating how unbalanced forces cause the observed changes in matter and energy transfer. We predict whether rock would behave like a piece of foam. We gather information from a reading. We ask questions about the relationship of our new ideas to what is happening in Earth systems. We figure out: • Changes in matter and energy transfers happen together. • Unbalanced forces transfer energy. • All solid materials deform elastically when force is applied to them, up to a point. • When solids deform past their elastic limit, they permanently deform; this includes a permanent change in shape, cracks, and/or breaking into smaller pieces.	
Material	Deformation in inches per 1,000 pounds of force applied to the sample*														
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copper	~0.002														
concrete	~0.0004														
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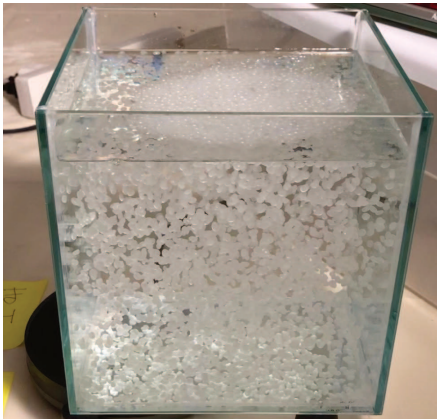
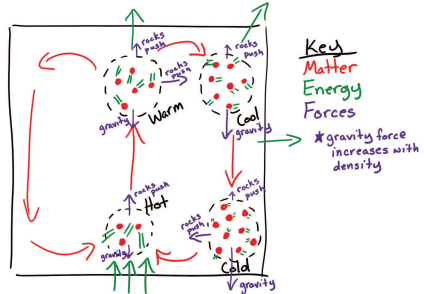
↓ **Navigation to Next Lesson:** We raised new questions about the force interactions, elastic behavior and elastic limits, and energy transfers in solids that could help explain how earthquakes occur.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 4 Lesson Set 1 2 days What is changing in the matter at a particle level before an earthquake, and when a solid elastically deforms or breaks? Investigation 	 <i>When two pieces of foam are pushed in perpendicular directions against each other, they suddenly slip, and sometimes smaller pieces break off the larger ones.</i>	We evaluate different models for understanding and explaining earthquakes, elastic deformation, and breaking of solid matter. We use a computer simulation to investigate how external forces on a solid affect matter changes and energy transfers at the particle level. We revise our M-E-F poster to account for the roles of fields, and we use these ideas to explain volcanic eruptions in an Electronic Exit Ticket. We figure out: • All changes in matter (bending, breaking, state change) are changes in motion, either macroscopic or at the particle level. • If unbalanced forces deform a solid too much, some of the particles in it move far enough apart that their bonds break. • Matter produces various fields (electric, magnetic, gravitational); fields exert forces that act across a distance on other particles. • Energy can be transferred to, transferred from, and stored in fields.	

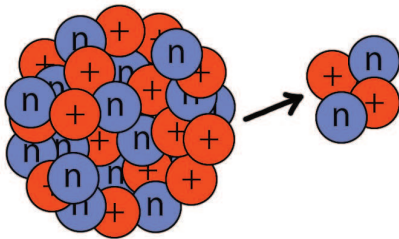
↓ **Navigation to Next Lesson:** Though we can explain earthquakes and volcanoes at plate boundaries, Afar is not very near a plate boundary, so we need additional data to determine what is different about what is happening in the plates or below them at Afar.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 5 Lesson Set 1 3 days How do we investigate the connection between matter in Earth's interior and surface features above? Investigation, Putting Pieces Together 	 <i>Mathematical representations of earthquake data reveal anomalies in the speed at which seismic waves travel through Earth.</i>	We wonder what could be happening in Earth's interior that could cause unbalanced forces on the crust of the Afar region. We investigate how energy transfers differently through different types of matter. We create a scale model to predict how long it should take seismic waves to reach various distances around Earth if the planet is made of solid rock. We analyze seismic data to determine how long it actually takes the waves to reach these distances. We graph the data to explore how well our model fits reality. We figure out: • The speed of a wave through matter depends on the matter through which it is passing. • Seismic velocity data provide evidence that Earth is composed of layers. • Earth has a solid inner core, a liquid outer core, a mantle, and a crust. • Differences in matter in the mantle cause unbalanced forces in different locations, which is why some regions have different kinds of surface features than others.	

↓ **Navigation to Next Lesson:** We wonder how temperature differences and motion in mantle matter could explain forces that cause change on Earth's surface.

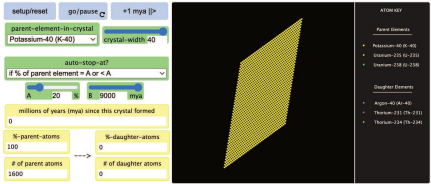
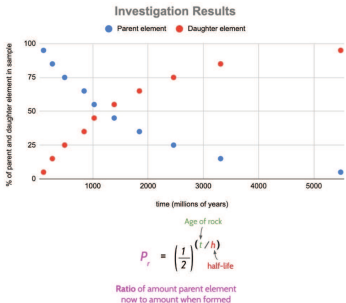
LESSON 6 Lesson Set 1 2 days How is temperature related to the behavior of the matter in the mantle? Investigation 	 <i>When liquid in a fish tank or a lava lamp is heated from below, the solid matter suspended in the liquid moves.</i>	We develop a model to explain the movement of material in the mantle. We analyze a video of a tank simulating the matter in the mantle to figure out what happens to the matter when heat is added. We observe convection in the tank and revise our model to represent it. We compare this model to tomography data and revisit our DQB. We figure out: • Increasing the temperature of matter in the mantle causes particles to move faster and farther apart, occupying a larger volume that results in a lower density. • The relationship between the gravitational force and the pushing forces from beneath that act on matter in different parts of the mantle explains the cycling of matter in Earth's interior through convection.	
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↓ **Navigation to Next Lesson:** We saw that heat affected the density of parcels in the mantle tank, and we think this is also happening in the matter in the mantle. Now we wonder what might be causing this increase in energy that causes the differences in parcel density.

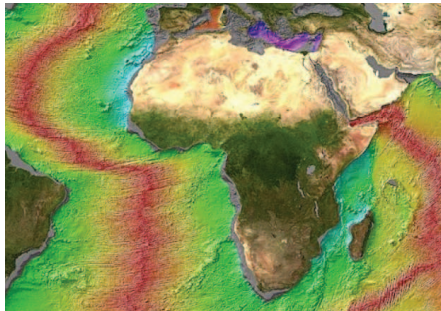
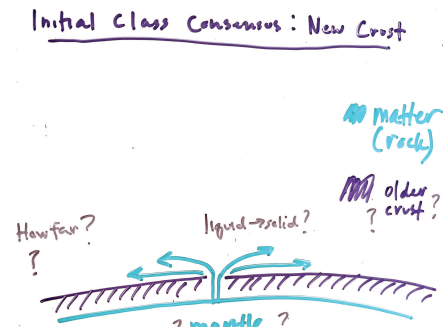
Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it																																										
LESSON 7 Lesson Set 1 2 days Where does the energy that drives convection come from? Investigation, Putting Pieces Together 	 Scientists have used models to predict that a large portion of the heat that drives mantle convection comes from nuclear-scale processes that are unimaginably tiny in comparison.	We want to know where the heat comes from that drives mantle convection. We jigsaw a series of articles that answer this question from a forces perspective, a matter perspective, and an energy perspective. We develop a cause-effect model that integrates these three perspectives to explain how radioactive decay results in the release of enough heat to drive convection in the solid rock of Earth's mantle. We figure out: - Nuclear energy can be modeled as being stored in the mass of the atomic nucleus itself. - An imbalance of forces (strong and electric) in an atomic nucleus can cause particles to leave the atom, transferring kinetic energy into the surrounding material. This is a type of radioactive decay. - Radioactive decay at the subatomic scale continually generates new energy, providing the primary source of the energy that drives mantle convection at the macroscopic scale.	<table><tr><td>1</td><td>Strong forces (for nucleon nuclei)</td><td>causes</td><td>the forces to be unbalanced</td><td>because</td><td>the particles in the nucleus (protons and neutrons) will be further away from each other as the strong forces will be weaker than the E.C. forces</td></tr><tr><td>2</td><td>Unbalanced forces</td><td>causes</td><td>protons and neutrons to be released from the nucleus, or electrons</td><td>because</td><td>the forces holding them together such as the strong or the electric, pulling them apart against</td></tr><tr><td>3</td><td>Particle leaving the nucleus</td><td>causes</td><td>the atom to change into a new atom in a predictable way</td><td>because</td><td>every atom has a unique atomic number and that determines what element it is</td></tr><tr><td>4</td><td>Particle leaving the nucleus, or energy travels out of the nucleus, or the alpha decaying</td><td>causes</td><td>Particles with high kinetic energy to move into the space between between atoms</td><td>because</td><td>the energy that was in the mass of the nucleus is now in the kinetic energy of the moving particles (potential and the mass of the nucleus itself)</td></tr><tr><td>5</td><td>The high KE particles leaving the nucleus</td><td>causes</td><td>Collisions with surrounding atoms</td><td>because</td><td>the neutrons and protons to move fast and collide with other atoms</td></tr><tr><td>6</td><td>Particle colliding with the surrounding atoms</td><td>causes</td><td>Heating of surrounding particles (kinetic particles, thermal energy, particles with high average kinetic energy)</td><td>because</td><td>Collisions transfer energy. The kinetic energy of the moving particles will transfer into the vibrations of the surrounding particles when they collide (thermal energy)</td></tr><tr><td>7</td><td>Heat from radioactive decay</td><td>causes</td><td>material from the mantle to move upward into the crust, and material from the crust to move down into the mantle</td><td>because</td><td>particles of hot material will be less massive per volume, so under natural lighter up will be pushed down, pushing the hot material up - this is called convection</td></tr></table>	1	Strong forces (for nucleon nuclei)	causes	the forces to be unbalanced	because	the particles in the nucleus (protons and neutrons) will be further away from each other as the strong forces will be weaker than the E.C. forces	2	Unbalanced forces	causes	protons and neutrons to be released from the nucleus, or electrons	because	the forces holding them together such as the strong or the electric, pulling them apart against	3	Particle leaving the nucleus	causes	the atom to change into a new atom in a predictable way	because	every atom has a unique atomic number and that determines what element it is	4	Particle leaving the nucleus, or energy travels out of the nucleus, or the alpha decaying	causes	Particles with high kinetic energy to move into the space between between atoms	because	the energy that was in the mass of the nucleus is now in the kinetic energy of the moving particles (potential and the mass of the nucleus itself)	5	The high KE particles leaving the nucleus	causes	Collisions with surrounding atoms	because	the neutrons and protons to move fast and collide with other atoms	6	Particle colliding with the surrounding atoms	causes	Heating of surrounding particles (kinetic particles, thermal energy, particles with high average kinetic energy)	because	Collisions transfer energy. 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↓ **Navigation to Next Lesson:** Radioactive decay helped us understand what might be driving some of the processes we see in Earth's mantle. We wonder whether we will find radioactive material in the rock in the Afar region.

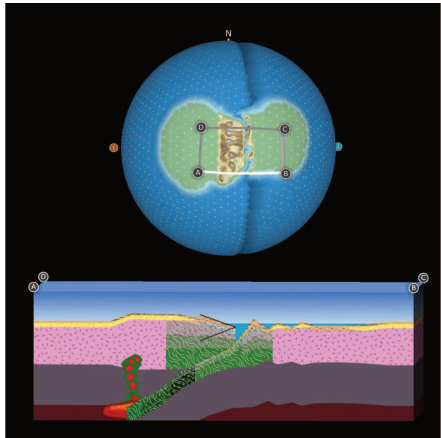
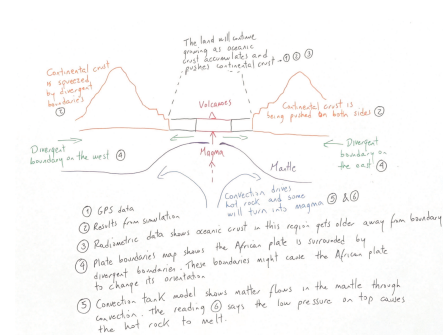
Lesson Set 2: How do forces determine what will happen on Earth's surface?

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 8 Lesson Set 2 3 days Is the rock at Afar radioactive, and what can that tell us? Investigation 	 Crystals from different rock samples around the Afar region contain different amounts of U-238 and K-40. The atoms in a simulation of radioactive elements within a crystal change over time from one type of atom to another.	We analyze the radioactive element composition of rocks from Afar. We use a simulation to collect data on how the amount of radioactive material in a rock crystal changes over time. We use mathematical thinking to compare patterns in our graphs to those in an equation of exponential decay, and we use that equation to determine the age of rocks from Afar. We figure out: - Radioactive decay of elements follows a characteristic exponential decay law, with a specific lifetime (timescale) for each; we can use this to determine the ages of rocks and other materials from the ratio of parent to daughter elements present. - Some of the rock on the western and eastern edges of Afar formed hundreds of million years ago. But most of the rock in the middle of the Afar region is very young, appearing over the last few million years.	

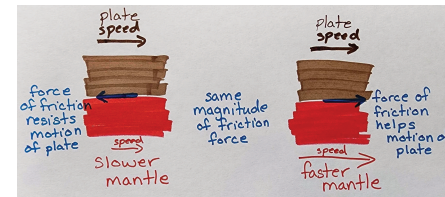
↓ **Navigation to Next Lesson:** Now that we have a way to determine the age of any rock, we think that comparing the ages of rocks found in other parts of the world to those found at Afar could help us figure out how long the processes going on Afar might continue, and how they might be similar or different to changes that have happened elsewhere on Earth.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 9 Lesson Set 2 2 days How does the rock in Afar compare to the rock around the world, and what does this tell us about the history and future of the region? Investigation 	 <i>A map of crustal ages on continents and in the ocean shows several puzzling patterns, including very young basalt in the Afar region.</i>	We look at data on the crustal ages of rocks around the world and notice that the farther the rock is from some plate boundaries in the ocean, the older it is. We model what might be going on at these boundaries. We determine the density of basalt (oceanic crust) and granite (continental crust) and wonder about how that affects forces and energy transfer. Finally, we add questions to the DQB about plate boundaries and types of crust. We figure out: - Continental crust is, on average, significantly older and less dense than oceanic crust. - As you move outward from some plate boundaries in the middle of the ocean, the basalt rocks get older, suggesting that the material originated at the boundary and was pushed outward over a large timescale. - The new rock in Afar is young basalt, suggesting that a similar process may be occurring there.	<u>Initial Class Consensus: New Crust</u> 

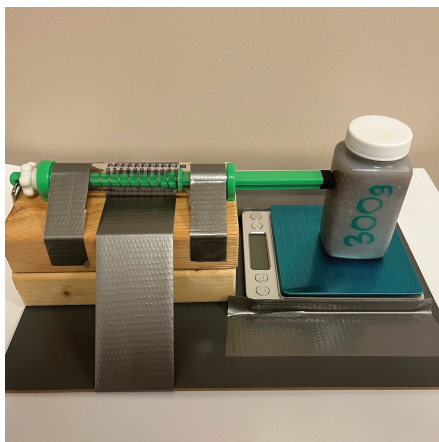
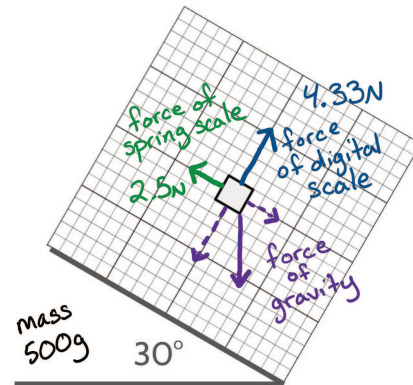
↓ **Navigation to Next Lesson:** We want to know whether all places where plates are in contact look like these lines in the ocean where basalt is forming. We decide to look more closely at plate boundaries where continental crust meets oceanic crust.

LESSON 10 Lesson Set 2 2 days What is happening at plate boundaries? Investigation 	 <i>The interactions of plates in a simulation show changes in matter in the mantle and on the surface near plate boundaries.</i>	We use a simulation to investigate how plates interact at divergent and convergent plate boundaries. We analyze data to compare the surface features on Earth to the surface features represented in the simulation. We develop a model that explains how the interactions of plates result in the surface features we identified. We wonder which forces are acting on plates that can help us explain the patterns we identified in their motion. We figure out: The movement of plates and their interactions at plate boundaries shape the planet's surface features, such as mountains, islands, earthquakes, and volcanoes.	
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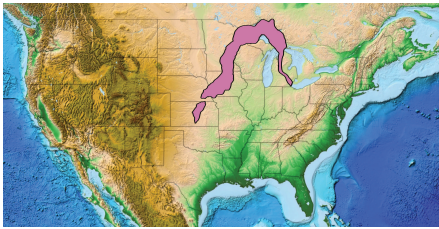
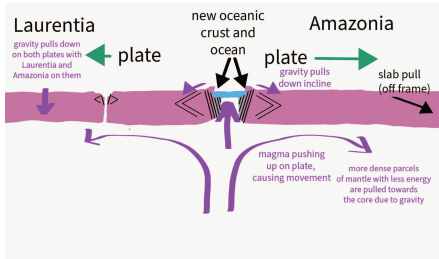
↓ **Navigation to Next Lesson:** We are wondering which forces are acting on plates that could help us explain their motion patterns on the surface and in the mantle.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 11 Lesson Set 2 2 days How might forces between the mantle and plates affect plate motion? Investigation 	 <i>Different objects require different amounts of force to drag them at a constant velocity.</i>	We investigate variables that we consider may affect friction forces between an object and the surface it slides over. We connect our conclusions from our investigations to properties of the plates and motion. We figure out: The force of friction depends on the mass of the object and the material of the surfaces rubbing together, but not on the surface area between the object and the surface.	

↓ Navigation to Next Lesson: We are still wondering how other forces, like gravity, affect plate motion.

LESSON 12 Lesson Set 2 2 days How do forces act on objects, such as the plates, when they are on inclines? Investigation, Putting Pieces Together 	 <i>Changing the incline of an object ramp changes the weight registered on a scale under the object and the magnitude of the force registered on a spring scale against the object.</i>	We model forces acting on plates and investigate forces on an object placed on an incline. We model how the force of gravity can be split into two vector components to make sense of how gravity pulls down inclines, and we connect this to plate motion to update our plate interactions model. We figure out: - The force of gravity can be broken into components that pull parallel and perpendicular to an incline, and as the incline gets steeper, the component of gravity parallel to the incline increases. - The force of gravity on an object is directly proportional to the mass of the object. - The force of gravity contributes to changes in plate motion through processes called slab pull and ridge push.	
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↓ Navigation to Next Lesson: We have revised our consensus model of plate interactions and are wondering how it might explain other Earth events.

Lesson Question	Phenomena or Design Problem	What we do and figure out	How we represent it
LESSON 13 Lesson Set 2 1 day How can we use our science ideas to explain what happened at the Midcontinent Rift? Putting Pieces Together 	 <i>The Midcontinent Rift started to tear apart like the Afar rift, but failed.</i>	We revisit our Scale Chart poster and Driving Question Board and complete a transfer task comparing the fate of the Midcontinent Ridge to the growing Afar rift. - Many processes on the Scale Chart poster have effects on other processes at different scales. - Processes that occurred at the Midcontinent Rift 1.1 billion years ago are similar to what is occurring at Afar today. - Thermal convection and the interaction of forces with plates can be used to explain how the Midcontinent Rift failed.	

↓ Navigation to Next Lesson: There is no next lesson.

LESSONS 1-13

27.5 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, non-latex 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 non-latex apron, and non-latex gloves during the set-up, 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, etc.). 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/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 teacher's instructions.
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 callout box.

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

This unit is the second in the OpenSciEd High School Physics course sequence. It is designed to build on student ideas about energy transfer and matter interactions from the course's first unit, *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*. In that first unit, 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 this unit, Earth science phenomena that transfer energy differently across scales of time and space will motivate the need for forces to explain observations. Students establish conventions for modeling

forces using free-body diagrams and think deeply about the connection between unbalanced forces, energy transfer, and motion. Although they do not quantify the relationship between forces and acceleration in this unit, they develop a robust intuitive understanding of forces, which will be fundamental to deriving and applying Newton's second law ($F=ma$), which will form the basis for the way forces are applied over the next several units.

In the course's third unit, *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*, students develop a more robust understanding of forces as vectors and use conservation of momentum to make predictions about the outcomes of collisions. In the fourth unit, *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)*, they expand their model of forces to include the force 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 fifth unit, *OpenSciEd Unit P.5: How do we use radiation in our lives and is it safe for humans? (Microwave Unit)*, they use energy transfer, electromagnetism, wave mechanics, and forces at a distance to explain how food heats up in a microwave and how this technology might be dangerous for humans. In the final unit, *OpenSciEd Unit P.6: Why do stars shine and will they shine forever? (Stars)*, students explore cosmology and the Big Bang, applying ideas about forces and energy from all five previous units on the largest scale.

What is the anchoring phenomenon and why was it chosen?

This unit is anchored by a puzzling Earth science phenomenon: the land in East Africa appears to be ripping apart. In 2005, a crack opened up very suddenly in a region called Afar in Ethiopia, accompanied by earthquakes and a volcanic eruption. This phenomenon provides the context in which to investigate the relationship between unbalanced forces and energy transfer through systems, how radioactive decay on the particle scale drives global-scale convection, and the role of plate tectonics in explaining Earth's surface features. This unit uses fundamental physics ideas about how unbalanced forces transfer energy through systems, causing motion. The unit then uses these ideas to describe and explain fundamental Earth science ideas about how the hidden processes playing out in Earth's interior over short and long temporal/spatial scales shape the surface patterns we see.

The Afar 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 1000 students from across the country, and in consultation with external advisory panels that include teachers, subject matter experts, and state science administrators. The phenomena in units 1, 3, 4, and 5 were chosen because they have high relevance to students' everyday experiences and communities. The phenomenon in this unit is playing out on a timescale at which it can be difficult to see the relevance to human lives. This more abstract and Earth-scale phenomenon was chosen with a purpose. The full physics course is designed to purposefully highlight a variety of different types of phenomena, some of which overlap: from justice-oriented (P1, P3), to everyday (P3, P5), to culturally embedded (P4), to more abstract (P2, P6). Though 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 homogeneous 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.

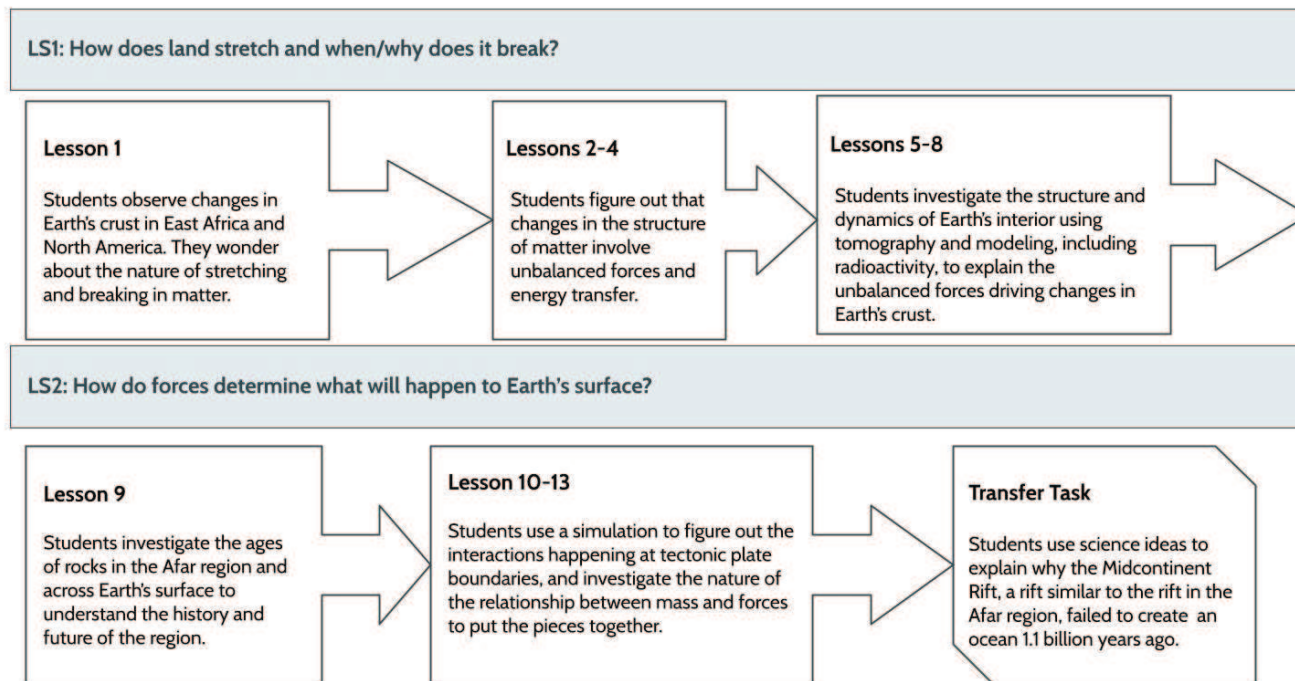
The Afar phenomenon was chosen for the following reasons:

- Students showed high interest in explaining unique and puzzling surface features in survey data.
- To provide a diverse suite of entry points across the course, we were seeking an event that allowed students to consider a global-scale phenomenon.
- Teachers and administrators saw the phenomenon as interesting and on grade band.
- Explaining the mechanisms of Earth's interior using physics concepts grounds abstract ideas about forces.
- Explaining the phenomenon addresses all the disciplinary core ideas in the bundle at a high school level.
- Explaining the phenomenon requires the use of both forces and energy in order to understand sudden and long-timescale change.

How is the unit structured?

The unit is organized into two main lesson sets. **Lesson Set 1** (Lessons 1-8) focuses on answering the question: *How does land stretch and when/why does it break?* In the first lesson set, students make observations of a series of changes in Earth's crust over short and long timescales that reveal patterns at a local scale in a region called the Afar Triangle in Ethiopia, and at a larger scale along the eastern half of the African continent. This leads them to wonder about the nature of stretching and breaking in matter. They work with manipulatives and simulations to establish the role of unbalanced forces in natural processes, which helps them figure out why some energy transfer processes in Earth's crust are slow and stable but others are sudden and unpredictable. Their investigations lead them to explore seismography and tomography data, which allows them to model the structure of Earth's interior and notice dynamic patterns in the mantle. To explain these patterns, students observe a model of mantle convection and read about radioactivity, which gives them the tools to describe mantle processes from a forces, matter, and energy transfer perspective.

Lesson Set 2 (Lessons 9-13) focuses on answering the question: *How do forces determine what will happen to Earth's surface?* In the second lesson set, students apply their new ideas about radioactivity to understand radiometric dating, and discover that many of the rocks in the Afar region are very young compared to the surrounding area. They explore the differences in density between oceanic and continental rocks (basalt and granite) and figure out that just as density differences can cause an unbalance of forces in the mantle, they can also cause an unbalance of forces in the crust due to an emergent relationship between mass and gravitational force, which can contribute to the movement of tectonic plates. Finally, students put the pieces together to predict what will happen to the Afar region in the geological future and apply their understanding to explain why the Midcontinent Rift failed 1.1 billion years ago.



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

This unit is designed to introduce students to the concept of force in an intuitive and grounded context, allowing them to make strong connections between forces, energy transfer, and matter changes that they can carry forward into the rest of the course and beyond. In addition, this unit supports students in understanding fundamental Earth science ideas related to plate tectonics, radioactivity, convection, and rock formation at a high school level.

The crosscutting concept of **scale, proportion, and quantity** is **intentionally developed** across this unit. Students add to a Scale Chart that they use to track important mechanisms and structures across scales of time and space, beginning with the spatial scale of the events in Lesson 1, and progressing to both spatial and temporal processes through the end of the unit. Throughout this unit, students **apply cause-and-effect reasoning** to build **complex mechanistic explanations** that span **across scales**; for example, how **nuclear processes at the scale of an atomic nucleus** can be part of a **cause-and-effect** chain that helps to explain **plate tectonics, and thus Earth's changing surface**. They use the Scale Chart (and their Progress Trackers) to keep track of new cause-effect connections across scales.

Students also use the Scale Chart to consider how **stability and change** manifest differently at different **scales** (i.e., a **system that appears stable at a macro scale might be unstable at an atomic scale**). In this way, the crosscutting concept of **stability and change** is also **intentionally developed across the unit**. To support this sensemaking, the crosscutting concepts of **cause and effect** and **scale proportion and quantity**, and the science and engineering practice of **constructing explanations**, are **intentionally developed** in this unit.

This unit **intentionally develops** students' engagement in **developing and using models** by providing opportunities for students to model **tectonic processes across scales** and to move flexibly between **different types of models**, including **manipulative models, diagrammatic models, cause-effect models**, descriptive models, cross-sectional models, and mathematical models. Students use evidence from a variety of sources to inform the development and **revision of these models**. Students apply the *Matter-Energy-Forces triangle framework* that they have developed to model key interactions within a system.

This unit **intentionally develops** the crosscutting concept of **energy and matter** using a tool called the *Matter-Energy-Forces triangle*. **Students model** the **transfer of energy** through **subsystems in Earth's geosphere**, such as through **convection** and volcanic eruptions, and keep track of how energy transfer impacts matter change and cycling. They add forces to their understanding of **energy and matter**, and develop an intuitive understanding of how forces transfer energy and deform matter. They also develop conventions for free-body diagrams, a type of modeling that is key to building explanations in classical mechanics and will be important in *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*, as students figure out Newton's second law.

This unit builds toward these performance expectations:

- HS-ESS1-5** Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks.
- HS-ESS2-1†** Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.
- HS-ESS2-3** Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection.
- HS-PS1-8†** Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay.

*This performance expectation is developed across multiple units. This unit reinforces these NGSS PEs in a physics context.

†This performance expectation is developed across multiple courses. This unit reinforces or works toward these NGSS PEs that students will have previously developed in the OpenSciEd Chemistry and/or Biology courses.

Science and Engineering Practices	Disciplinary Core Ideas*	Crosscutting Concepts
Developing and using models in 9–12 builds on K–8 experiences and progresses to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds. The following elements of this practice are intentionally developed across this unit: - Evaluate merits and limitations of two different models of the same proposed tool, process, mechanism, or system in order to select or revise a model that best fits the evidence or design criteria. - 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. - Develop and/or use multiple types of models to provide mechanistic accounts and/or predict phenomena, and move flexibly between model types based on merits and limitations. - Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems. Constructing explanations and designing solutions in 9–12 builds on K–8 experiences and progresses to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories. The following elements of this practice are intentionally developed across this unit: - Make a quantitative and/or qualitative claim regarding the relationship between dependent and independent variables. - Construct and revise an explanation based on valid and reliable evidence obtained from a variety of sources (including students' own investigations, models, theories, simulations, peer review) and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future. Elements from the following practices are also key to the sensemaking in this unit: - Asking Questions - Obtaining, Evaluating, and Communicating Information - Planning and Carrying Out Investigations - Using Mathematics and Computational Thinking - Analyzing and Interpreting Data	PS2.B: Types of Interactions - 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) - Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects. (HS-PS2-6, secondary to HS-PS1-1, secondary to HS-PS1-3) This DCI is associated with a performance expectation that is not included in the bundle for this unit, and is addressed in the OpenSciEd HS Chemistry course. Applying this idea is key to building the ideas necessary to explain breaking in Earth's crust.) PS3.A: 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) (- 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) This DCI is associated with a performance expectation that is not included in the bundle for this unit, and is addressed in the first unit in this course. Applying this idea is key to building the ideas necessary to explain breaking in Earth's crust.) 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-PS3-2) This DCI is associated with a performance expectation that is not included in the bundle for this unit, and is addressed in the first unit in this course. Applying this idea is key to building the ideas necessary to explain breaking in Earth's crust.) PS4.A: Wave Properties The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing. (HS-PS4-1) This DCI is associated with a performance expectation that is not included in the bundle for this unit, and the parts that are crossed out here are addressed in the fifth unit in this course, when students investigate electromagnetic waves. - Geologists use seismic waves and their reflection at interfaces between layers to probe structures deep in the planet. (secondary to HS-ESS2-3) PS1.C: Nuclear Processes	Scale, Proportion, and Quantity. In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system. The following elements of this crosscutting concept are intentionally developed across this unit: - Some systems can only be studied indirectly as they are too small, too large, too fast, or too slow to observe directly. - Patterns observable at one scale may not be observable or exist at other scales. Energy and Matter. Tracking energy and matter flows, into, out of, and within systems helps in understanding their system's behavior. The following elements of this crosscutting concept are intentionally developed across this unit: - The total amount of energy and matter in closed systems is conserved. - 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. - Energy cannot be created or destroyed—it only moves between one place and another place, between objects and/or fields, or between systems. Cause and Effect. Events have causes, sometimes simple, sometimes multifaceted. A major activity of science is investigating and explaining causal relationships and the mechanisms by which they are mediated. The following elements of this crosscutting concept are intentionally developed across this unit: - Cause-and-effect relationships can be suggested and predicted for complex natural and human-designed systems by examining what is known about smaller-scale mechanisms within the system. Patterns. Observed patterns in nature guide organization and classification and prompt questions about relationships and underlying causes. The following elements of this crosscutting concept are intentionally developed across this unit: - 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. - Classifications or explanations used at one scale may fail or need revision when information from smaller or larger scales is introduced, thus

	• Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process. (HS-PS1-8) • 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 to HS-ESS1-5, secondary to HS-ESS1-6) ESS1.C: The History of Planet Earth • Continental rocks, which can be older than 4 billion years, are generally much older than the rocks of the ocean floor, which are less than 200 million years old. (HS-ESS1-5) ESS2.A: Earth Materials and Systems • Earth's systems, being dynamic and interacting, cause feedback effects that can increase or decrease the original changes. (HS-ESS2-1, HS-ESS2-2) • 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) ESS2.B: Plate Tectonics and Large-Scale System Interactions • The radioactive decay of unstable isotopes continually generates new energy within Earth's crust and mantle, providing the primary source of the heat that drives mantle convection. Plate tectonics can be viewed as the surface expression of mantle convection. (HS-ESS2-3) • 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. (ESS2.B Grade 8 GBE) (secondary to HS-ESS1-5) • 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. • Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust. (HS-ESS2-1)	requiring improved investigations and experiments. • Mathematical representations are needed to identify some patterns. • Empirical evidence is needed to identify patterns. Stability and Change. For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system are critical elements of study. The following elements of this crosscutting concept are intentionally developed across this unit: • Much of science deals with constructing explanations of how things change and how they remain stable. The following crosscutting concepts are also key to the sensemaking in this unit: • Structure and Function • Systems and Systems Models
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*"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)

Connections to the Nature of Science (NOS)	
Which elements of NOS are developed in the unit?	How are they developed?
Scientific Knowledge Is Based on Empirical Evidence. Science includes the process of coordinating patterns of evidence with current theory.	In Lesson 5, students coordinate patterns of evidence with a model of Earth's interior. They respond to a reflection question during the navigation into day 2 on how empirical evidence helped them identify patterns and anomalies in seismic velocities to support their reasoning about the plausibility of the layers model.
Scientific Investigations Use a Variety of Methods. Scientific inquiry is characterized by a common set of values that include: logical thinking, precision, open-mindedness, objectivity, skepticism, replicability of results, and honest and ethical reporting of findings.	In Lesson 2, students are asked to consider whether they need to collect more trials in light of their empirical results. The class discusses data accuracy, the number of trials needed, potential causes of errors, outliers, and uncertainty in an investigation. In Lesson 8, students assess the accuracy and replicability of their results as they investigate radioactive decay using a simulation. Working in groups and as a class, they discuss the importance of accuracy and replicability in scientific investigations.
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 13, the Scale Chart is revisited to determine that the models, mechanisms identified, and explanations used in the unit up to Lesson 13 represent the Theory of Plate Tectonics. The items on the Scale Chart are grouped and labeled the Theory of Plate Tectonics.
Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena. Scientists often use hypotheses to develop and test theories and explanations.	In Lesson 11, students use sentence stems to develop explanatory hypotheses that describe how they predict independent variables are related to the dependent variable of the amount of friction force acting on an object.

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

OpenSciEd units support students in integrated development and use of the three dimensions. No single dimension can be developed in isolation from the others, as reflected in three-dimensional lesson-level performance expectations (LLPEs), which detail the specific dimensions and elements used and assessed in each lesson. However, some practices and crosscutting concepts are more productive for investigating particular anchoring phenomena, so focal practices and crosscutting concepts are articulated in each unit. All 46 SEP and 29 CCC elements are developed at some point in the high school OpenSciEd program, so all elements of a given SEP or CCC may not be present even in a unit that emphasizes developing that SEP or CCC.

This unit uses and builds upon the following **disciplinary core ideas (DCIs)** and other science ideas that students should have previously developed in the **OpenSciEd High School Biology and Chemistry courses**:

- We can trace energy flow in systems using computational models because energy is conserved. (*Serengeti Unit* and *Fuels Unit*)
- Thermal energy transfer through particle collisions may result in phase change of matter as the average kinetic energy (temperature) of the matter rises or falls. It is easier to raise the temperature of a substance with less mass. (*Polar Ice Unit*)
- Atoms have nuclei with protons and neutrons--the number of nuclear particles is conserved in nuclear processes. (*Electrostatics Unit* and *Fuels Unit*)

This unit uses and builds upon **DCIs** and other science ideas that students should have previously developed in this course:

- Energy transfers through systems and is conserved. (*Electricity Unit*)
- Energy can be transformed into less useful forms. (*Electricity Unit*)
- Matter and energy can flow together. (*Electricity Unit*)

This unit also reinforces and builds from the following **DCI elements** from the **OpenSciEd Middle School sequence**:

- Thermal energy describes the average kinetic energy of particles in a system, and can be transferred through particle collisions. (*Cup Design Unit*)
- Mechanical waves transfer energy through space by changing the position of particles in a medium such as water or air. (*Sound Unit*)
- Earth's crust is broken into plates that move and change surface features as they interact. (*Everest Unit*)
- Forces cause matter changes, and energy transfer (*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 forces and Earth dynamics derived from previous classroom experiences, intuitive understandings of the way the world works, everyday experiences with movement, and conversations they have had with parents, friends, and family members.

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

1. A continuous force is needed for continuous motion.
2. Direction of motion implies direction of force.
3. The mantle is liquid, and convection can only occur in a liquid.
4. Only continents move, floating on top of oceans.
5. Most crust motions (especially those associated with processes of mountain building or deep sea trench formation) are due to vertical motions, not lateral.
6. The only place magma reaches the surface is at volcanoes.
7. Plate movement is imperceptible on a human time frame.
8. Plate motion is rapid enough that continent collision can injure animals and plants.
9. The weight of oceans is responsible for the higher density of oceanic crust.
10. The edge of a continent is the same thing as a plate boundary.
11. A plate boundary type is the same thing as a plate. For example, a plate has to be divergent or convergent.

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. For example, in Lesson 5, students explore the idea that Earth might be solid rock all the way through. In fact, Earth most likely has a liquid outer core, in addition to small pockets of magma throughout the mantle. Building explicitly from these ideas to draw connections is a productive pedagogical tool that will help students construct a new, more accurate conceptual model for convection.

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

This is the second 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 Physics first, or teaching this unit earlier in the Physics course. These include the following adjustments:

- If taught before OpenSciEd High School Chemistry, supplemental teaching of the particle model of matter will be required, including a conceptual understanding of the nature of electrons, nuclei, and atoms. You will also need to review the nature of thermal energy and thermal energy transfer.
- 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 as part of an AP physics course, be prepared to provide students with additional support around equations that are not treated in depth.

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 8: Shorten the investigation time within the lesson.
- Lesson 9: Instead of conducting the Rock Sample Density Lab, give students the data from this investigation to work with instead.
- Lessons 11-12: You could give students the data, instead of having them conduct the investigation, or give them the investigation design to collect their own data.
- The first half of the unit attends more heavily to DCIs related to physics, whereas the second lesson set attends more heavily to the interdisciplinary connections between physics and Earth science. Though it is not recommended, there are two other options for condensing. To focus on primarily a physics perspective, you could teach Lessons 1-6, 11-12, and modify the assessment in Lesson 13. To focus primarily on an Earth science perspective, you could teach Lessons 1, 4-10, add in ideas of slab push and ridge pull to 10, and modify the assessment in Lesson 13.

To extend or enhance the unit, consider the following:

- Lesson 1: Use the guidance given in Lesson 1 about collaborating with the English Language Arts department to create expository texts.
- Lesson 4: There is an information tab in the simulation that describes the model rules further and a code tab that lets students inspect, modify, and recompile the code for the model, for students who are interested.
- Lesson 10: This lesson utilizes specific features of the simulation. Consider allowing students to further explore the features of the simulator, and build in class time for them to come to consensus around their findings.
- Lesson 12: Discussions could be led around how increasing the incline made the perpendicular component of gravity read by the digital scale decrease, and how this means that friction would decrease as the angle increased, among other discussions.
- 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 but is not math-intensive. Students apply the Pythagorean theorem to understand how forces function as vectors. Students need to gather and represent data in ways that can help them identify patterns in investigation results, tomography, seismic data, and maps.

The unit does not assume fluency 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 listed below:

Category	Code	Domain and Heading	Standard	Relevant Lessons
Number and Quantity	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.	2, 11, 12, 13
Number and Quantity	CCSS.MATH.CONTENT.HS.N-VM.3	Vector and Matrix Quantities: Represent and model with vector quantities.	Solve problems involving velocity and other quantities that can be represented by vectors.	2, 11, 12
Algebra	CCSS.MATH.CONTENT.HS.A-SSE.1b	Seeing Structure in Expressions: Interpret the structure of expressions.	Interpret complicated expressions by viewing one or more of their parts as a single entity. For example, interpret $P(1+r)^n$ as the product of P and a factor not depending on P .	8
Algebra	CCSS.MATH.CONTENT.HS.A-CED.2	Creating Equations: Create equations that describe numbers or relationships.	Create equations in two or more variables to represent relationships between quantities; graph equations on coordinate axes with labels and scales.	5
Geometry	CCSS.MATH.CONTENT.HSG.SRT.C.8	Similarity, Right Triangles, and Trigonometry: Define trigonometric ratios and solve problems involving right triangles.	Use trigonometric ratios and the Pythagorean theorem to solve right triangles in applied problems.	12

See individual lessons referenced above for details.

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 that are integrated throughout the OpenSciEd routines and are intended to increase relevance and provide access to science learning for all students. These equity goals are supported 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) offering specific strategies for supporting emerging multilingual students in science classrooms.

Many of these strategies are highlighted in the *Teacher Guide* in sidebar callout boxes with these headings:

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

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 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 (**PS2.B: Types of Interactions**, **PS3.A: Definitions of Energy**, **PS3.B: Conservation of Energy and Energy Transfer**, **PS4.A: Wave Properties**, **PS1.C: Nuclear Processes**, **ESS1.C: The History of Planet Earth**, **ESS2.A: Earth Materials and Systems**, **ESS2.B: Plate Tectonics and Large-Scale System Interactions**), 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 are recommended resources that can help build your understanding of the phenomena and performance expectations bundle for this unit:

- To learn more about the culture and history of the Afar region, and the events in 2005:
 - <https://www.nationalgeographic.com/magazine/article/africas-afar-depression>
 - <https://www.newscientist.com/article/dn18114-giant-crack-in-africa-formed-in-just-days/>
 - https://www.esa.int/Applications/Observing_the_Earth/Envisat/ESA_s_Envisat_satellite_witnesses_Earth_s_largest_crack
- To learn more about what geologists believe might be happening beneath the surface in East Africa, and the future of the continent:
 - <https://www.nbcnews.com/science/environment/african-continent-very-slowly-peeling-apart-scientists-say-new-ocean-n1234128>
 - <https://www.livescience.com/10592-giant-crack-africa-create-ocean.html>
 - <https://www.discovermagazine.com/planet-earth/africas-big-break>
 - <https://www.scientificamerican.com/article/a-superplume-is-the-reason-africa-is-splitting-apart/>
 - <https://www.nature.com/articles/s41467-019-13181-7>

How do I support students' emotional needs?

In this unit, students analyze data on earthquakes and volcanoes. It is important to keep in mind throughout this unit that these events can be traumatic, and recalling past experiences or learning about others' experiences can be triggering. Adolescents may develop symptoms following a geologic hazard, such as difficult behaviors or emotions shown at home or school. According to the CDC, "Adopting a trauma-informed approach is not accomplished through any single particular technique or checklist. It requires constant attention, caring awareness, [and] sensitivity."

Before beginning this unit, make sure to reach out to the counselor at your school for student-specific support and strategies that might be needed in regard to the students in your classroom, and consider asking the counselor to join you on the first day of instruction. Also consider planning follow-up check-ins with the counselor in regard to any students who may need additional emotional support.

Reach out to students' support systems at home before the unit, using *Afar Unit Home Communication*. This letter is a way to communicate with trusted adults and make them aware of the unit's content. The letter also provides an opportunity for trusted adults to share important context with you about students' experiences and background that might be relevant. This topic can be sensitive for those who have experienced injury, trauma, or loss due to a geologic hazard. Please be mindful of this and provide safety and support by sharing awareness. If there is time, consider beginning the class with a brief mindfulness activity (see *Afar SEL Supports* for suggestions).

Be aware that students who are struggling may demonstrate a variety of behaviors including but not limited to: fidgeting, withdrawal, disruption or distraction, rapid breathing, holding their breath, change in body language or tonation. If you notice a student might be struggling, share what you are observing and ask if they need some help.

Often in science classrooms, we are focused on evidence and data. When addressing a phenomenon or design solution that straddles the nature-cultural divide, like this one, supporting students in using an empathy or socio-emotional lens will also be important. Make space for students to process, and validate their feelings and reactions. For more support around Social and Emotional Learning, visit <https://casel.org>. For more trauma-informed strategies to support your students' emotional needs, please visit <https://tra nsformingeducation.org/>.

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 notebooks. 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 only 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. These are not intended as a vocabulary list for students to study before a lesson, as that would undermine the authentic and lasting connection they 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-construct	Words and equations with meanings we encounter
L1		
L2	vector, magnitude, force, balanced forces, unbalanced forces, net force, contact forces, plate	vector component
L3	elastic behavior, deformation, elastic limit	
L4	bond, electric field, pressure	compression, tension, nucleus, protons, electrons, magnetic field
L5	heterogeneous, seismic waves, anomaly	homogeneous, seismic waves, Moho, tectonic plates
L6	convection	
L7	radioactive decay	neutron
L8		crystal, spectrometer, parent element, daughter element
L9	plate boundary, continental crust, oceanic crust	
L10	convergent boundary, divergent boundary, transform boundary	
L11	friction	
L12	slab pull, ridge push	
L13		

HOME COMMUNICATION

Dear Guardian,

Your child's high school physics class is starting a unit called, *How do forces in Earth's interior determine what will happen to the surface we see?* as part of the OpenSciEd high school science curriculum. This unit establishes fundamental physics ideas about how unbalanced forces transfer energy through systems, causing motion. Those ideas are then used to describe and explain fundamental Earth science ideas about how the hidden processes playing out in Earth's interior over short and long temporal/spatial scales shape the surface patterns we see.

This unit is anchored by a puzzling Earth science phenomenon: an area of land in East Africa appears to be ripping apart. In 2005, a crack opened up very suddenly in a region called Afar in Ethiopia, accompanied by earthquakes and a volcanic eruption. This phenomenon provides the context in which to investigate the relationship between unbalanced forces and energy transfer in systems, how radioactive decay on the particle scale drives global-scale convection, and the role of plate tectonics in explaining Earth's surface features.

Students may come home with questions about earthquakes, volcanoes, and other Earth science phenomena. Share your experiences, ideas, and questions with them.

Geologic hazards can be traumatic, and recalling past experiences or learning about other people's experiences can be triggering. If your child or someone close to your child has sustained an injury, lost a loved one, or experienced any trauma due to an earthquake or a volcanic event, please contact me at _____, if you are comfortable doing so. You can also contact the school counselor at _____. By knowing about these experiences in advance, we can be sensitive to students' needs and provide support if they experience any strong emotions during this unit.

Adolescents will sometimes develop difficult behaviors after a geologic hazard. It is important for trusted adults to understand that these behaviors and emotions are common when children experience trauma. Students may be more aggressive or withdrawn, and go through periods of sadness or anger or emotional "numbing." Contact a counselor if you see any of the following behaviors in your child:

- problems sleeping, nightmares
- changes in school performance
- truancy
- risk-taking behavior
- conflicts with peers
- new or increasing psychosomatic complaints, including stomachaches and headaches
- depression or suicidal thoughts

Being able to talk to someone who is removed from the situation is often helpful to both adults and children after a traumatic event. After experiencing trauma, children are best supported when their parents or trusted caregivers accept their feelings and are open to listen and talk. Let your child come to you. Do not overwhelm them if they are not ready to talk. Respect their need to take breaks.

Reach out to a counselor or support center if you are concerned about trauma your child may have due to experiences related to a geologic hazard.

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,

Querido tutor,

La clase de física de la escuela secundaria de su hijo está comenzando una unidad llamada, *¿Cómo determinan las fuerzas en el interior de la Tierra lo que sucederá con la superficie que vemos?* como parte del currículo de ciencias de secundaria OpenSciEd. Esta unidad establece ideas físicas fundamentales sobre cómo las fuerzas desequilibradas transfieren energía a través de sistemas, provocando movimiento. Luego, esas ideas se utilizan para describir y explicar ideas fundamentales de las ciencias de la Tierra sobre cómo los procesos ocultos que se desarrollan en el interior de la Tierra en escalas temporales/espaciales cortas y largas dan forma a los patrones de superficie que vemos.

Esta unidad está anclada en un fenómeno desconcertante de las ciencias de la Tierra: un área de tierra en el este de África parece estar destrozándose. En 2005, de repente se abrió una grieta en una región llamada Afar, en Etiopía, acompañada de terremotos y una erupción volcánica. Este fenómeno proporciona el contexto en el que investigar la relación entre las fuerzas desequilibradas y la transferencia de energía en los sistemas, cómo la desintegración radiactiva a escala de partículas impulsa la convección a escala global y el papel de la

tectónica de placas a la hora de explicar las características de la superficie de la Tierra.

Los estudiantes pueden regresar a casa con preguntas sobre terremotos, volcanes y otros fenómenos de las ciencias de la Tierra. Comparta sus experiencias, ideas y preguntas con ellos.

Los peligros geológicos pueden ser traumáticos y recordar experiencias pasadas o conocer las experiencias de otras personas puede ser un desencadenante. Si su hijo o alguien cercano a él sufrió una lesión, perdió a un ser querido o experimentó algún trauma debido a un terremoto o evento volcánico, comuníquese conmigo al _____, si se siente cómodo haciéndolo. También puede comunicarse con el consejero escolar al _____. Al conocer estas experiencias de antemano, podemos ser sensibles a las necesidades de los estudiantes y brindarles apoyo si experimentan emociones fuertes durante esta unidad.

Los adolescentes a veces desarrollan comportamientos difíciles después de un peligro geológico. Es importante que los adultos de confianza comprendan que estos comportamientos y emociones son comunes cuando los niños experimentan un trauma. Los estudiantes pueden ser más agresivos o retraídos y pasar por períodos de tristeza, enojo o "adormecimiento" emocional. Comuníquese con un consejero si observa alguno de los siguientes comportamientos en su hijo:

- problemas para dormir, pesadillas
- cambios en el rendimiento escolar
- ausentismo escolar
- comportamiento de riesgo
- conflictos con compañeros
- quejas psicosomáticas nuevas o crecientes, incluidos dolores de estómago y de cabeza
- depresión o pensamientos suicidas

Poder hablar con alguien que está alejado de la situación suele ser útil tanto para adultos como para niños después de un evento traumático. Después de experimentar un trauma, los niños reciben mejor apoyo cuando sus padres o cuidadores de confianza aceptan sus sentimientos y están abiertos a escuchar y hablar. Deje que su hijo venga a usted. No los abrume si no están listos para hablar. Respete su necesidad de tomar descansos.

Comuníquese con un consejero o centro de apoyo si le preocupa el trauma que su hijo pueda tener debido a experiencias relacionadas con un peligro geológico.

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: What is happening in the Afar region?

PREVIOUS LESSON *There is no previous lesson.*

THIS LESSON

ANCHORING PHENOMENON

2.5 days



Asfawossen Asrat, 2005

We explore a StoryMap about the Afar region, presenting a strange series of events in 2005 that left a giant crack in Earth's crust. We connect to prior experiences with earthquakes and explore maps of earthquakes. We read about historic North American earthquakes. We ask our communities about their earthquake experiences. We compare the North American cases with Afar and develop initial models for before, during, and after earthquakes. We develop questions for our Driving Question Board and ideas for investigations.

NEXT LESSON

We will analyze plate motion data and develop a physical model to identify force interactions between plates. We will carry out investigations of the conditions that result in stability and change in an object's motion when multiple forces act on it. We will use free-body diagrams to explain and predict how the magnitude of forces at different scales impacts stability and changes in the matter within the system.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

1.A Develop a diagrammatic model of relationships between Earth systems to explain what causes land to crack, break, and move, and to predict what will happen to the land in the Afar region in the future. (SEP: 2.3; CCC: 2.2; DCI: ESS2.B)

1.B Ask questions about the mechanisms driving changes in Earth's crust that arise from careful observation of patterns in the Afar region, in order to seek additional information from indirect evidence because aspects of the phenomenon are too slow and too large to study directly. (SEP: 1.1; CCC: 3.2, 3.3; DCI: ESS2.B)

WHAT STUDENTS WILL FIGURE OUT

- A crack opened up in Earth's crust in 2005 in a region called Afar.
- Earthquakes seem to happen mostly along plate boundaries, but some happen in the middle of plates. They all seem to be connected to faults.
- Earthquakes happen underground and can cause cracking and moving of Earth's surface.

Lesson 1 • Learning Plan Snapshot

Part	Duration	Summary	Slide	Materials
1	5 min	NAVIGATE Introduce students to a new phenomenon and motivate the need to further explore it.	A-B	
2	10 min	EXPLORE THE AFAR EARTHQUAKE Share the StoryMap about the Afar region, and complete a Notice and Wonder chart.	C-D	https://arcg.is/OyeCyj1 , Afar Noticings and Wonderings poster, chart paper markers
3	3 min	ELICIT PRIOR KNOWLEDGE ABOUT EARTHQUAKES Uncover student ideas around why earthquakes happen on plate boundaries, and why it is unusual for them to happen elsewhere.	E-F	
4	8 min	EXPLORE A MAP OF EARTHQUAKES Look for patterns of earthquakes to try to determine whether the Afar events could happen in the United States.	G-I	https://www.openscienced.org/general/earthquake-volcano-map/
5	7 min	READ ABOUT OTHER EARTHQUAKE CASES Read earthquake cases in small groups, and compare information from these cases to Afar.	J	<i>Case Comparisons</i> , https://arcg.is/iKS58 (optional), <i>Earthquake Cases</i> , Afar Noticings and Wonderings poster
6	10 min	JIGSAW THE EARTHQUAKE CASE READINGS Discuss the earthquake case readings in small groups and complete Steps 2-3 of the <i>Case Comparisons</i> .	K	<i>Case Comparisons</i> , https://arcg.is/iKS58 (optional), <i>Earthquake Cases</i>
7	2 min	NAVIGATE: ASSIGN HOME LEARNING Introduce the home learning assignment of collecting earthquake stories from the community.	L	
<i>End of day 1</i>				
8	4 min	NAVIGATE: SHARE EXPERIENCES OF RELATED EARTH PHENOMENA Share related experiences from the home learning assignment and compare them with Afar.	M	<i>World Map</i> , 3x3 sticky notes, Community Agreements poster
9	10 min	REVISIT AFAR AND SHARE PATTERNS IN EARTHQUAKE CASE READINGS In small groups, review noticings and wonderings about Afar. Compare Afar with other earthquake cases, and complete Step 3 of the <i>Case Comparisons</i> . Conduct an Initial Ideas Discussion.	N-P	<i>Case Comparisons</i> , https://arcg.is/iKS58 (optional), <i>Earthquake Cases</i> , Afar Noticings and Wonderings poster, dry erase marker

Part	Duration		Summary	Slide	Materials
10	8 min		DEVELOP AN INITIAL MODEL FOR AFAR AND OTHER EARTHQUAKES Develop an initial model to show what happens before, during, and after an earthquake at Afar and the other earthquake cases. Compare models in pairs.	Q-R	<i>Case Comparisons, Initial Afar Models</i>
11	5 min		REVISIT OUR COMMUNITY AGREEMENTS Reflect on strategies for supporting our Community Agreements. Then review these strategies as a class.	S	Community Agreements poster
12	7 min		DEVELOP AN INITIAL CONSENSUS MODEL FOR AFAR Develop an initial consensus model in a Scientists Circle to show what is happening under Afar that could cause the observable changes on the surface.	T	<i>Initial Afar Models</i> , Initial Consensus Model for Explaining Changes in the Afar Region poster, chart paper markers
13	6 min		INTRODUCE AND USE THE SCALE CHART POSTER Consider the temporal and spatial scales of the events at Afar, and record these on the Scale Chart poster.	U	Scale Chart poster, Initial Consensus Model for Explaining Changes in the Afar Region poster, 3x5 sticky notes, permanent marker
14	5 min		NAVIGATE: DEVELOP AN INITIAL CONSENSUS MODEL FOR OTHER CASES On the initial consensus model, document how other earthquake cases might have occurred, and what might make them similar to and different from Afar.	V	<i>Case Comparisons</i> , https://arcg.is/iKS58 (optional), Initial Consensus Model for Explaining Changes in the Afar Region poster, chart paper markers, whiteboard, Scale Chart poster, 3x5 sticky notes, permanent marker
<i>End of day 2</i>					
15	15 min		NAVIGATE: BUILD THE DRIVING QUESTION BOARD Develop questions for the Driving Question Board. Join in a Scientists Circle to add the questions to the DQB.	W-X	3x3 sticky notes, permanent marker (dark), Afar Noticings and Wonderings poster, Initial Consensus Model for Explaining Changes in the Afar Region poster, Community Agreements poster, Driving Question Board
16	3 min		REFLECT ON OUR USE OF COMMUNITY AGREEMENTS Look back at the Community Agreements and consider whether any revisions need to be made.	Y	sticky dot (green), sticky dot (yellow), Community Agreements poster
17	5 min		BRAINSTORM INVESTIGATION IDEAS Develop ideas for investigation. Consider whether any potential causes for the earthquakes are operational before the earthquakes occur.	Z-AA	Driving Question Board, Ideas for Investigations/Data We Need, chart paper markers
<i>End of day 3</i>					

Lesson 1 • Materials List

	per student	per group	per class
Lesson materials	- science notebook https://arcg.is/OyeCyj1 https://www.openscienced.org/general/earthquake-volcano-map/ <i>Case Comparisons</i> https://arcg.is/iKS58 (optional) <i>Initial Afar Models</i> 3x3 sticky notes - permanent marker (dark) - sticky dot (green) - sticky dot (yellow)	<i>Earthquake Cases</i>	- Afar Noticings and Wonderings poster - chart paper markers <i>World Map</i> 3x3 sticky notes - Community Agreements poster - dry erase marker - Initial Consensus Model for Explaining Changes in the Afar Region poster - Scale Chart poster 3x5 sticky notes - permanent marker - whiteboard - Driving Question Board - Ideas for Investigations/Data We Need

Materials preparation (20 min 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.

Make copies of the handouts for this lesson:

- Case Comparisons* - 1 per student
- Initial Afar Models* - 1 per student
- Earthquake Cases* - 1 for each group of 5-6 students

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

- Afar Noticings and Wonderings
- Initial Consensus Model for Explaining Changes in the Afar Region
- Scale Chart
- Driving Question Board
- Ideas for Investigations/Data We Need

Make sure the Community Agreements poster, developed in *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (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.

Test the 3 student links:

- A Sudden Crack in Ethiopia:** <https://arcg.is/OyeCyj1>
- Earthquake Cases Storymap:** <https://arcg.is/iKS58>
- Earthquake and Volcanism Map:** <https://www.openscienced.org/general/earthquake-volcano-map/>

Watch https://youtu.be/Pkork9_yEj8 to learn how to use the Earthquake and Volcanism Map features, and watch https://youtu.be/KeS_Bk_kwuw to learn about how to use the Earthquake Cases Storymap.

This lesson utilizes earthquake cases from several locations across the United States and elsewhere in North America; however, earthquakes occur in many other places in this region. Consider creating a more localized case, using the *Local Case Creation* reference, for students to investigate. Add your localized case to the *Case Comparisons* handout.

Use the image on the *World Map* reference (or a similar world map) to create a space for students to record their earthquake experiences. For example, consider either scaling up the image and printing a copy on 11x17 copy paper, or creating a jamboard and using the image as a background.

Lesson 1 • Where We Are Going and NOT Going

Where We Are Going

Because this is the first lesson in a new unit, the goal is not to establish any ideas associated with the relevant disciplinary core idea (DCI, ESS2.B), but rather to get student ideas related to that DCI on the table. Therefore, we do not specify which element of this DCI is being addressed. Students will have ideas about volcanoes, earthquakes, mountains, and so forth. Some may bring in ideas about mantle convection and plate tectonics. Accept all ideas without judgment right now, even if they are scientifically inaccurate.

If a student shares an idea that feels very inaccurate, you can respond for now with one of the following:

- *Wow, that's an interesting idea! Does anybody disagree?*
- *Let's follow up on that for sure. How could we investigate the claim _____ made? Let's add it to our ideas for investigations later.*
- *What an interesting idea. Could you reframe it as a question for our Driving Question Board?*

In this lesson, it is important for students to recognize that parts of the African continent are moving in different directions at different velocities. This leads them to wonder what is happening beneath the surface to cause changes like the 2005 crack in Afar, motivating the need to look at the forces acting on this part of Earth's crust.

Similarly, some student engagement with the science and engineering practice (SEP) and crosscutting concept (CCC) elements in this lesson may not reach grade-band level. That is OK, as the lack of DCI mastery may limit their access to full engagement. Assessment in this lesson should be used formatively.

The CCC of *scale, proportion, and quantity* is essential to this unit, and its elements 3.2 and 3.3 are introduced in this lesson. These and other elements will be intentionally developed across multiple lessons. The Scale Chart poster, which will be revisited across the unit, is one representation meant to scaffold students' thinking. In this lesson, only a spatial scale is included on the chart; a temporal scale will be added in Lesson 2.

Students may not know what a tectonic plate is at this point, and that is OK. If they ask, say it is a great question to put on the DQB, or allow other students to suggest a meaning. You will co-develop a meaning for what a plate is over the next several lessons, and encounter a formal definition in Lesson 5. 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.

In this lesson, students also have the opportunity to share their own experiences related to earthquakes. Keep in mind that although some might readily share, not all may want to, and some experiences could be difficult to retell or relive. Do not require anyone to share, and do not press if students do not want to. In addition, make sure to provide a space for students who do not want to hear about others' earthquake experiences.

Before the unit starts, reach out to students' support systems at home using the Pre-Unit Letter Home. This letter is a way to communicate with trusted adults and make them aware of the unit's content, such as earthquakes. It also gives them an opportunity to share important context with you about students' experiences and background that might be relevant.

This lesson's topic can be sensitive for those who have experienced injury, trauma, or loss due to earthquakes. Please be mindful of this and provide safety and support by sharing awareness. If there is time, consider starting the class period with a brief mindfulness activity; see the Afar SEL Supports reference for suggestions.

Consider beginning the unit by saying: *As we work through this unit, be mindful of any impact you're noticing within yourself based on your own personal experiences. The events we're going to study do impact people every day. If you need to talk, process, or regain some grounding in the here and now, please let me or the school counselor know.*

Be aware that students who are struggling may demonstrate various behaviors including but not limited to: fidgeting, withdrawal, disruption/distraction, rapid breathing, holding their breath, and change in body language or tonation. If you notice a student may be struggling, share what you are observing and ask whether they need some help.

Where We Are NOT Going

Students who had instruction aligned with Next Generation Science Standards (NGSS) in middle school may have learned about the creation of continental and ocean floor features by plate interactions (MS-ESS2-3), such as two plates converging to form mountains. The high school level focus is less about explaining specific surface features and more about how the motion and forces causing them are an expression of mechanisms related to changes in the matter, energy, and forces responsible for mantle convection.

We intentionally avoid naming the structures and properties of Earth's interior in this lesson, as these will be explored in future lessons.

LEARNING PLAN for LESSON 1

1 · NAVIGATE

5 min

MATERIALS: None

Exploring a new phenomenon. Present slide A. Read the summary on the slide:

- *In October 2005, people in northeast Africa took this photo of a huge crack in the ground that was not there before.*

Point out that the left side of the photo shows a series of people standing along the side of the crack, giving us a sense of its spatial scale. Pose the question on the slide to elicit initial ideas about this phenomenon, as shown in the table below.

Suggested prompt	Sample student response
<i>What might have caused this change in Earth's surface?</i>	An earthquake. Erosion, water. The ground shook and broke open. Plate tectonics, faults.

Say, It sounds like we have a lot of ideas about why this crack might have occurred!

Briefly consider what data might be helpful. Present slide B. Ask, *If we want to understand why this happened, what would you like to know more about, related to this event and the area where it occurred?* Accept all ideas, listening for students to suggest that they want to know whether anybody was injured, whether there are earthquakes in the area, weather-related reports, plate maps, or if any of the things they just suggested possibly caused the event. Take only 1-3 ideas and move on quickly.

Say, It sounds like we have some initial ideas and want to know more about the region. I have a tool that tells the story of what happened in 2005, and it allows us to look at the region surrounding the event. This may provide some of the information we're looking for to help us dig deeper into these phenomena.

2 · EXPLORE THE AFAR EARTHQUAKE

10 min

MATERIALS: science notebook, <https://arcg.is/OyeCyj1>, Afar Noticings and Wonderings poster, chart paper markers

Set up the science notebook. Display slide C. Give students a moment to prepare a T-chart like the one on the slide. They can do this directly in their notebooks or on loose-leaf paper to add to it.

Share the StoryMap link. Distribute computers to students and share <https://arcg.is/OyeCyj1>. It is recommended to have students access this StoryMap individually, but groups of 2-3 are also an option. Instruct them to read through the StoryMap, which has information about what happened in the Afar region in 2005, and to record what they notice and wonder on their T-chart.

Facilitate an Initial Ideas Discussion. Display slide D. On the Afar Noticings and Wonderings poster, 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.

✱ 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.

KEY IDEAS

Purpose of this discussion: To collect students' observations and questions about the data they have seen so far, to then motivate looking at additional data. This is not the time to critique ideas or push for evidence.

Listen for these ideas:

- There was a volcanic eruption.
- There were lots of earthquakes/aftershocks before and after the crack was formed.
- The crack is not located at a plate boundary.
- The earthquakes occurred on fault lines.
- The land is really low in this part of the world (below sea level).
- The land to the left and right of the crack moved in different directions and changed in elevation.
- People generally feel earthquakes over a magnitude of 4.

Potential questions students could ask:

- Did the volcano's eruption cause the crack?
- How long will this keep going on?
- What is a fault line?
- Does this only happen in the desert, because the land was dried out?
- Can this happen where I live?
- How do earthquakes happen at places that are not on plate boundaries?

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.

3 · ELICIT PRIOR KNOWLEDGE ABOUT EARTHQUAKES

3 min

MATERIALS: None

Elicit experiences with related events. Project slide E. Say, *We just learned that the people in Afar experienced several phenomena--earthquakes, a volcanic eruption, and a giant crack in the ground. Do any of you have experience with those phenomena?*

Ask for a show of hands for each phenomenon to elicit generally whether students have had experiences with them. Some may have experienced all three, but most are likely to have seen or heard of earthquakes, perhaps some with cracks in the ground.

Motivate looking deeper into earthquakes. Point out that it seems the class has more experience with earthquakes than the other phenomena. Suggest that in looking for the cause of this giant crack in Afar, we start with earthquakes, because they are more familiar. If students want to share specific stories of their experiences, assure them they will have a chance to do so later in the lesson.

Consider why earthquakes might occur. Project slide F. Use the slide's questions to problematize:

- *What do we know about earthquakes that might cause them to happen in some places but not others?*
- *Can earthquakes happen anywhere, even at non-plate boundaries?*

Allow students to share their ideas regarding where earthquakes generally occur and why. Here are a few possible ideas and questions to listen for and probe for details:

- Most earthquakes happen on plate boundaries.
- The earthquakes in Afar happened around the time a volcano erupted. Are volcanoes and earthquakes related?
- Earthquakes are related to plate motion.

4 · EXPLORE A MAP OF EARTHQUAKES

8 min

MATERIALS: science notebook, <https://www.openscienced.org/general/earthquake-volcano-map/>

Introduce the idea of earthquake patterns and scale. Explain that we can look at a map showing earthquakes and plate boundaries to see whether earthquakes are happening at unexpected places. We can also look for patterns related to earthquakes that might help explain the events at Afar.

Display **slide G**. Pose the slide's prompts:

- *What patterns might we notice when looking at any potential earthquakes?*
- *At what scale might we see those patterns?*

Ask students to share their answers. Accept all potential patterns, including the idea that earthquakes might occur in lines or clusters on plate boundaries, as well as other patterns that make sense from a student's perspective.

Identify potential earthquake patterns and scale. Present **slide H**. Tell students to take 5 minutes to individually look at the map and generate a list of potential patterns they notice, as well as any noticings and wonderings, in their notebooks. Share the map using the link on the slide: <https://www.openscienced.org/general/earthquake-volcano-map/>. * Ask students to consider the first three questions as they work:

- *Do earthquakes happen in our region?*
- *What patterns do you notice?*
- *At what scale are these patterns?*

ADDITIONAL GUIDANCE

If students have never used a web app like this, it may be beneficial to take some time to walk them through the map's features. Show https://youtu.be/Pkork9_yEj8 for an explanation of the useful features, or share this video with students as needed.

If students finish early, ask them to consider the last question on the slide:

- *Why might we expect earthquakes to happen in some places but not others?*

Bring the class back together and have students share their answers to the first three questions.

* ATTENDING TO EQUITY

Universal Design for Learning: The colors of this map were intentionally chosen to increase accessibility for color-blind students.

* SUPPORTING STUDENTS IN DEVELOPING AND USING SCALE, PROPORTION, AND QUANTITY

In this unit, students will use extensive scale thinking. It is important to scaffold their understanding of different scales early. If they struggle with understanding what is meant by patterns being observable at one scale but not another, zoom in and out on the map to various scales at different locations to show that some clusters and lines are only observable at a particular scale. If the zoom is too close, the earthquake pattern may not be visible, and if the zoom is too far out, the pattern may also not be visible.

If students struggle to understand what is meant by scale in general, talk about how scales describe how things vary in size or time span. Point out the scale key on the map's lower left corner, and how the numbers change when you zoom in and out. Note that this is a scale representation using a ratio between distance on the map and distance on Earth. Scale thinking often involves comparing relative sizes or time spans and what can be observed at the scale being used.

KEY IDEAS

Purpose of this discussion: Establish any patterns of earthquakes that students see, and work toward considering what is causing these patterns.

Listen for these ideas:

- Though some earthquakes appear to be isolated events, earthquakes are generally grouped in lines or clusters.
- These lines and/or clusters are also present in Afar in the region of the 2005 earthquake.
- There are a lot more earthquakes on plate boundaries than other places, but earthquakes do occur in lines and/or clusters in other regions away from plate boundaries.

Use questions like these to push student thinking:

- *Why do you think these earthquakes might be in lines or clusters?*
- *What is the scale of the lines or clusters of earthquakes?*
- *Do earthquakes only happen on plate boundaries?*
- *Why might earthquakes happen primarily at plate boundaries? What could be causing the other earthquakes that are not at plate boundaries?*
- *For the patterns we've identified that are similar to Afar, what might we see on the surface after these earthquakes?*

Determine the scale at a plate boundary. Display <https://www.openscienced.org/general/earthquake-volcano-map/>. Students should notice that they do not need to zoom in on the west coast and other plate boundaries to see earthquake patterns in lines; these earthquakes are clustered along a plate boundary, with many on this line.

Determine the scale of the lines of earthquakes. Display slide I. Pose the first prompt:

- *Do you think all earthquake lines or clusters are visible at the same scale?*

Have the class choose a particular set of lines or clusters that are **not** on a plate boundary, such as the lines in the southeast corner of Missouri. Display these on the map. Ask students at what scale they began to see the line or cluster that seems to be a pattern for most earthquakes. Guide them to determine that some patterns are more visible at different scales. *

Pose the second prompt:

- *Why might we expect earthquakes to happen in some places but not others?*

Allow students a moment to reflect quietly before sharing out. They might say it makes sense for an earthquake to happen on a plate boundary because the plate is moving, but plates are not colliding or sliding past each other in the middle of the United States. Listen for and use any ideas about why earthquakes are expected in some regions and not others to move into the slide's third prompt:

- *How might these earthquakes that are not located at plate boundaries be similar to or different from what occurred in Afar?*

Accept all responses. Then tell the class these earthquakes were puzzling to you as well, so you have collected some earthquake cases from various parts of North America to learn more about how and why these might also be occurring, and whether they are similar to the Afar earthquakes.

5 · READ ABOUT OTHER EARTHQUAKE CASES

7 min

MATERIALS: *Case Comparisons*, <https://arcg.is/iKS58> (optional), *Earthquake Cases*, Afar Noticings and Wonderings poster

Read about earthquakes. Present slide J. Assign students to groups of 5, or groups of 6 if you created an earthquake case using the *Local Case Creation* reference. Explain that each student in the group will read a different earthquake story. *

Distribute the *Case Comparisons* handout to each student and the *Earthquake Cases* handout to each group. Have each student select a case to read. ** In lieu of using the *Earthquake Cases* handout, they can access the information as a digital StoryMap at <https://arcg.is/iKS58>.

* ATTENDING TO EQUITY

Universal Design for Learning: Not all students will *perceive* the text in the same way. Consider offering an auditory

ADDITIONAL GUIDANCE

If the class is not easily divisible by 5 (or by 6 if a local case was added), make sure any smaller groups at least read about an earthquake at a plate boundary (e.g., San Francisco) and an earthquake closer to your location.

In addition, if students are using the StoryMap but have not seen one of this style, cue them on how to view multiple pictures associated with each earthquake case. For information about how to use this StoryMap, see https://youtu.be/KeS_Bk_kwuw.

Explain that as students read their case, they should compare it to Afar, looking back at the Afar Noticings and Wonderings poster if needed. Tell them to note any similarities, differences, and other potentially relevant information that might help explain why their earthquake occurred on *Case Comparisons*, to share with their group. Give them 4 minutes to read their case and complete Step 1 of the handout.

alternative. This can be done by using text-to-speech capabilities of various platforms with the Google Docs or PDF version of the text, allowing for a partner or “intervener” to read the text aloud, or by creating a narrated video (including images) of each case, among other options.

* ATTENDING TO EQUITY

Universal Design for Learning: Offering individual choice of earthquake case increases *engagement* by allowing students to weigh their own perceived level of challenge of each text and their level of personal interest in each location. Give them time to make this assessment and choose their own case within their groups to increase the degree that they feel connected to their learning.

* ATTENDING TO EQUITY

The *Earthquake Cases* are provided in multiple modalities to increase accessibility. The digital StoryMap version may be a more convenient or engaging way to access the material; its motion, however, may be overwhelming for some students. Consider using the PDF or Google Docs version of the text for those who would benefit from reduced sensory stimulation.

6 · JIGSAW THE EARTHQUAKE CASE READINGS

10 min

MATERIALS: *Case Comparisons*, <https://arcg.is/iKS58> (optional), *Earthquake Cases*

Share patterns in small groups. Present slide K. Say, *Now that we’ve learned more about some of the earthquakes that are and are not on plate boundaries, let’s see if we’ve noticed any similarities that might indicate patterns, or differences that might explain why earthquakes occurred in these different regions.*

Ask each student to share what they learned about their specific earthquake case, one by one within their group, spending no more than 1 minute apiece in explaining their case. Remind them to also share any similarities and differences with the Afar earthquakes. As the group members listen, they are to complete Step 2 on the *Case Comparisons*.

As the groups work, circulate and listen to their stories. Accentuate any observations about cracks in the ground, multiple earthquakes happening in the same location (aftershocks and the like), and all earthquakes being located on faults/seismic zones. After 7 minutes of sharing and recording ideas in groups, bring the class back together.

Tell students they will be able to share any patterns and similarities their group uncovered in the next class period. In the meantime, we will collect and use stories from our community to learn more about earthquakes that we, or others who we know and trust, have experienced.

7 · NAVIGATE: ASSIGN HOME LEARNING

2 min

MATERIALS: None



Introduce the home learning. Project slide L. Explain that because we are looking at the sudden events on Earth's surface--like volcanic eruptions and cracks--surrounding a series of earthquakes, it might be helpful to learn about the experiences that other people in our community have had with earthquakes, volcanoes, or other sudden Earth changes. * Instruct students to ask trusted friends and adults about their experiences before, during, and after an earthquake, volcanic activity, or some other sudden change to Earth's surface, and ask them what they noticed. The interviewees can also share what they have heard about past earthquakes.

Tell students to record these stories in any way they see fit, or just listen. Let them know they will be invited, but not required, to share the stories in the next class period. Remind them that the event should be a sudden change to Earth's surface itself, not a weather event or a fire.

*

ALTERNATE ACTIVITY

Consider creating a digital space, like a post in Google Classroom or a Flip link, where students can share these stories on day 2. If most or all students know someone with an experience to share, this is also a great opportunity to collaborate with an English language arts teacher for students to create expository texts using Common Core standards such as CCSS.ELA-LITERACY.W.9-10.2 or CCSS.ELA-LITERACY.W.9-10.3.

ADDITIONAL GUIDANCE

Students may bring in stories of erosion events, such as the creation of a sinkhole, cracking in dry soil, or a landslide. Keep the focus on sudden and unexpected changes related to the events in Afar, such as volcanic activity or earthquakes, but do not shut down other ideas or questions or mark them as irrelevant. Keep track of these events on the Scale Chart poster and allow for questions about them on the DQB; however, these will not all be addressed in this unit, particularly surface processes related to water and weather.

If these questions and ideas are lingering at the end of the unit, encourage students to investigate the cause on their own. Help them see that the same tools we used in this unit to investigate stability and change across scales can be used to understand processes like the formation of the Grand Canyon (erosion over great time and great space) and a mudslide (erosion over small time and small space).

* ATTENDING TO EQUITY

Supporting empathy and emotions: Often in science classrooms, we focus on evidence and data. When addressing a phenomenon or design solution that straddles the nature-cultural divide, like this one, supporting students in using an empathy or social and emotional lens is also important. Earthquakes can be traumatic and devastating; for some students, their lives and families may have been (or may still be) greatly affected by an earthquake. Acknowledge this without putting anyone on the spot. For more guidance around supporting the development of social and emotional learning, visit <https://casel.org/>.

* ATTENDING TO EQUITY

Framing students' families and communities as legitimate funds of knowledge serves multiple purposes: it (1) helps students feel that they belong in the science classroom by situating their family and community knowledge as productive resources for science, (2) engages their families in conversations about what is happening in the classroom, and (3) helps them make connections between the science classroom and their everyday lives.

End of day 1

8 · NAVIGATE: SHARE EXPERIENCES OF RELATED EARTH PHENOMENA

4 min

MATERIALS: *World Map*, 3x3 sticky notes, Community Agreements poster

Share experiences. Set the stage by reminding the class that events like earthquakes and eruptions can be devastating and traumatic. Have students look back at our Community Agreements poster and choose one that will make the classroom space feel safer for people who feel comfortable sharing. Invite them to share stories from the home learning, but remind them that this is optional.

Display slide M. Use the first two prompts to structure sharing with the class:

- *Where did the event you learned about, or have experienced, occur?*
- *What happened before, during, and after the event?*

ADDITIONAL GUIDANCE

Social and Emotional Learning (SEL): Some students may have experienced trauma related to earthquakes or other events like those in the Afar region. Prior to teaching this lesson, please review the *Afar SEL Supports*. Be mindful of any changes in students' behavior, such as body language adjustments, intonation, and distraction. If a student exhibits any changes, consider asking them privately and quietly whether they would like to step out and see the counselor or take a moment to themselves for a break in the hallway or bathroom.

As students share, use sticky notes to add the events to the world map you prepared ahead of time (as a wall artifact or digitally; see the Materials Preparation section). On each sticky, include the location, a very short description of the event's observable effects, and the person who shared it.

Use the slide's third prompt to ask other students to compare the shared event to Afar:

- *Were there any similarities or differences between this event and the events that occurred in the Afar region?*

Record the similarities on the map, elevating any cracks or changes in land and whether any volcanic activity occurred with an earthquake. After students have shared their stories, thank them for sharing.

9 · REVISIT AFAR AND SHARE PATTERNS IN EARTHQUAKE CASE READINGS

10 min

MATERIALS: *Case Comparisons*, <https://arcg.is/IKS58> (optional), *Earthquake Cases*, Afar Noticings and Wonderings poster, dry erase marker

Revisit the Afar events. Project **slide N**. Remind students that as we learned more about our earthquake cases, we were comparing these to Afar to try to explain what was happening there, and to determine whether that could also occur at their case's location. Have them gather in their groups again and look back at the Afar Noticings and Wonderings. Direct them to discuss similarities and differences between their cases and Afar, and to complete Step 3 of the *Case Comparisons*.

Share similarities and differences. Display **slide O**. Ask students to share any interesting similarities and differences between Afar and their case sites with the class, one case at a time. As they share similarities across a couple of cases, ask whether they think these could possibly be a pattern. Have them record these ideas on their handouts if they have not already, while you do this on a whiteboard or other highly visible space in the classroom. Make sure to elevate the similarity that all the earthquakes resulted in cracks or shifts in land, as in the Afar region.

Listen for the following:

- Similarities:
 - The earthquake cases and Afar had a lot of earthquakes around the time of the bigger events.
 - **All the earthquake cases seem to have cracks or shifts in land, like Afar.**
 - They are all in areas where earthquakes occur.
 - All the earthquakes, as well as Afar, occurred on fault lines.
- Differences:
 - The earthquake cases are not near volcanoes, but the Afar earthquake was near an active volcano.
 - The cracks seem way bigger in Afar than in North America.

If students do not mention the volcanic eruption at Afar, draw their attention back to the phenomena observed there, and guide them to make this observation again. Ask whether this is similar to or different from the events at the other sites, and add this to the whiteboard and *Case Comparisons*.

* STRATEGIES FOR THIS INITIAL IDEAS DISCUSSION

Be explicit with students about your role in this Initial Ideas Discussion. You are not pressing for evidence; rather, you are capturing their ideas about what they think is happening at Afar. Accept all ideas in this discussion.

ADDITIONAL GUIDANCE

A rich, well-utilized visual and textual environment can be helpful for emerging multilingual learners to access content. If wall space is available, consider creating a class record on chart paper instead of the whiteboard, detailing the similarities and differences listed above. This can be utilized when students create their initial and consensus models, and in later lessons for navigation to determine what still needs to be explained about what makes the Afar earthquake different. If you do not create this class chart, have students refer to their handouts as needed.

After a minute or two, say, *It looks like we've found some similarities between Afar and our other earthquake cases, and also things that make them different. We've started thinking about how patterns in the data might give us clues about what could be causing the giant crack in Afar. Let's think more deeply about what could be causing those patterns of earthquakes and cracks.*

Share initial ideas about causes across cases. Present slide P. Ask students to share their initial ideas about what could be causing the patterns of earthquakes and cracks. ✱ Use the slide's prompts to foster the discussion:

- *What is cracking or shaking, and how?*
- *What is happening to the surface in an earthquake?*
- *What is causing the changes at the surface in our cases and Afar?*
- *Are the processes at Afar and all the cases the same? What evidence do we have?*

Accept all responses. The purpose of this step is to generate potential causes while also raising uncertainty for students to attempt to explain in their models.

10 · DEVELOP AN INITIAL MODEL FOR AFAR AND OTHER EARTHQUAKES

8 min

MATERIALS: Case Comparisons, Initial Afar Models

Develop an initial model individually. Say, *It sounds like we're arguing that the ground at all the cases, including Afar, might be changing in some way over time. But what is really cracking or breaking, how fast is it cracking or breaking, how much is cracking or breaking, and what is causing this?*



Present slide Q. Say, *Let's try to develop a model to explain what might have happened before the events at Afar, and what might happen there in the future. We think similar things might be happening in the regions of our earthquake cases, so let's also try to explain that in the model, to better understand if what's happening at Afar is happening at our cases as well.*

ADDITIONAL GUIDANCE

Before modeling, explicitly introduce an element of the Anchoring Phenomenon Routine: attempting to make sense. Say, *You may recall that at this point in a unit, we develop an initial model to explain something the class hasn't yet figured out. This is our "first draft" thinking. Remember, modeling can help us make sense of things--even what we don't know yet! For initial models, there are no right or wrong answers. The purpose is to get the ideas in our heads down on paper so we can clarify our own thinking and share our ideas. Then, we'll revisit our initial models throughout this unit as we make progress on figuring out the uncertainties we uncover today.*

Distribute the *Initial Afar Models* handout to each student. Emphasize that their models should include information about what is happening below Earth's surface; see the assessment guidance below. Reserve at least 4 minutes of this step for students to compare their models in pairs.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Indication of movement, force, and/or energy transfer (e.g., arrows) between components of the model. (SEP: 2.3)
- Modeling changes in the shape or composition of the matter that makes up material at and/or below the surface, related to the changes at the surface. (SEP: 2.3)
- Discussion of different timescales, gradual versus sudden change, either in models or in written responses. (DCI: ESS2.B)
- A cause-and-effect relationship between something happening inside Earth and something happening at the surface. (CCC: 2.2)

What to do:

- If students' initial models lack information about Earth's interior, point or refer back to surface effects (e.g., cracking, shaking, crumpling, tearing). Ask students what happened in their models to create those effects. Then ask how Earth could do something similar.
- Verbally prompt students to show which direction(s) the components are moving.
- Ask students to be specific about what timescales they are thinking about for the changes. When they make predictions, are they thinking of 10 years in the future, or more, or less? Why? Do all the changes happen at the same pace?

Building toward: 1.A Develop a diagrammatic model of relationships between Earth systems to explain what causes land to crack, break, and move, and to predict what will happen to the land in the future. (SEP: 2.3; CCC: 2.2; DCI: ESS2.B)

Compare models. Present slide R. Have student pairs compare their models using the prompts:

- What do you have in your models that is similar? Add a check mark to indicate where your models are similar.
- What do you have in your models that is different? Add a question mark to indicate where your models diverge, where you disagree, or where you have questions.

11 · REVISIT OUR COMMUNITY AGREEMENTS

5 min

MATERIALS: Community Agreements poster

Reflect on strategies for supporting Community Agreements. Say, *Next, we'll build on your ideas about what's happening below Earth's surface to make a class consensus model. This kind of sensemaking can be challenging. We made real progress in supporting each other and engaging in work like this when we reflected on and refined our Community Agreements at various points in our last unit. Let's do that again, so we can continue to push our growth as a learning community.*

Display slide S. Orient students to the Community Agreements poster, and give students 1-2 minutes to individually consider the question on the slide:

- What strategies were productive for supporting our Community Agreements when we worked together in a Scientists Circle in our prior unit?

Review these strategies as a class. Discuss any new strategies that students suggest. If the class decides to adopt a strategy as a Community Agreement, add it to the poster. *

* ATTENDING TO EQUITY

One of the reasons that OpenSciEd uses the term *community agreements* is to highlight that there is not a "normal" way to collaborate. Norming 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 can mean different things in different communities. For example, one student may define kindness as not calling out a peer in public when they say something offensive; but another student may define kindness as being honest with peers, and sharing what is on their mind and heart right away. Whose version of kindness receives priority? When

these ideas are not explored, norms can be used to police or silence justifiable hurt and anger, particularly when it comes from students who identify with marginalized communities. For examples of inclusive agreements that support equitable spaces, visit <https://www.theequitylab.org/blog/why-start-with-agreements>.

12 · DEVELOP AN INITIAL CONSENSUS MODEL FOR AFAR

7 min

MATERIALS: *Initial Afar Models*, Initial Consensus Model for Explaining Changes in the Afar Region poster, chart paper markers

Convene in a Scientists Circle to review our goal. Have students bring their chairs and initial models into a Scientists Circle. Say, *We just developed our own initial models for what could be causing changes at Afar and compared those with our earthquake cases. We had a lot of agreement across our models, and also some divergent ideas. Before moving on, we need to come to consensus around what we know and what we want to figure out. Let's start with the case we learned about together--the Afar case.*

Facilitate a Consensus Discussion. * Present slide T. Ask students to look at their *Initial Afar Models* and share components, mechanisms, or interactions that were similar across models. * Use the prompts in the guidance box below to elicit important systems and interactions. Sketch the components, mechanisms, and interactions that students name on the Initial Consensus Model for Explaining Changes in the Afar Region poster at the front of the classroom. Put question marks on the poster to show where the class has divergent ideas about the Afar region's past and future. We will return to this model and reevaluate these initial competing ideas as we gather more evidence throughout the unit.

KEY IDEAS

Purpose of this discussion: To develop an initial consensus model that captures the ideas we agree upon, disagree upon, or are uncertain about for what is happening below Earth's surface to cause the patterns in the cracking and breaking of land, as well as volcanic activity, at the surface in East Africa.

Listen for these areas of agreement on components that the model *may* include:

- Earth's layers
- lava and/or magma
- arrows to show movement
- changes to the shape of the land on Earth's surface
- breaking or cracking at the surface

Listen for these areas of uncertainty or disagreement:

- temporal scales of the changes (how long they take)
- changes that may be seen in the future, and how far in the future to show those changes
- spatial scales of the changes
- events at a fault line
- type(s) of changes to the shape of the land over time (e.g., some models showed the land building up, others showed it breaking apart)
- breadth and depth of the crack both above and below the surface (e.g., some models showed events deep inside Earth, others only showed them right underneath the surface)
- differences in the structure, material, state of matter, and temperature below the surface
- role of lava and/or magma in the changes observed at the surface

* STRATEGIES FOR THIS CONSENSUS DISCUSSION

Your role as facilitator in a Consensus Discussion is to press students to take stock of where the class agrees and disagrees. Tell them explicitly that you are not writing down everything they say. Say, *Remember, my role here is to put ideas into the public arena so we can debate them and clarify where we stand as a class, even if it means we agree that we have areas of disagreement. So I might say, "What do others think of that idea?" or, "With a show of hands, how many agree with that idea, and how many disagree?" I'll only write something down when we've taken stock of it as a class.*

Encourage as many students as possible to contribute so the model represents the diverse thinking of all students. Be careful not to favorably respond to any idea over others so as not to give away what might be going on in the phenomena.

* ATTENDING TO EQUITY

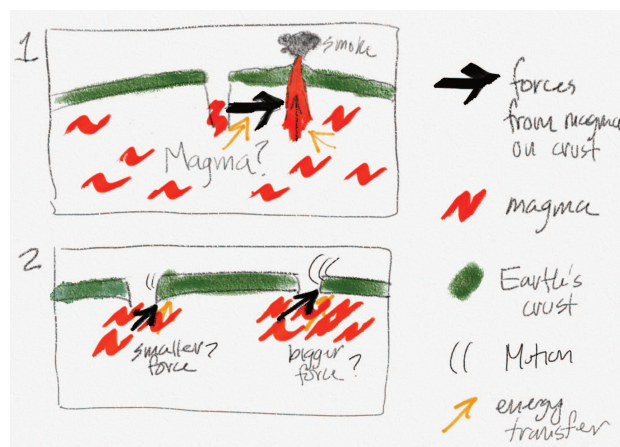
Emerging multilingual learners: If some students have not had the chance to learn about components, mechanisms, and interactions, take a moment to introduce these terms now. Until students are comfortable with them, consider moving interchangeably between the new terms and student-friendly language (such as "parts" for "components") to allow them to develop their meanings.

ADDITIONAL GUIDANCE

The initial consensus model may look something like the image below, but keep in mind that the model your class creates should represent the ideas and symbols your students come up with. If they do not come up with the idea of forces yet, do not include forces. If they already know the mantle is primarily solid rock, do not push to include magma; as we will figure out later, the role of magma is relatively small in explaining the causes of these phenomena.

Do not push scientific vocabulary that students aren't comfortable with, but encourage them to apply familiar science phrases they have practiced in previous units to their descriptions, such as "energy transfer". For example: *I hear you saying that something would push on the rock and make it move...is it fair to say that what you just described might be a form of energy transfer?*

Listen to your students, ask clarifying questions to revoice their ideas, and make sure you understand. For example: *I heard you say _____, is that right? How should I represent that idea to capture what _____ just described? Will you come up and add that component to our consensus model?*



13 · INTRODUCE AND USE THE SCALE CHART POSTER

6 min

MATERIALS: Scale Chart poster, Initial Consensus Model for Explaining Changes in the Afar Region poster, 3x5 sticky notes, permanent marker

Begin developing the Scale Chart poster. Ask students to remain in the Scientists Circle. Point back to the consensus model and say, *Our model is trying to explain things that are both very big and very small. It's 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 think back to what we saw happening in Afar that we documented in our model.*

Discuss the scale of the Afar phenomena. Present slide U. Start by asking students to consider the scale of the events at Afar, as shown in the table below.

* SUPPORTING STUDENTS IN DEVELOPING AND USING PATTERNS

In high school, students should practice recognizing patterns at multiple scales. In this data set, they have the opportunity to observe several spatial scales. When patterns at multiple scales change together, it can provide evidence for correlation or even causality. In this unit, students will explain how unbalanced forces arising from

Suggested prompt	Sample student response
<i>What observable events happened at Afar?</i>	A crack occurred! A volcano exploded! The ground shook! The ground got lower!
<i>What scale did those events happen at?</i>	The crack happened over a large space. People all over the area felt the earthquake. The volcano didn't take up as much space as we think. The crack was really big, but not compared to some of the areas or continents we looked at on the earthquake and plate boundary map.

properties of Earth's interior cause surface effects at both global and local scales. These surface effects occur in recognizable patterns that allow geologists to make inferences about the behavior of Earth's mantle.

Say, *Great. Let's see whether we can put these observable events on this chart. Let's start with the crack.*

Add the Afar crack to the Scale Chart poster. Work with students to determine where the Afar crack should end up on the poster in relation to other observable features, such as the continent of Africa and the volcanic eruption. Example prompts and responses are shown in the table below.

Suggested prompt	Sample student response
<i>Let's put the Afar crack on this chart. Does anyone remember how big it was?</i>	It was a series of cracks that were like 37 miles long! There was the big main crack, but we could still see people standing on the sides of it.
<i>So, let's think about where this might fall on our chart. Is it closer to something we would classify as a large space or a small space?</i>	It seems like a large space--37 miles is a lot! It seems small, though, compared to the continent--we had to zoom in a lot on the continent to see the Afar region well.
<i>So, it sounds like we're saying that depends on what we compare it to?</i>	Yes! It's big compared to people, but small compared to the whole continent.

Write "Afar crack" on a 3x5 sticky note and place it somewhere on the "Large space" side of the chart. Make sure the sticky can be easily moved in later lessons as we learn more about our dynamic Earth.

Quickly add the other Afar events to the chart. Repeat this process, but ask students where this particular earthquake would fall on the map. Write "Afar earthquake" on another sticky and add it to the chart. Wherever students situate this earthquake is OK for now; this will be refined later. Repeat this process, asking about the volcanic eruption, and add a sticky for "Afar volcano" to the chart. *

ADDITIONAL GUIDANCE

It is important to note that the Scale Chart poster is a living document, to be updated throughout the unit. In this lesson, it is not critical for events to be placed in the “correct” location. This is why sticky notes are utilized, to be repositioned as our understanding develops.

Later, students will reconsider relative placement as processes like mantle convection and radioactive decay are added. Be sure the stickies can be easily moved from one location to another. Students will also generalize the events from being Afar-specific, such as changing “Afar earthquake” to a more general “earthquake” note as we learn more about the theory of plate tectonics.

14 · NAVIGATE: DEVELOP AN INITIAL CONSENSUS MODEL FOR OTHER CASES

5 min

MATERIALS: *Case Comparisons*, <https://arcg.is/iKS58> (optional), Initial Consensus Model for Explaining Changes in the Afar Region poster, chart paper markers, whiteboard, Scale Chart poster, 3x5 sticky notes, permanent marker

Extend the consensus model discussion to other earthquake cases. Display slide V. Ask students to consider how our initial consensus model does or does not reflect what we think is occurring with the other cases, or any of the events brought in from the community. Remind them that we already generated a similarities and differences list on the *Case Comparisons* and on the whiteboard chart earlier in class. Have them reflect on why these similarities--and more importantly, differences--exist.

Have students share their ideas about why the events might be different in words. Document these ideas on the right side of the consensus model poster; do not create a second visual model at this point. If students do not mention that some earthquakes occur on plate boundaries (e.g., San Francisco) but some don't, remind them, and ask how those cases might be different. If they do not bring up that their earthquake cases do not have volcanic activity, like Afar did, repeat this process.

If students wish to add a sticky note for “other earthquakes/events in North America” to the Scale Chart poster, do so now. In Lesson 2, when we learn more about earthquakes, a new 3x5 sticky that simply says “earthquakes” will be created to encapsulate the earthquakes felt around the world. Make a note to consolidate all the earthquake stickies on the Scale Chart poster into one in Lesson 2.

End of day 2

15 · NAVIGATE: BUILD THE DRIVING QUESTION BOARD

15 min

MATERIALS: 3x3 sticky notes, permanent marker (dark), science notebook, Afar Noticings and Wonderings poster, Initial Consensus Model for Explaining Changes in the Afar Region poster, Community Agreements poster, Driving Question Board

Orient students to where we have been and where we are going. Make sure the Afar Noticings and Wonderings, Initial Consensus Model for the Afar Region, and Community Agreements posters are visible at the front of the room. Display the Driving Question Board.

Say, We've been wondering what causes land on Earth's surface to crack, break, or otherwise change over time. We looked at data for Afar and locations closer to us that seem to be breaking apart and changing. We developed initial models about what could be happening inside Earth to cause these changes at and below the surface. So, now that we've had time to think more about it, let's start building our Driving Question Board.

Write initial questions for the DQB. Present slide W. Distribute 3-4 sticky notes and a permanent marker to each student. Remind students of what they have engaged in so far by referencing slide W. *Say, On these sticky notes, write at least one of your questions related to any of the data and phenomena we've considered so far. Write only one question per sticky, please, big and bold so we can all see it clearly, and don't forget to add your initials so we know who contributed it.*

* ATTENDING TO EQUITY

Universal Design for Learning: It is important to use the Community Agreements to cultivate an equitable learning community that promotes trusting and caring relationships fostering student *engagement*. The agreements should remind students to value the diversity of classroom community members, as well as equity in the sensemaking work we will do together this school year. It is critical that the agreements



Gather in a Scientists Circle around the DQB. Present **slide X**. Instruct the class to bring their sticky notes with questions to a Scientists Circle around the DQB. Explain that students will take the lead, as we did in the *Electricity Unit*. Ask for a volunteer to begin the process, and then step back. Students should use the directions on the slide for guidance. Step in when necessary to point to the relevant Community Agreements to encourage equitable participation. *

ADDITIONAL GUIDANCE

If this unit is the first of the year, consider spending some time establishing the process of creating a DQB. Explain that one purpose of the unit is to answer our questions about these earthquake cases, and in order to know our class mission, we must identify what we need to figure out. Go over the steps on **slide W** and emphasize that students lead the process. Remind them that if they have a question for the DQB but do not want to share it aloud, they can ask someone else to share it, or leave it for you to post at the beginning of the next class.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Questions that arise from our work together about things that are too large, too slow, or too inaccessible to observe directly (e.g., properties and motion deep inside Earth). (SEP: 1.1; CCC: 3.2, 3.3)
- Questions that arise from our work together along a variety of timescales (e.g., short-term effects versus long-term geologic change). (SEP: 1.1; CCC: 3.2, 3.3)
- Questions that arise from our work together that connect observations of the Afar region to larger-scale tectonic phenomena. (SEP: 1.1; DCI: ESS2.B)

What to do: Focus students on the crosscutting concepts of *patterns, cause and effect, and scale, proportion, and quantity* by posing the following questions:

1. What kinds of questions do we have about changes to the Afar region and our other earthquake cases over **different scales** of time and space?
2. What kinds of questions do we have about parts of this system that are too large, too fast, or too slow to study directly?
3. What kinds of questions do we have about what is happening inside Earth to **cause different effects** at the surface in our earthquake cases and in Afar?

Building toward: 1.B Ask questions about the mechanisms driving changes in Earth's crust that arise from careful observation of patterns in the Afar region, in order to seek additional information from indirect evidence because aspects of the phenomenon are too slow and too large to study directly. (SEP: 1.1; CCC: 3.2, 3.3; DCI: ESS2.B)

Support safe and fair participation and interrupt cultural norms or stereotypes that could make science experiences feel uncomfortable.

16 · REFLECT ON OUR USE OF COMMUNITY AGREEMENTS

3 min

MATERIALS: sticky dot (green), sticky dot (yellow), Community Agreements poster

Reflect on how the class has been doing on the Community Agreements. Display **slide Y**. Say, *In the last class, we revisited our Community Agreements. Think back to our discussions to develop our consensus model and build the DQB. Which agreements did we do well with, and which do we need to work on?* Direct students to mark the Community Agreements poster with green and yellow sticky dots as described on the slide. Below is an example of how this might look.

Our Community Agreements

Respectful Our classroom is a safe space to share.	• We provide each other with support and encouragement. • We share our time to talk. We do this by giving others time to think and share. • We critique the <i>ideas</i> we are working with, but not the <i>people</i> we are working with.
Equitable Everyone's participation and ideas are valuable.	• We monitor our own time spent talking. • We encourage others' voices whom we have not heard from yet. • We recognize and value that people think, share, and represent their ideas in different ways.
Committed to our community We learn together.	• We come prepared to work toward a common goal. • We share our own thinking to help us all learn. • We listen carefully and ask questions to help us understand everyone's ideas. • We speak clearly and loud enough so everyone can hear.
Moving our science thinking forward We work together to figure things out.	• We use and build on others' ideas. • We use evidence to support our ideas, ask for evidence from others, and suggest ways to get additional evidence. • We are open to changing our minds. • We challenge ourselves to think in new ways.

● Copy a green sticky dot and move it to mark one agreement you think we've done well with.
● Copy a yellow sticky dot and move it to mark one agreement you think we need to improve on.

Note any patterns. Quickly elicit students' ideas to implement and add to the poster as needed.

ALTERNATE ACTIVITY

If you have a digital representation of the Community Agreements that the whole class can access at once (see the Materials Preparation section), have students mark the agreements virtually instead, with green and yellow squares/stickies or circles/dots.

17 · BRAINSTORM INVESTIGATION IDEAS

5 min

MATERIALS: Driving Question Board, Ideas for Investigations/Data We Need, chart paper markers

Develop ideas for future investigations. Present slide Z. Ask the question on the slide:

- *What kinds of investigations could we carry out, and what additional sources of data might we need, to figure out the answers to our questions?*

Capture students' ideas on the Ideas for Investigations/Data We Need poster, and save this poster for future reference.

Point out that over the course of this lesson, the class has discussed many events at different locations, but all the locations had one thing in common. Say, *Because earthquakes seem to be a common thread, and we are not sure whether all these events are related, how about we start with the event we have the most common experiences with--earthquakes.*

Navigate with a Stop and Jot. Present slide AA. Pose the prompts on the slide:

- *What could be causing the land to move or crack?*
- *Does land only move and crack during an earthquake, or could it happen where there is no perceptible shaking?*

Have students consider what could be happening at the land where an earthquake occurs. Ask for volunteers to share their responses with the class. Encourage students to respond to each other's ideas to draw out a variety of thoughts. Tell them that in our next lesson, we will need to explore the changes that might occur to the land.

Additional Lesson 1 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

CCSS.ELA-LITERACY.RST.9-10.1 Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

Students read about an earthquake case and compare and contrast it with information from the Afar StoryMap text. They also compare their case to other cases to determine what they have in common, citing specific evidence from the text.

CCSS.ELA-LITERACY.SL.9-10.1 Initiate and participate effectively in a range of collaborative discussions (one-on-one, in groups, and teacher-led) with diverse partners on grades 9-10 topics, texts, and issues, building on others' ideas and expressing their own clearly and persuasively.

Students discuss earthquake cases in diverse groups and share text-based information about their cases, building on each other's ideas to find similarities between the sites and the Afar case. Students also share their initial models with partners and with the class in the larger Consensus Discussion. In addition, students share their ideas across multiple diverse groups throughout the lesson.

CCSS.ELA-LITERACY.SL.9-10.1.A Come to discussions prepared, having read and researched material under study; explicitly draw on that preparation by referring to evidence from texts and other research on the topic or issue to stimulate a thoughtful, well-reasoned exchange of ideas.

Students utilize information from their earthquake case reading and the Afar StoryMap to engage in the Consensus Discussion, using evidence from texts to engage in a thoughtful exchange of ideas related to the potential cause for the earthquake and potentially related surface features in the earthquake regions.

LESSON 2: What allows a system to remain stable when forces are acting on it, and what causes it to suddenly change?

PREVIOUS LESSON We explored a series of events in the Afar region that left a giant crack in Earth's crust in 2005, and noticed patterns across earthquake data near us. We read about other earthquakes and compared them to Afar. We developed initial models, a Driving Question Board, and investigation ideas.

THIS LESSON

INVESTIGATION

3 days



We analyze plate motion data. We develop a physical model to identify force interactions between plates. We carry out investigations to determine the conditions that result in stability and change in the motion of an object when multiple forces act on it. We use free-body diagrams to explain and predict how the magnitude of forces applied at different scales would impact stability and changes in the matter within the system.

NEXT LESSON

We will explore changes in a piece of foam as higher-magnitude forces are applied to it. We will develop a model relating unbalanced forces to changes in matter and energy transfer. We will predict whether rock would behave like a piece of foam. We will gather information from a reading and ask questions about the relationship of our new ideas to what is happening in Earth systems.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

2.A Plan and conduct an investigation to determine the contact force interactions that result in the observed stability and change in the motion of an object. (SEP: 3.2; CCC: 4.2, 7.1; DCI: ESS2.A.1)

2.B Develop and use free-body diagrams (models) to explain and predict how the magnitude of the force interactions applied to matter at different scales would impact the stability and changes within a system. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1)

WHAT STUDENTS WILL FIGURE OUT

- All systems change; “stability” is dependent on scale.
- Changing scales is an important tool that scientists and engineers use to help develop explanations for why phenomena occur in every science discipline.
- Objects in contact exert contact forces on each other.
- The net force is the sum of all the forces acting on an object; it is zero when the forces are balanced along every axis.
- Each part of a two-dimensional vector is known as a component.
- Forces at different scales can help explain why matter remains in a stable state and why its motion changes.
- Large-scale changes in Earth systems such as earthquakes, variation in plate motion, or the sudden crack in Afar could be the result of differences in forces acting on the matter in the system.

Lesson 2 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	3 min		NAVIGATE Revisit the anchoring phenomenon and connect it to the scope of the next few lessons.	A	
2	7 min		ANALYZE PLATE MOTION DATA Learn about vectors and differences in plate motion with a map of Earth's plates.	B-D	<i>GPS Plate Map</i>
3	7 min		ADD TO THE SCALE CHART POSTER Add a time axis to the Scale Chart poster. Define stability, and identify a new phenomenon that appears to be stable at one scale but would actually be changing at another scale.	E-G	<i>GPS Plate Map</i> , Scale Chart poster, 3x5 sticky notes, permanent marker
4	7 min		DEVELOP A PLATE STRUCTURE MODEL Analyze photographs of exposed plate material and layers of sediment. Use these to develop an initial model of the general structure of two plates.	H-K	Scale Chart poster, 2 pieces of chart paper
5	6 min		USE A PHYSICAL MODEL TO IDENTIFY PLATE INTERACTIONS Use three foam shapes to simulate plate motions and interactions. Identify what could happen to any object when contact forces act on it.	L-M	M-E-F poster, M-E-F expansion panels, clear tape, 3-Plate Interaction Demonstration
6	5 min		ORIENT TO THE SPRING SCALES AND MAKE PREDICTIONS Identify the units used to measure the magnitude of forces with a spring scale. Predict the relationship between the magnitude of four forces acting on a stationary object in two conditions.	N-O	1 push-pull spring scale (5 N)
7	10 min		PLAN AND CARRY OUT INVESTIGATIONS A AND B AND NAVIGATE Review the scale calibration protocol. Carry out <i>Investigations A and B</i> in small groups.	P-Q	https://youtu.be/YwxlfBUDggQ , Investigations A and B
End of day 1					
8	6 min		NAVIGATE: COMPARE RESULTS FROM INVESTIGATIONS A AND B Review the investigations handout. Discuss data accuracy, trials needed, potential causes of error, outliers, and uncertainty in an investigation.	R-S	
9	6 min		INTRODUCE FREE-BODY DIAGRAMS AND NET FORCE Create free-body diagrams for <i>Investigations A and B</i> . Learn about negative forces and net force.	T	1" grid chart paper, chart paper markers
10	12 min		DEVELOP AND EVALUATE A FREE-BODY DIAGRAM Create a free-body diagram of an object with three contact forces acting on it. Evaluate whether this is a reasonable model for explaining why the Caribbean plate appears to not be moving.	U-V	<i>Investigations A&B</i> , <i>GPS Plate Map</i>

Part	Duration		Summary	Slide	Materials
11	17 min		USE MATHEMATICAL THINKING TO EXPLORE VECTOR RELATIONSHIPS FOR OFF-AXIS FORCES Make predictions about the net force of objects with irregular shapes. Review the Pythagorean theorem and use manipulatives to support sensemaking about forces on an angle acting on an object.	W-Y	<i>Free-Body Placemat</i> , 1 clear sandwich bag containing 12 cutouts from <i>Free-Body Manipulatives</i> , calculator, M-E-F poster, M-E-F expansion panels, clear tape
12	4 min		NAVIGATE: MAKE A PREDICTION Have students discuss their predictions about removing or adding an additional spring scale acting on a foam rectangle when it is in a stable condition.	Z	
End of day 2					
13	5 min		NAVIGATE: PLAN INVESTIGATIONS C AND D Review our progress in explaining stability from a forces perspective. Review the procedure to investigate unstable systems. Plan conditions to test in small groups.	AA	M-E-F poster, M-E-F expansion panels, clear tape, https://youtu.be/LR1Ui-IVsO4 , computer
14	12 min		CARRY OUT INVESTIGATIONS C AND D Set up the system(s), carry out the investigation(s), and collect data in groups. Record results on the handout.	BB	Investigations C and D
15	12 min		ANALYZE AND INTERPRET DATA Discuss the relationship between the changes in the force interactions on the system and the observed changes in motion.	CC-FF	<i>Investigations C&D</i> , https://youtu.be/LR1Ui-IVsO4 , M-E-F poster, M-E-F expansion panels, 3x3 sticky note, clear tape
16	4 min		DEVELOP AN INITIAL EXPLANATION FOR A LARGER-SCALE PHENOMENON Use what we figured out about matter and forces to explain why one phenomenon from the larger-scale Earth system occurred (e.g., an earthquake, the variation in plate motion, the sudden crack at Afar).	GG	
17	8 min		ORIENT TO THE NEW PROGRESS TRACKER AND ADD AN ENTRY Compare prior versions of the Progress Tracker to the new one for this unit. Set up the new tracker and add an individual entry.	HH-II	3 copies of <i>Progress Tracker</i> , loose-leaf paper
18	3 min		REFLECT ON OUR COMMUNITY AGREEMENTS Complete an exit ticket reflecting on our Community Agreements.	JJ	1 piece of copy paper or forced copy of the Electronic Exit Ticket (https://docs.google.com/forms/d/1AB7Onbf_9qGMfkD1hqN7sARigc-ssTOjD1wHTY5izfA/copy), Community Agreements poster
19	1 min		NAVIGATE Brainstorm potential additional outcomes from increasing the magnitude of the forces on a stable object, and ways to investigate this.	KK	
End of day 3					

Lesson 2 • Materials List

	per student	per group	per class
3-Plate Interaction Demonstration materials	• <i>GPS Plate Map</i>		• 3 pre-prepared interlocking foam pieces • 3x3 sticky note • colored marker (red) • copy paper
Investigations A and B materials	• <i>Investigations A&B</i> • science notebook	• 4 push-pull spring scales (5 N) • 8 sticky tack tabs • 1 foam rectangle • ruler	
Investigations C and D materials	• <i>Investigations C&D</i>	• 4 push-pull spring scales (5 N) • 8 sticky tack tabs • 1 foam rectangle • ruler	
Lesson materials	• science notebook • <i>GPS Plate Map</i> • <i>Investigations A&B</i> • <i>Investigations C&D</i> • 3 copies of <i>Progress Tracker</i> • loose-leaf paper • 1 piece of copy paper or forced copy of the Electronic Exit Ticket (https://docs.google.com/forms/d/1AB7Onbf_9qGMfkD1hqN7sARigc-ssTOjD1wHTY5izfA/copy)	• 1 push-pull spring scale (5 N) • <i>Free-Body Placemat</i> • 1 clear sandwich bag containing 12 cutouts from <i>Free-Body Manipulatives</i> • calculator	• Scale Chart poster • 3x5 sticky notes • permanent marker • 2 pieces of chart paper • M-E-F poster • M-E-F expansion panels • clear tape • https://youtu.be/YwxlfBUDgqQ • 1" grid chart paper • chart paper markers • https://youtu.be/LR1Ui-IVsO4 • computer • 3x3 sticky note • Community Agreements poster

Materials preparation (90 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.

Print 1 double-sided copy of these handouts for each student:

- *Investigations A&B*
- *Investigations C&D*

Print 3 double-sided copies of the *Progress Tracker* handout for each student. Students will use these for their tracker entries for the entire unit.

Three-hole-punch the 2 sets of handouts above so they can be added to students' science notebooks.

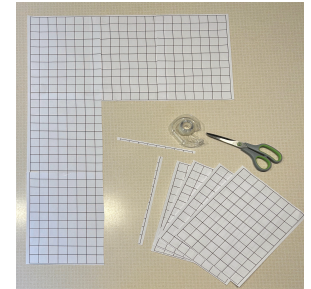
Print 1 copy of the *GPS Plate Map*, in color if possible, for each student in your largest class. Place each copy in a sheet protector if available.

Print 1 copy of the *Free-Body Placemat* for each pair of students in your largest class. Place each copy in a sheet protector if available.

You will use a single piece of 1" grid chart paper for each class. If this paper is not available, you can prepare the following as an alternate for each class:

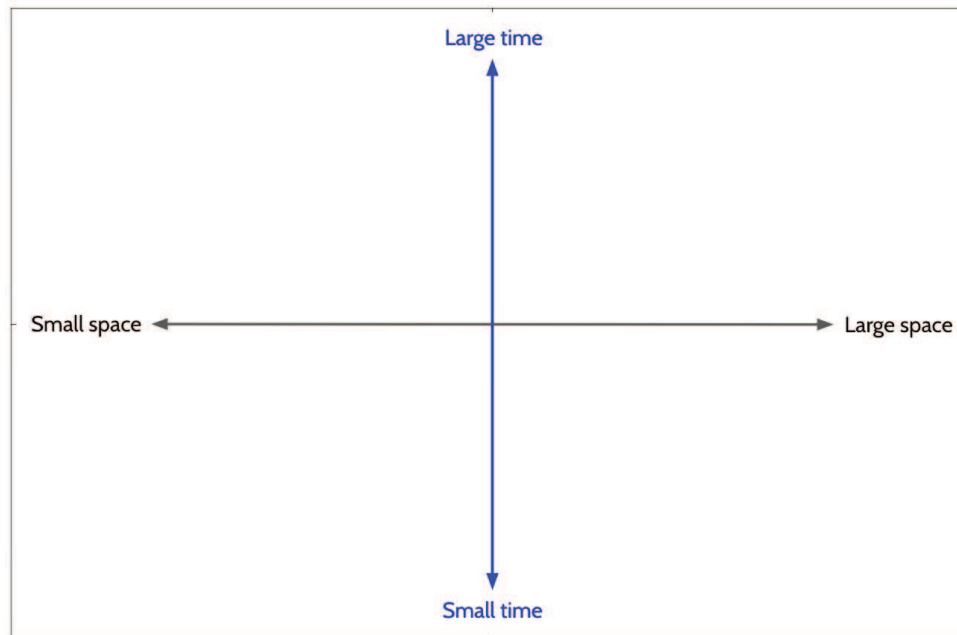
- Print 9 copies of the *1" Grid Paper* reference. Trim and tape these together to form a continuous grid. An example showing taped copies is on the right.

Use scissors to cut out the 12 *Free-Body Manipulatives* pieces printed on cardstock for each pair of students in your largest class. If you are printing these, print 1 copy for your own use. Place each set into a clear sandwich bag for distribution, collection, and reuse across classes. Preparing the arrow cutouts is time-consuming; consider providing each student pair with scissors to do this themselves.



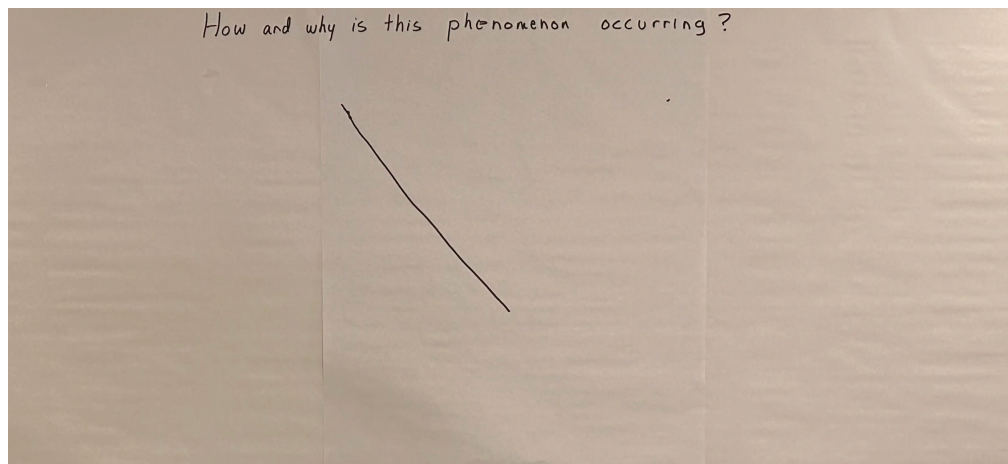
NOTE: The formatting in Google docs may not work for *Free-Body Placemat* and *Free-Body Manipulatives*. Use the PDFs of these files for correct sizing.

Add a time axis to the Scale Chart poster from Lesson 1. Cover the axes with chart paper to keep this addition hidden until it is introduced in each class.

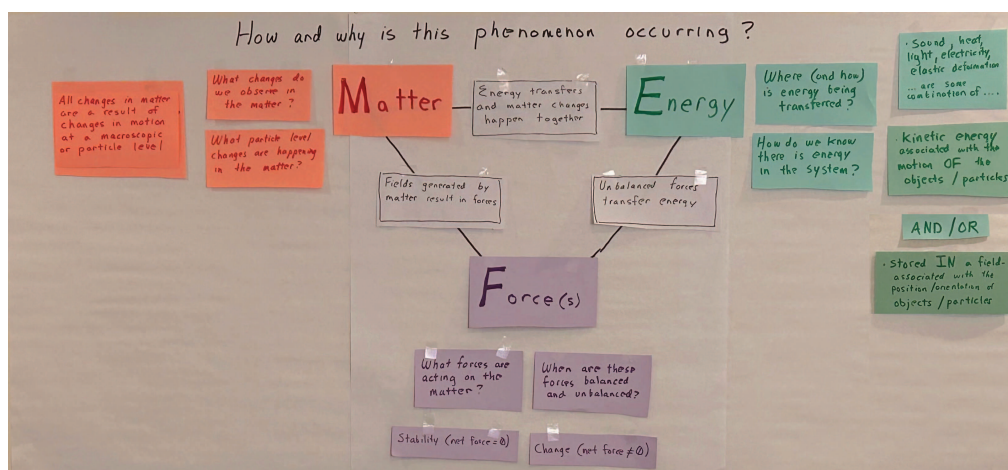


Connect 3 pieces of chart paper. Write “How and why is this phenomenon occurring?” across the top, having the title span the three pieces of chart paper. This will serve as the M-E-F poster. To see how this develops over time, see *Developing the M-E-F poster*, located in Lesson 3, where lines are added connecting matter, energy, and forces.

Add a diagonal line to the M-E-F poster as shown in the image below. Make a set of chart paper panels using the colors shown for the text; temporarily tape these to the poster to ensure that the layout shown below will work once you reach the end of Lesson 4. Don't draw in the other two black lines yet; these will eventually connect energy to matter and forces.



This is what the M-E-F poster looks like at the start of this lesson.



This is what the M-E-F poster looks like by the end of Lesson 4.

Now remove the M-E-F expansion panels from the poster. You will tape them on for each class at various points in Lessons 2-4. You will also remove some of them and reset the M-E-F poster to its previous state (as it was at the start of the class) before the next class, so it can be co-constructed at appropriate points with every class you teach.

Test the 3 student videos:

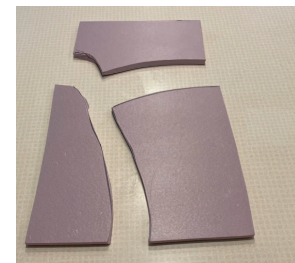
- Scale calibration and alignment procedure: <https://youtu.be/YwxIfBUDgqQ>
- Removing or adding one force to a stable spring-scale system: <https://youtu.be/LR1Ui-IVsO4>
- Slow motion removal of a force from a stable 4 spring-scale system: <https://youtu.be/5FhG36Lw1c4>

At the end of the lesson, students complete an exit ticket to reflect on the class Community Agreements. They can do this on paper, but a digital form might facilitate collecting their answers. If you would like to use an Electronic Exit Ticket, see the *How to Create Electronic Exit Tickets* reference located in Lesson 4 for how to make a copy of the Electronic Community Agreements Exit Ticket. Make this copy before the beginning of the period, and share your personal copy with the class during this reflection. Access the link below to make a copy of this exit ticket:

- https://docs.google.com/forms/d/1AB7Onbf_9qGMfkD1hqN7sARigc-ssTOjD1wHTY5izfA/copy

Day 1: 3-Plate Interaction Demonstration

- **Group size:** Whole class.
- **Setup:** In 1 foam panel (~16" x 8" x ½"), trace 3 puzzle pieces with shared curved edges. Cut these out using a box cutter. Ensure that the pieces fit together snugly.
- **Disposal:** Materials are all reusable and do not need to be thrown away.
- **Storage:** All materials can be stored and reused next year or for other investigations.



Day 1: Investigations A and B

- **Group size:** 4-5 students.
- **Setup:** Cut the foam panel into 7 rectangles and prepare 28 push-pull spring scales (5N) with sticky tack as outlined in the *Preparing Foam Blocks* reference. Each group needs 4 spring scales and 1 foam rectangle. A video demonstrating those steps is available at: <https://youtu.be/qtCSuxoThRU>. Clean the surfaces where students will secure their sticky tack, to increase its effectiveness.
- **Safety:** Have students wear indirectly vented chemical splash goggles during this investigation, as applying forces to the foam rectangles may result in the foam or scales unexpectedly jumping out of the system.
- **Disposal:** Materials are all reusable and do not need to be thrown away.
- **Storage:** All materials can be stored and reused next year or for other investigations.

Day 2: Investigations C and D

- **Group size:** 4-5 students.
- **Setup:** Prepare the same 7 foam rectangles and 28 push-pull spring scales (5N) with sticky tack that students used during *Investigations A and B*. Each group needs 4 spring scales and 1 foam rectangle.
- **Safety:** Have students wear indirectly vented chemical splash goggles during this investigation, as applying forces to the foam rectangles and removing 1 of them may result in the foam or scales unexpectedly jumping out of the system.
- **Disposal:** Materials are all reusable and do not need to be thrown away.
- **Storage:** All materials can be stored and reused next year or for other investigations.

Lesson 2 • Where We Are Going and NOT Going

Where We Are Going

This lesson builds a foundation for understanding balanced versus unbalanced forces in terms of net force, and the relation of these to stability and change in motion. However, in middle school, the idea of summing forces to determine whether the resulting net force is zero or not zero is limited to considering only one dimension. According to pilot testing, ideas about force interactions on, in, and between plates do not tend to show up on initial models created in Lesson 1 of this unit; therefore, it is essential to redevelop and add these ideas before moving on to high school level ideas about forces in subsequent lessons.

This lesson is designed to coherently build ideas related to the following disciplinary core ideas (DCIs):

- **ESS2.A.1 Earth Materials and Systems:** Earth's systems, being dynamic and interacting, cause feedback effects that can increase or decrease the original changes. (HS-ESS2-1, HS-ESS2-2)
- **PS2.A Force and Motion:** The motion of an object is determined by the sum of the forces acting on it; if the total force on the object is not zero, its motion will change. (from middle school)
- **PS2.A Force and Motion:** Newton's second law accurately predicts changes in the motion of macroscopic objects.

The work we are doing takes the idea of summing forces beyond middle school level understanding, which (as noted above) is limited to forces in one dimension. Newton's second law describes the relationship between net force on an object and its acceleration, based on its mass. Therefore, we reestablish the net force piece of this high school level idea in this lesson.

To understand the dynamic interactions of Earth systems and the resulting changes, students need an operational definition of what is changing and which types of interactions to track. The prior unit focused on monitoring changes in energy and matter. Although we recognize that these often occur simultaneously, we lack a mechanism to explain the interactions between systems. Therefore, forces will serve as the primary interaction mechanism for the remainder of the course. Reintroduction of the middle school concept of balanced and unbalanced forces is a foundation for comprehending the feedback effects caused by force interactions, energy transfer, and changes in matter between Earth systems.

To integrate these ideas into a sensemaking framework, we introduce a key anchor chart, the Matter, Energy, and Forces poster, abbreviated hereon as the M-E-F poster. Over the course of this and subsequent units, this will become a public record of important ideas and questions that students ask to explore the dynamic interactions between matter, energy, and forces. Lessons 3 and 4 include major additions to this poster.

This lesson is also designed to engage students in the following science and engineering practice (SEP):

- Plan and conduct an investigation ~~individually~~ and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.

To deepen students' fluency in planning and carrying out investigations, this lesson explicitly discusses how determining the accuracy of data needed to produce reliable measurements often needs to be adjusted as results come in. As this is the first lesson in the unit in which students engage in this practice, they work on this in small groups. In Lesson 8, they will have an opportunity to consider data accuracy individually.

Students are introduced to two connections between crosscutting concepts (CCCs) through the idea that all phenomena in science can be considered either stable or changing, depending on the scale at which they are studied. Additionally, they learn that much of science deals with constructing explanations of how things change and how they remain stable, while also determining that changing scales to study a phenomenon can help us explain *why* it occurs. These ideas are introduced in parallel with expansion of the Scale Chart--a key sensemaking tool to support connecting CCCs in subsequent lessons.

Students also reflect on their use of CCCs in this unit's first Progress Tracker entry, as they consider how thinking about *stability and change* over time, and thinking at/across different scales, helped us figure something out. The self-reflection prompts related to the use of these CCCs will recur over the course of the unit, each time a new tracker entry is made.

This lesson is designed to support students toward the Next Generation Science Standards (NGSS) Nature of Science Understanding titled **Scientific Investigations Use a Variety of Methods** (Appendix H). The relevant element reads:

- Scientific inquiry is characterized by a common set of values that include: logical thinking, precision, open-mindedness, objectivity, skepticism, replicability of results, and honest and ethical reporting of findings.

During this lesson, students consider whether they need to conduct more trials in light of their empirical results. The class discusses data accuracy, number of trials needed, and potential causes of errors, outliers, and uncertainty in an investigation.

Students encounter and/or co-develop definitions for the following terms in this lesson: *vector, magnitude, force, balanced forces, unbalanced forces, net force, contact forces, plate, vector component*. They may not yet know what a plate is, and that is fine. If they ask, say that it is a great question and have them post it on the Driving Question Board, or allow other students to suggest a meaning and begin an entry in their Personal Glossaries, leaving room for more information. We will co-develop a meaning in the next several lessons, and encounter a formal definition for *tectonic plate* in Lesson 5. **Do not** ask students to define or keep track of any words until after your class has developed a shared understanding of their meaning.

Where We Are NOT Going

Newton's law describes the relationship between net force on an object and its acceleration, based on its mass. We will reestablish the net force piece of this high school level idea in subsequent lessons in this unit. However, the quantitative relationship between mass, force, and acceleration will not be developed until the next unit, *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*.

Net torque of zero is a type of force balance that is also needed to keep an object from rotating. It is beyond the target DCIs for high school and is not a focus of this lesson.

LEARNING PLAN for LESSON 2

1 · NAVIGATE

3 min

MATERIALS: None

Recall the anchoring phenomenon. Say, *Last time, we explored data from earthquakes and the cracks in the ground that sometimes open up after them. We saw this had happened at multiple locations on Earth, beyond the event we started with in the Afar region in 2005. Display slide A.* Instruct students to take a moment to think about the questions on the slide on their own. Then discuss these as a class, as shown in the table below.

Suggested prompt	Sample student response
<i>What could be causing the land to move or crack?</i>	Lava underneath is pushing the ground from below. Earth's plates are moving. Material below the plates is interacting with the material above them. The land in some places, like Afar, might be too dry, so it cracks.
<i>Does land only move and crack during an earthquake, or could it happen when or where there is no perceptible shaking?</i>	(Accept all answers.)
<i>What measurements or data would you want to analyze to see whether any of these things are happening before an earthquake occurs?</i>	Data about whether the land in the area is moving or whether it is changing elevation over time. Samples of rocks from the surface or below the surface. Something like sonar or radar images to see what is happening below the ground. Weather or climate data related to rainfall and humidity.

Connect this to the scope of upcoming lessons. Say something like, *Let's plan to analyze some of these different types of data sets over the next few lessons.*

2 · ANALYZE PLATE MOTION DATA

7 min

MATERIALS: science notebook, *GPS Plate Map*

Introduce the plate map. Distribute the *GPS Plate Map* to each student. Say, *I have a piece of data about plate motion. Let's start out with the data overlay shown on this map and see what it tells us about what is happening across Earth over time.*

Present **slide B**. Give students a minute to analyze the map data on their own. Then ask for a few responses to the questions on the slide, as shown in the table below.

Suggested prompt	Sample student response
<i>What do the arrows represent?</i>	How fast plates are moving. The direction plates are moving.
<i>Why are some arrows longer than others?</i>	Some plates are moving faster than others.

Compare arrow lengths. Say something like, *In this representation, the length of the arrow is proportional to the speed of the plate at that location. This means that for an arrow that's half the length of the one shown in the key, the rate of motion at that location is half as much as in the key.* Ask students to find an example on the map of an arrow that is half the size of the arrow in the key, and identify what the rate is there. They should find an arrow that represents approximately 2.5 cm per year.

Introduce vectors. Say, *Because the length of the arrow is proportional to a measured quantity, it is considered a vector representation of the data. Vectors are often used in physics to represent any quantity that also has a direction to it.*

Display **slide C**. Discuss the question as a class:

- *What does this data tell us about what is happening to Earth's plates?*

Listen for the following ideas:

- Different plates are moving in different directions.
- Different plates are moving at different speeds.
- There is variation in direction of motion across a plate.

If students don't notice the variation in direction of motion across a plate, draw their attention to the South American plate or the African plate.

Problemalyze the differences in plate motion. Explain that these differences in plate motion can be hard to account for if we consider what we know so far about plates. Point out that based on this map, there seems to be no measurable motion for the Caribbean plate, but in other cases, plates that are right next to each other are moving in different directions.

ADDITIONAL GUIDANCE

The Caribbean plate is actually missing GPS motion data. The claim that there seems to be no measurable motion of this plate is based on the limited data available on this map at this time. The smaller plates are missing motion data as well. All the plates do have GPS motion data associated with them, but that is more apparent when viewed at a different scale. These data are not visible at the scale chosen for the rendering of this world map.

Leaving out the rendering of some parts of the vector data set for smaller parts of a system is a common visualization choice built into computer programs that allow zooming in or out of a system to adjust the scale of viewing. One reason for this is to prevent vectors that overlap other parts from being mistakenly attributed to the wrong part of the system. That choice was made for this map, and it is a useful artifact to keep included for sensemaking in the next part of the lesson. In reality, the Caribbean plate is moving eastward at a rate of 2.2 cm per year relative to the South American plate.

Interpret data on plate motion. Display **slide D**. Cue students to discuss the question with a partner for a minute:

- *Why might a plate that we are living on appear to us to be stable, even though it is moving at a scale of a few centimeters per year?*

Then have them share out as a class. Listen for the following ideas:

- Plates are huge, but they only move a few centimeters in an entire year.
- They move too slowly for us to feel it.
- We might not always feel it, but some places might feel it only for a very short bit, when they are near an earthquake.

Ask why plate motion would be a more noticeable phenomenon if we measured changes over millions of years. Accept all answers, but listen for students to suggest that millions of years would result in plates moving millions of centimeters, which would translate to large distances.

3 · ADD TO THE SCALE CHART POSTER

7 min

MATERIALS: GPS Plate Map, science notebook, Scale Chart poster, 3x5 sticky notes, permanent marker

Expand the Scale Chart poster. Present slide E. Remind the class that last time, we developed a Scale Chart poster to organize phenomena according to size. Explain that we are now adding a new scale of time. Say, *It's hard to detect continents moving day to day; that would be easier to detect over millions of years. In our example, we're now considering the length of time of the phenomena. I've added another axis to our poster to represent time.* Remove the chart paper covering to reveal the poster.

Orient to the new time axis. Discuss where to add the plate motion measurement if it were measured over a day. Then discuss where to move the Scale Chart poster's existing sticky notes along the new time axis. Follow students' lead, and do not play guess-what's-in-my-head. Similarly to Lesson 1, use a sticky note for each phenomenon you add to the poster.

Remember that the images shown below are only one possible configuration. This poster is a public record of the class's thinking at the time; it does **not** need to match the example images.

* SUPPORTING STUDENTS IN DEVELOPING AND USING SCALE, PROPORTION, AND QUANTITY

This is a moment in which students have an opportunity to use an important crosscutting concept for a phenomenon of their choice. This can help them see the generality of this idea for making sense of phenomena beyond those that are the focus of this unit:

- Some systems can only be studied indirectly as they are too small, too large, too fast, or too slow to observe directly.

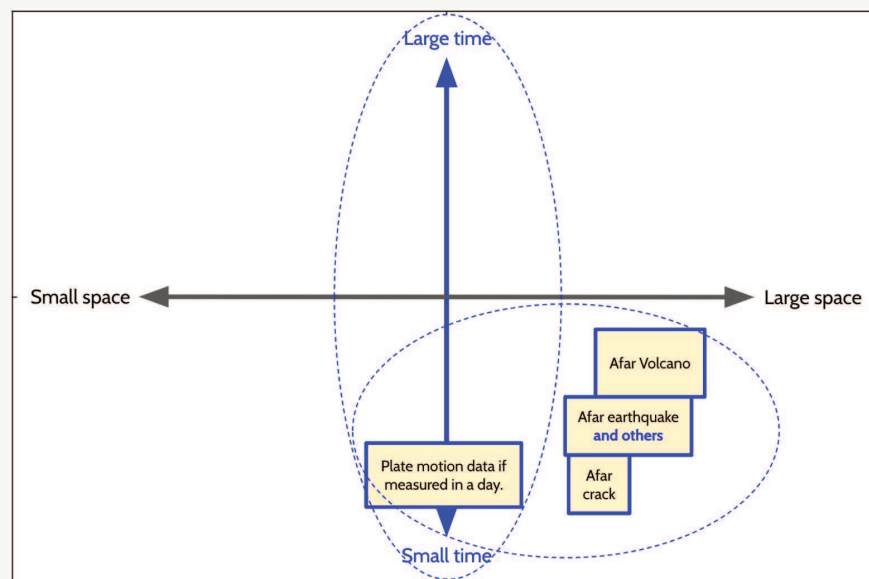
The chart paper covering the newly added time axis was removed.

Plate motion, if measured over a day, was added to the middle bottom.

The Afar crack was moved downward to reflect its sudden occurrence.

The Afar volcano was moved downward, but not to as short a time as the crack, to reflect the eruption occurring over a longer period.

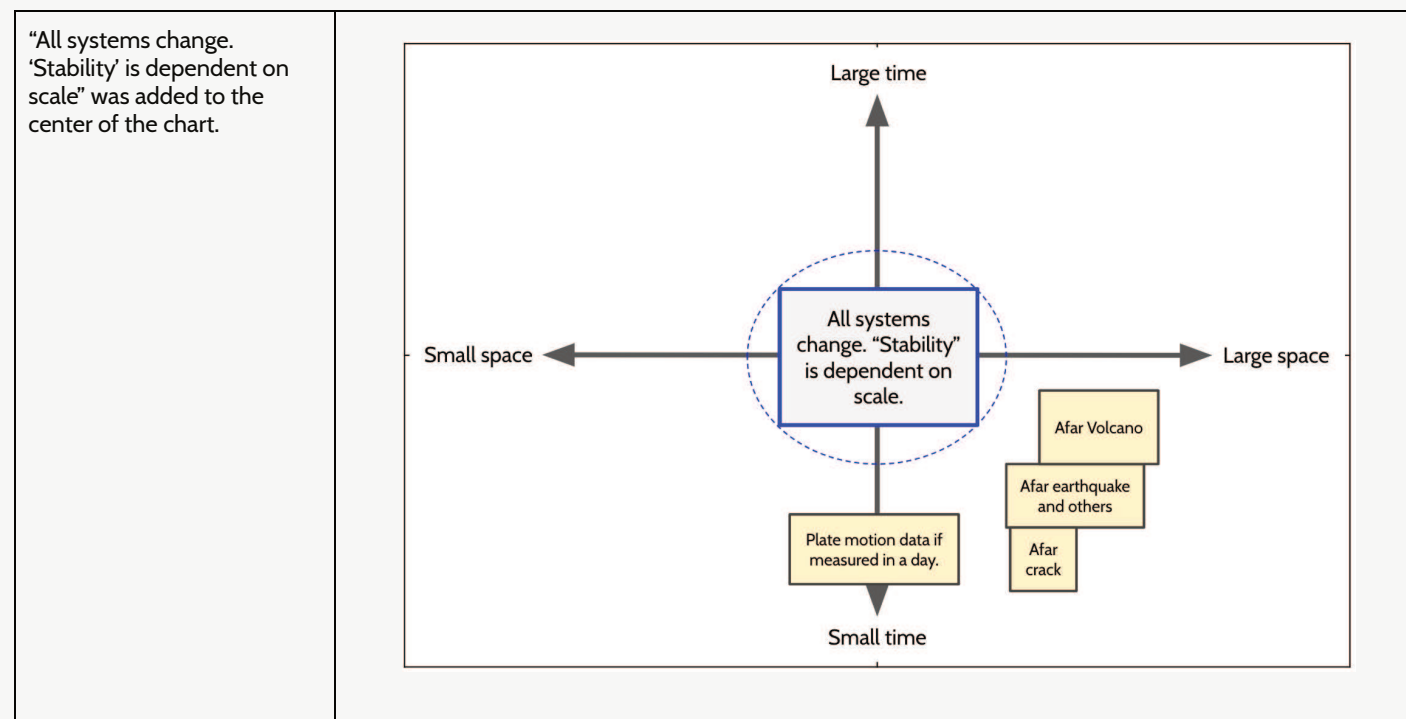
Other phenomena were added to the Afar earthquake and moved downward to reflect occurrence over a relatively short period. Space can vary for hypocenter or distance felt, or plate movement at a boundary. The timescale is likely between the Afar volcano and the Afar crack.



Introduce stability as a relative measure. Present **slide F**. Note that the plate motion data measured over a day isn't the only example of something that appears stable at one scale but is actually changing at another. As a second example, choose an object in the room that is stable and discuss the slide's prompts, as shown in the table below. *

Suggested prompt	Sample student response
<i>Under what conditions is it stable?</i>	If nobody or nothing moves it.
<i>What if we changed the temperature in the room?</i>	It might get warmer, but it would remain stable.
<i>What if we changed the temperature and looked at the particle scale?</i>	The particles would speed up as the temperature increases.
<i>What if we left the object here for hundreds of years? Would it still be stable?</i>	No, gravity would eventually pull it down over time.

Add the related idea about stability and change to the Scale Chart poster. See the image below.



Display **slide G**. Say, *Let's consider some other phenomena this applies to.* Have students reflect on the slide's prompts:

- Brainstorm at least one phenomenon in an Earth system in which something appears to be stable at one scale, but would actually be changing at another scale.

- How does changing the scale allow us to see something different in this particular phenomenon?

Give them 2 minutes to record a response in their notebooks.

4 · DEVELOP A PLATE STRUCTURE MODEL

7 min

MATERIALS: Scale Chart poster, 2 pieces of chart paper

Elicit ideas about plate composition and size. Present **slide H**. Say, *We've been discussing the scale of the plates and considering aspects of change and stability related to them. Let's take stock of what else we know about their scale and structure.* Discuss the slide's prompts, as shown in the table below.

Suggested prompt	Sample student response
<i>How big across are the plates?</i>	Hundreds or thousands of miles across. Huge--sometimes they have continents and an ocean on them.
<i>What material(s) are plates made of?</i>	Rock/stone.
<i>In some places, plate material is buried below layers of sediment, but in other places, it is not. What are some places where you have seen plate material exposed at the surface?</i>	I never have. Mountains. Rock faces or cliffs.

Analyze and interpret data of plate sample images. Say something like, *Let's analyze some additional data to compare it to our predictions on what plates are made of and some of the places we can find it.* Present **slide I**. Orient the class to the images, which are exposed bedrock (plate material) at three locations. Discuss the prompt:

- What does this tell us about what the plates are made of?

Listen for students to suggest solid rock and thick pieces of rock.

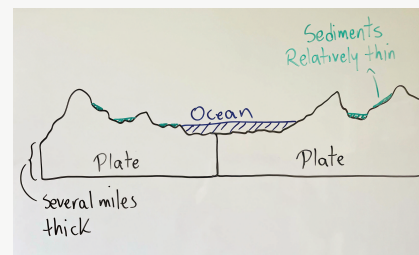
Introduce drill depth limits. Say, *It does seem that plates may be made of solid rock. Scientists have drilled as deep as 5 miles into the plate material at the bottom of the Pacific Ocean, and even deeper into the plate material in Russia--they have yet to reach the bottom of the plate in either location.*

Analyze and interpret data of relative depth of sediments. Present **slide J**. Say, *Let's use these images to get a sense of how thick the surface sediments are as compared to the underlying plate material.* Elicit a few ideas with the prompt:

- How would the relative thickness of most sediments on Earth's surface compare to the thickness of the plate below them?

Listen for the following ideas:

- Sediments are much thinner than the thickness of the plate below them.
- Plates are much thicker than the sediments at the surface above them.



Display **slide K**. Suggest using the board to sketch and label a cross section of two plates that represents some of the ideas we discussed. As you do so, check whether each characteristic represents what the class agreed on.

5 · USE A PHYSICAL MODEL TO IDENTIFY PLATE INTERACTIONS

6 min

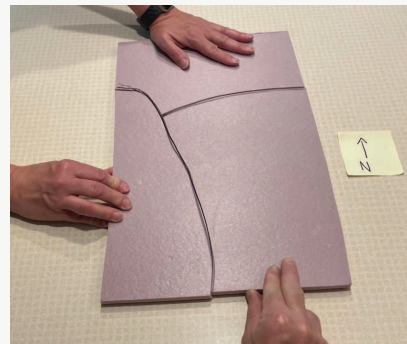
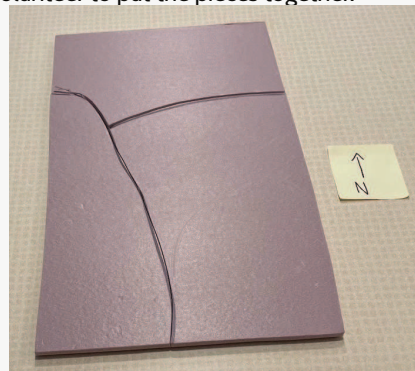
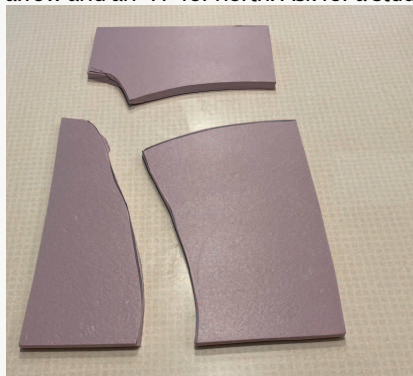
MATERIALS: 3-Plate Interaction Demonstration, M-E-F poster, M-E-F expansion panels, clear tape

Explore plate interactions. Display **slide L**. Read the text aloud to emphasize these two points:

- *Changing scales is an important tool that scientists and engineers use in every science discipline to help develop explanations for why phenomena occur.*
- *Understanding why a system appears “stable” at one scale, for example, may require analyzing it at a different scale where changes are more evident. **

Orient to the apparent stability of the Caribbean plate. Use the slide to identify where the Caribbean plate is. Note that it appears to be stable, and that the Nazca and South American plates appear to be moving in opposite directions. Suggest that we re-create this type of motion using smaller-scale manipulatives to understand the interactions that would be occurring between the plates.

Explore plate motion with a physical model. Have students gather around a table with the prepared foam pieces. Suggest we use these to represent the Caribbean, Nazca, and South American plates, bearing in mind that the scale is of course much smaller and some of the differences in elevation or inclusion of sediments, as shown in our cross section plate diagram, are not represented. Label a sticky note with an arrow and an “N” for north. Ask for a student volunteer to put the pieces together.



* SUPPORTING STUDENTS IN DEVELOPING AND USING STABILITY AND CHANGE

At this moment, you are making this crosscutting concept explicit: “Much of science deals with constructing explanations of how things change and how they remain stable.” You are doing this by connecting it to the ideas that (1) all phenomena in science can be considered either stable or changing, depending on the scale at which they are studied, and (2) determining the appropriate scale(s) to study a phenomenon is what helps us explain *why* things change and why they remain stable.

Reference **slide L** again. Say, *We also saw that two of the plates are moving in different directions toward other plates that appear to be stable. Let's use these manipulatives to re-create that motion and figure out what sort of interactions might be going on.* Ask three volunteers to simulate what the map shows for these three plates:

1. One student holds down one piece of foam to simulate the stationary Caribbean plate.
2. The second student tries to move another piece of foam toward the Caribbean plate, simulating the South American plate moving north. This will prove problematic, because the first piece of foam is in the way.
3. The third student moves the third piece of foam toward the second one at a right angle (eastward) to simulate the movement of the Nazca plate. This will also prove problematic, because the second piece of foam is in the way.

Ask why it seems impossible to keep moving the plates in these directions when they are arranged in this way. Listen for students to say that the plates are jammed against each other with no room to move any farther.

ADDITIONAL GUIDANCE

Students may suggest alternate plate interactions, including things like one plate sliding over or under another, or the plates crumbling or breaking along the edges. Accept all answers, then encourage them to jot down any new questions these ideas raise on sticky notes and add them to the Driving Question Board.

Suggest that because the plates in this system are in contact, it might be useful to try to figure out what is happening between two plates where they are touching. Ask for predictions in response to this prompt: *What would we feel if we placed a finger between these plates where they meet while these very slow motions are occurring?* Listen for students to say that the finger would feel a push, a compression, or a force on it.

Make sense of contact force interactions. Present slide M. Say, *Whenever two objects are in contact, they exert forces on each other, which are called contact forces. Let's make sense of how contact force interactions on a solid object might affect it.* Have students reflect for a moment on the slide's prompt:

- Consider **any** piece of matter at **any** scale (e.g., a small piece of foam or a large plate). What are all the different things that can happen to solid matter when contact forces in different directions are acting on it?

Share out ideas as a class. Listen for students to suggest the following:

- It can break.
- It can crack.
- It can move.
- It can bend (change its shape).

Use a red marker to list each shared idea on a piece of copy paper.

Follow up by asking, *Does this mean that whenever forces are acting on matter, it's going to change in one of these ways? Or is it possible that none of these things would happen?* Listen for the suggestion that there may be no change. Add this last possibility to the list of ideas:

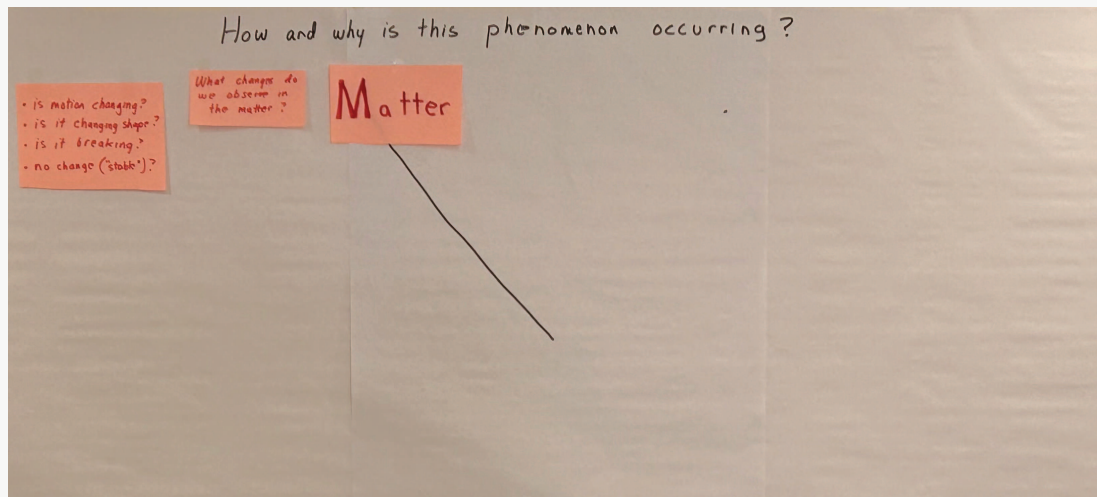
- No change ("stable").

Then note that we just saw an example that appeared to meet this condition--the Caribbean plate.

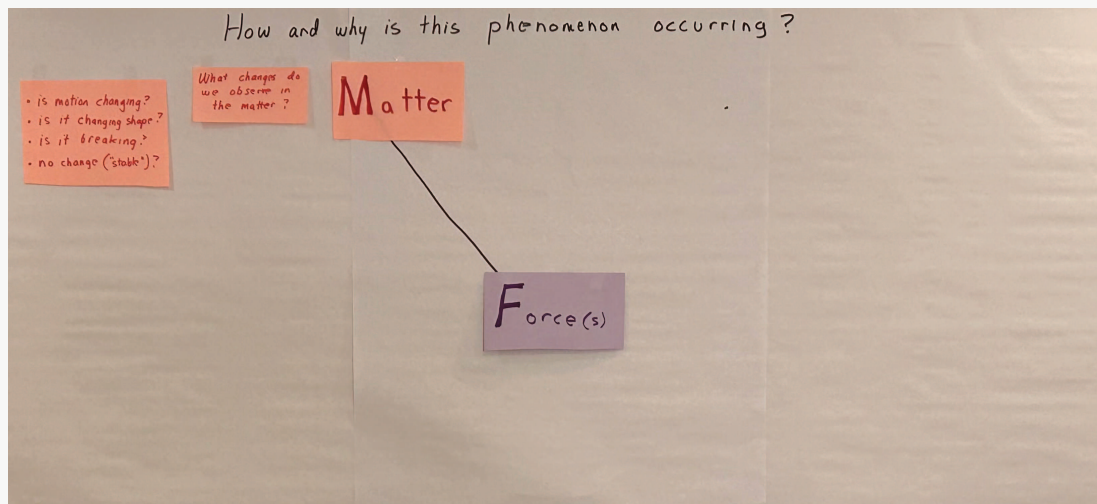
Start creating the M-E-F poster. Remind the class that in the *Electricity Unit*, we analyzed the electrical grid from a matter perspective and an energy perspective, and working across both of those helped us explain our phenomena more fully. Highlight that looking at changes in matter seems to be a first step to understand why a phenomenon is occurring. Add the M-E-F expansion panels to the poster as shown below.

Add the prepared panels that read "Matter" and "What changes do we observe in the matter?"

Add the panel that lists the changes (in the form of questions) that students predicted they might observe in the matter.



Point out that we are saying that the changes in matter we are now predicting would be caused by forces, so this suggests that forces are another important lens that can help us make sense of phenomena. Add the panel with "Force(s)" on it to the bottom black line that connects it to "Matter".



ADDITIONAL GUIDANCE

If your students did not complete the *Electricity Unit*, you could instead reference their experiences with any of these prior year high school Biology or Chemistry units: *OpenSciEd Unit B.1: How do ecosystems work, and how can understanding them help us protect them?* (*Serengeti Unit*), *OpenSciEd Unit C.1: How can we slow the flow of energy on Earth to protect vulnerable coastal communities?* (*Polar Ice Unit*), *OpenSciEd Unit C.2: What causes lightning and why are some places safer than others when it strikes?* (*Electrostatics Unit*), *OpenSciEd Unit C.5: How can chemistry help us evaluate fuels and transportation options to benefit the Earth and our communities?* (*Fuels Unit*). Alternatively, you could ask them for examples they recall from science experiences in grades 5-8.

Collect the *GPS Plate Map* handouts.

6 · ORIENT TO THE SPRING SCALES AND MAKE PREDICTIONS

5 min

MATERIALS: 1 push-pull spring scale (5 N)

Introduce the spring scale. Say, *We identified contact forces between the foam pieces and decided to investigate that from a forces perspective. To do that, we need a device to measure force interactions.*

Present **slide N**. Say, *I have a device we can use to take measurements of contact forces--it's a push-pull spring scale.* Distribute a scale to each student pair. Ask them to push it a few times (without removing the sticky tack on it) and to note any changes in the units measured. Elicit 1-2 ideas with the prompt:

- *What units does a spring scale measure?*

Listen for students to point out the “g” and “N” on the scale. If they aren't sure what those stand for, identify them as grams and newtons. Ask where we have seen those before and what they are used to measure. Students may recognize grams as a unit for mass. It is OK if they are not familiar with newtons; simply mention that scientists use newtons to measure forces. Say, *Because we want to use the spring scales to measure force, we'll pay attention to the newtons reading. In future lessons, we'll use the grams measurement to make sense of how a force measurement tool can tell us mass.*

ADDITIONAL GUIDANCE

Students will use this relationship again as they investigate friction and gravity in Lessons 11-12. They will further develop the understanding of the relationship between mass and the force of gravity in general in *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)*.

Introduce the word *magnitude*. * Point out that:

- The spring scale allows us to measure the magnitude of the contact forces acting on it.
- The word *magnitude* here refers to the strength or size of the forces in the system.
- *Magnitude* is a general term in physics that refers to the numerical value of **any** quantity we can measure in a system.
- An example of magnitude that we saw earlier was the GPS motion arrows on the map, which were scaled to the magnitude of the average speed measured at that location over a year.

Predict the magnitude of forces. Present **slide O**. Have students turn and talk about the prompt:

- *What magnitudes of these 4 contact forces would keep the object stationary (“stable”)?*

Ask students to share out; accept all predictions. If students don't generate any controversy, and they all say the magnitude of the forces would need to be equal on every spring scale, follow up by asking, *Does every force from each spring scale in the system need to be the same magnitude, or can some be larger or smaller than others?*

Accept all responses and say, *Let's test these predictions.*

* ATTENDING TO EQUITY

Universal Design for Learning: This might be a good place to reference prior use and *representations* of this word. This can help students build an idea of what the term *magnitude* means from past experiences to better understand what it means in this context. Examples of what we may have said or read:

- “We did not realize the magnitude of the problem.”
- “The amount of damage from an earthquake is often related to its magnitude.”

The latter is how students came to understand the term's use in the *OpenSciEd Middle School Unit 6.4: Plate Tectonics and Rock Cycling (Everest Unit)*. It is not important at this time to distinguish that the measure of earthquake magnitude is a measure of energy transfer from the source to the surroundings.

7 · PLAN AND CARRY OUT INVESTIGATIONS A AND B AND NAVIGATE

10 min

MATERIALS: Investigations A and B, <https://youtu.be/YwxIfBUDggQ>

Review the calibration protocol. Present slide P. Prompt the class to get ready to carry out an investigation to obtain the data we need to either support or refute our predictions. Emphasize that each group has important considerations to discuss before starting an investigation. Play the video <https://youtu.be/YwxIfBUDggQ> to demonstrate how to calibrate a spring scale and align several scales along the same axis.

Organize the class in groups of 4-5. Give groups 2 minutes to discuss the questions on the slide:

- *How might our results be affected if we skip zeroing the scales?*
- *Why is it important to align the spring scales along the same axis for each condition we test?*

ADDITIONAL GUIDANCE

Friction between the tip of the spring scale and the foam produces additional shear forces along the edge of the block. Knowing that this effect exists is not the focus of this lesson. However, these forces may contribute unanticipated variation in the data being collected for the force balance conditions. This variation can be minimized and will appear insignificant if the force application from each spring scale is kept parallel to the aligned marks on the sides of the foam rectangles. The calibration video (<https://youtu.be/YwxIfBUDggQ>) shows how to ensure this by using a ruler. Watch for this as students carry out their investigations, and help them adjust their setup if you notice the spring scales are not parallel to the marks.



Plan Investigations A and B. Distribute the *Investigations A&B* handout to each student. Help the class make sense of the images on the handout to plan two investigations testing forces applied by the scales to the foam.

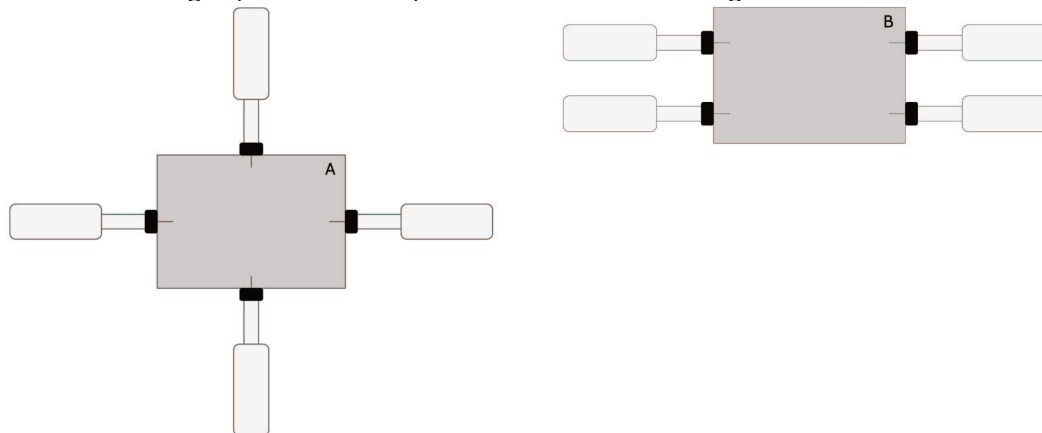
Present slide Q. Have groups follow the first prompt and raise their hands when they have agreed upon the conditions to test:

- *Discuss the conditions you want to test for Investigations A and B, and record them on your handout.*

Carry out the investigations. Distribute lab materials to each group as they request supplies for their investigations. The procedure for this lab is detailed in the handout.

ADDITIONAL GUIDANCE

In *Investigations A and B*, students collect force measurements of 4 spring scales acting on the foam rectangle. The arrows in this image represent where to place the scales for each investigation.



For each condition tested, students increase or decrease the magnitude of the forces pushing on the foam, and record the force measurements when the system is stable; that is, when the foam is not moving and nobody is touching it.

Walk through the classroom as groups collect their data. Encourage students to record their results individually on their handout.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- A record of the direction and magnitude of force interactions from 4 spring scales labeled in newtons. (SEP: 3.2; DCI: ESS2.A.1)
- A description of how the group decided they had carried out enough tests to determine what keeps the system stable in every condition. (SEP: 3.2; CCC: 7.1)

What to do: If you collect the *Investigations A&B* handout, you can provide written feedback on this assessment opportunity; otherwise, you can visit groups and provide verbal feedback/guidance while they investigate. If you do the latter, and a group has finished their data collection, ask them to tell you their ideas in response to **slide Q's** last prompt. Accept all answers, but prime a few groups who have different ideas about this. Invite them to share their ideas next time during the class discussion. See the *Investigations A&B* Key for sample responses.

Building toward: 2.A.1 Plan and conduct an investigation to determine the contact force interactions that result in the observed stability and change in the motion of an object. (SEP: 3.2; CCC: 4.2, 7.1; DCI: ESS2.A.1)

Summarize what we have done, and forecast the next class. Say, *In all the conditions we investigated, multiple forces were acting on the object, similarly to what happens to a plate, but these forces did not cause any changes in the object's motion. Next time, we'll share our results and explore how that can help us explain the behavior we are observing in plates.* If you have decided not to collect the *Investigations A&B* handout, remind students to put it in their notebook so they will be ready to report out at the start of the next class period.

ADDITIONAL GUIDANCE

If you have additional classes, remove the sticky notes from the Scale Chart poster now, and cover the time axis again. Do the same for the M-E-F poster, so both can be constructed for the next class at the appropriate point in the lesson. However, if this is your last class for day 1 of this lesson, leave both posters intact.

End of day 1

8 · NAVIGATE: COMPARE RESULTS FROM INVESTIGATIONS A AND B

6 min

MATERIALS: None

Facilitate a Building Understandings Discussion. Present slide R. If you collected the *Investigations A&B* handout in the prior class period, return it to students. Give them 2 minutes to individually review what they wrote on their handout.

KEY IDEAS

Purpose of this discussion: Help students argue for ideas based on their evidence. You may want to explicitly remind them of your role in this type of discussion. Before starting, say something like, *I'm going to press for evidence in this discussion, regardless of whether I agree or disagree with your claim. And I'll ask others whether their evidence supports or refutes the idea as well.*

Have a volunteer share their findings. Then elicit more with these prompts:

- *Does anyone else have a similar result? What were those results?*
- *Did any group find something different? What were those results?*

Listen for these ideas:

- **Investigation A:** The magnitude of each force in the horizontal direction was approximately equal. This is also true for the forces in the vertical direction. But the magnitude of the vertical forces did not need to be equal to that of the horizontal forces.
- **Investigation B:** The sum of the magnitudes of all forces on each side of the object was equal.

Consider the need for additional trials. Display slide S. Elicit students' ideas with the prompts:

- *Do our results suggest that we need to carry out more trials for Investigations A and B?*
- *Why or why not?*

If some groups found that the forces on the same axis are different, ask what might have caused that. If variation did not occur, ask them to consider what could cause that. Listen for these ideas:

- Maybe some groups didn't calibrate their spring scales.
- Maybe some groups had faulty equipment.
- If there are outliers in a few groups but not others, the outliers likely need to run more trials.

Emphasize that knowing how many trials to carry out in any investigation is not constrained only by how much time and resources students have, but also by the level of (un)certainly in their results. *

* SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

You may want to suggest the following to support students in future use of this practice:

- Because knowing the certainty of results is based on the variation in the data being collected, it is not something they can necessarily know with a great degree of certainty until the data starts coming in.
- It is best practice to be ready to change a data collection plan as they go, particularly if they uncover unexpected results or possible sources of error.
- When they do this, it is also best practice to make note of what uncertainty in the data is leading them to make this change.

9 · INTRODUCE FREE-BODY DIAGRAMS AND NET FORCE

6 min

MATERIALS: 1" grid chart paper, chart paper markers

Introduce free-body diagrams. Present **slide T**. Explain that one way scientists represent what is happening when multiple forces act on an object is to create a free-body diagram showing those forces. Ask students to recall examples of any free-body diagrams they have drawn before. If they have completed *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*, they made these diagrams for objects in various collision scenarios, and you can ask for examples of those (a cart, cushion, helmet, sports player, ball, and so forth).

If students have not completed the *Vehicle Collisions Unit* unit, introduce this type of diagram now. Explain that it is a drawn model of a single object in a system, which shows the forces acting on that object from other things but doesn't show those other things.

Start free-body diagrams for the investigation results. Draw and label a foam rectangle on a piece of grid chart paper for each investigation (A and B). Ask how students have represented forces before, and how they have shown when one force is larger or smaller than another. Listen for them to say that they used arrows of different sizes. *

Explain that in a free-body diagram, each force is represented as a vector, and when vectors represent a quantity, we use an arrow to show its direction, scaling the arrow's length so it is proportional to the magnitude of the force.

Have a group share a set of the magnitudes they found for the force values acting on the block in *Investigation A*. Show the class how to use the grid paper (e.g., 1 square = 1 newton) to create 4 proportionally scaled force arrows representing these results. Repeat this for *Investigation B*.

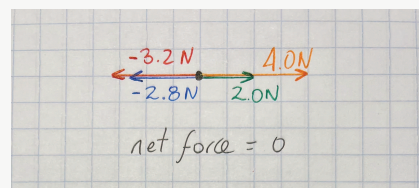
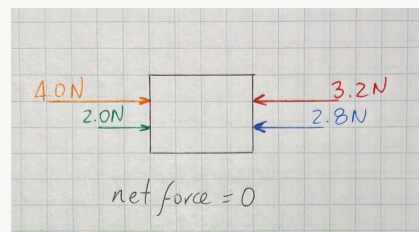
Ask students to restate what they notice about how the lengths of the vectors compare in *Investigation B*. Listen for them to say that the lengths of the vectors for the forces on one side of the object add up to be equal to the lengths of the vectors for the forces on the other side.

Introduce negative forces and net force. Say, *Another way to describe this mathematical relationship is to picture an x-y coordinate axis in the system, defining the object at the origin.* Ask students to point in the direction of the positive x-axis and negative x-axis, and then the y-axis. Explain that by using this convention, we can assign forces a positive or negative value depending on which direction they are acting. Update the values in the free-body diagram to reflect this. Ask students what the sum total of the forces along each axis would be; they should say zero.

Write these statements under the free-body diagram on the grid paper:

- When an object (matter) is stationary:
 - Any forces acting on it along each axis are balanced.
 - The net force equals zero.

Ask whether students encountered the term *net force* in prior grades; if not, that is fine. Emphasize that going forward, we will use *net* as a synonym for *sum total* when we add vector quantities.



* ATTENDING TO EQUITY

Supporting Universal Design for Learning: Some free-body diagram conventions draw the arrow for each force acting on an object with the base of the arrow originating from the object's center of mass. However, students are likely to have ideas about how to represent the direction of force vectors. Therefore, this convention may confuse them right now, as it makes it seem that forces are pulling on the object rather than contact forces pushing on it.

The materials in this unit show contact force arrows pointed toward the object, perpendicular to the corresponding surface they are acting on. The recommended approach is to develop a consensus convention that makes sense to your classroom community. You will use this representation again in Lesson 12.

Later free-body diagrams beyond this unit may not use a representation of the object's shape, instead representing every object as a small circle. For this unit, however, representing the object's general shape is recommended.

ADDITIONAL GUIDANCE

Though the term *net force* is used in a disciplinary core idea referred to in the foundations boxes for PS2.A, the performance expectation (PE) for grade 3 (3-PS2-1) does not use this term, and the clarification statement specifies qualitative comparisons only. The related force and motion PE in middle school (MS-PS2-2) also does not refer to net force. Both PEs use the term *balanced and unbalanced forces*.

Because students do not encounter negative numbers in the Common Core until grade 6, it is unlikely that the mathematical representation of net force that we are developing now was considered in prior grades. We are only asking whether students recall using the term to ensure that we don't miss an opportunity to draw on relevant prior instruction.

10 • DEVELOP AND EVALUATE A FREE-BODY DIAGRAM

12 min

MATERIALS: *Investigations A&B, GPS Plate Map*



Create a free-body diagram individually. Present slide U. Cue students to use the bottom of the *Investigations A&B* handout to respond to the slide's first prompt:

- *Create a free-body diagram to represent a stationary object with three contact forces acting on it in the horizontal direction (along the x-axis).*

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: In students' free-body diagrams:

- Two arrows pointed in one direction and one arrow pointed in the other, each with the magnitude labeled in newtons. (SEP: 2.6; DCI: ESS2.A.1)
- Negative values for any vector(s) pointed to the left and positive values for any vector(s) pointed to the right. (CCC: 7.1)
- Each arrow length proportionally scaled to its magnitude. (SEP: 2.6; CCC: 7.1, DCI: ESS2.A.1)

What to do: Refer students to your free-body diagram to help them identify elements missing from theirs. See the *Free-Body Placemat Key* for sample responses.

Building toward: 2.B.1 Develop and use free-body diagrams (models) to explain and predict how the magnitude of the force interactions applied to matter at different scales would impact the stability and changes within a system. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1)

After students have started, distribute the *GPS Plate Map*. Remind them to refer to this as they write responses to the slide's second prompt on their handout:

- *Do you think your free-body diagram is a reasonable model for explaining why the Caribbean plate appears to be stable (not moving)? Why or why not?*

Display slide V. Facilitate a Consensus Discussion around the prompt: * *

- *Do we think the free-body diagram any of us created is a reasonable model to use for explaining why the Caribbean plate appears to be stable? Why or why not?*

* STRATEGIES FOR THIS CONSENSUS DISCUSSION

The purpose of this discussion is to establish agreement around these ideas:

- The apparent stability of the object (the Caribbean plate) must be a result of balanced forces on it (or a net force of zero).
- The free-body diagrams students created, though one possible way that might happen, are very likely an oversimplification, because:
 - The number of contact forces acting on the plate is probably much greater.
 - Those forces are likely acting on the plate along many different axes/angles, not just along one axis.

Ask students to restate others' ideas and indicate which parts they agree or disagree with, in order to quickly reach consensus on these points.

These additional prompts may help you facilitate this discussion, if needed:

- *Do we think that there are only three contact forces, or more than three, acting on the Caribbean plate? From interactions with what?*
- *What are the possible directions of those contact forces?*

- *Would all these forces in these different directions still need to add up to a net force of zero if this plate remains stationary (stable)?*

* SUPPORTING STUDENTS IN DEVELOPING AND USING SCALE, PROPORTION, AND QUANTITY

This is the first attempt in this unit to apply a model across very different scales, but it comes after identifying earlier that the same data at different scales can be used to argue for why a system appears to be stable at one scale but changing at another. Students also reflect on whether (and how) thinking at/across different scales helped them figure something out in their Progress Tracker, although it is not used as a formative assessment. The self-reflection prompts related to this crosscutting concept will continue over the unit with each new tracker entry.

11 · USE MATHEMATICAL THINKING TO EXPLORE VECTOR RELATIONSHIPS FOR OFF-AXIS FORCES

17 min

MATERIALS: science notebook, *Free-Body Placemat*, 1 clear sandwich bag containing 12 cutouts from *Free-Body Manipulatives*, calculator, M-E-F poster, M-E-F expansion panels, clear tape

Connect to the previous argument. Say, *Because the plates are irregularly shaped, and we're arguing that forces could be acting on them from various directions, let's consider a more irregular shape and forces that aren't acting along the same axis.*

Make a prediction. Present **slide W**. Give students a minute to think about the prompts on their own:

- *The net force on the five-sided object below would not be zero.*
 - *Where else would we need to apply a contact force in order to have zero net force on the object?*
 - *What would the magnitude of that additional force need to be?*

Use mathematical thinking. Display **slide X**. Have students turn and talk about why the forces applied to each block in the slide's free-body diagrams would keep it stationary. After a couple of minutes, ask them to share their ideas. Accept all responses. At this point, it is unlikely that students are completely certain of a mathematical reason why these conditions would result in a net force of zero. Reinforce any mathematical reasoning that they are wrestling with.

Remind students that they might have encountered this in prior mathematics classes--needing to explain the angles and relationships between them for more complex shapes. Explain that we might also be able to break out shapes into more simplistic representations and look at part of the shape to determine what these forces might be.

Introduce the Pythagorean theorem. Display **slide Y**. Read the text and directions aloud:

- *The Pythagorean theorem ($a^2 + b^2 = c^2$) describes the relationship between the three sides of any right triangle. Record any additional net force relationships you discover in these stable systems in your science notebook.*

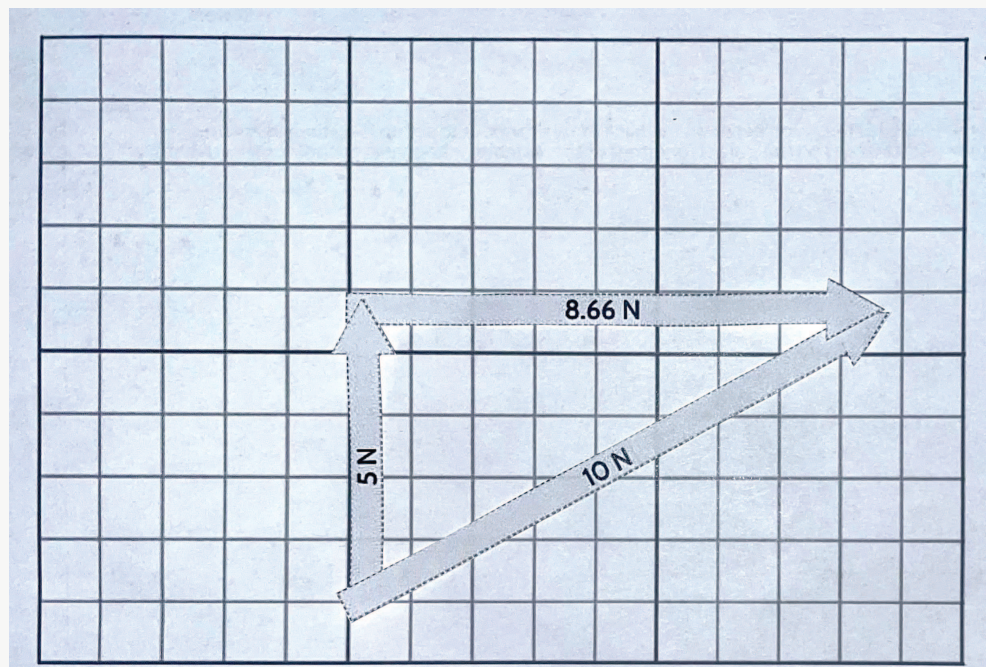
* SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

Encourage students to manipulate attributes of the model, both geometrically or algebraically. The former could include translating the vector representation to see whether they form the three sides of a right triangle. The latter could include performing calculations and recording results on scratch paper.

* SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

The rise between two points on a line on a coordinate graph is the difference in their y-values. The run between two points on a line on a coordinate graph is the difference in

Explore with the manipulatives. Distribute one copy of the *Free-Body Placemat* and one clear sandwich bag of the *Free-Body Manipulatives* to each pair of students. Cue them to use a calculator and work with these manipulatives for about 5 minutes to see what they can figure out. The image below shows an example of how students could represent one of the cases using the manipulatives.



their x-values. Students would have developed this idea in grade 7 and used it in grade 8.

* SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

You may want to ask the math teacher(s) at your school how your students have used (or will use) the Pythagorean theorem this year. That theorem would have been developed in grade 8 in the CCMS (CCSS.MATH.CONTENT.8.G.7), but many applications and derivatives are explored in subsequent high school courses when students begin to work with vector and matrix quantities. Two of the most relevant for this lesson are:

- **CCSS.MATH.CONTENT.HS.N-V.1 Represent and model with vector quantities.** Recognize vector quantities as having both magnitude and direction.
- **CCSS.MATH.CONTENT.HS.N-V.4b Perform operations on vectors.** Given two vectors in magnitude and direction form, determine the magnitude and direction of their sum.

ALTERNATE ACTIVITY

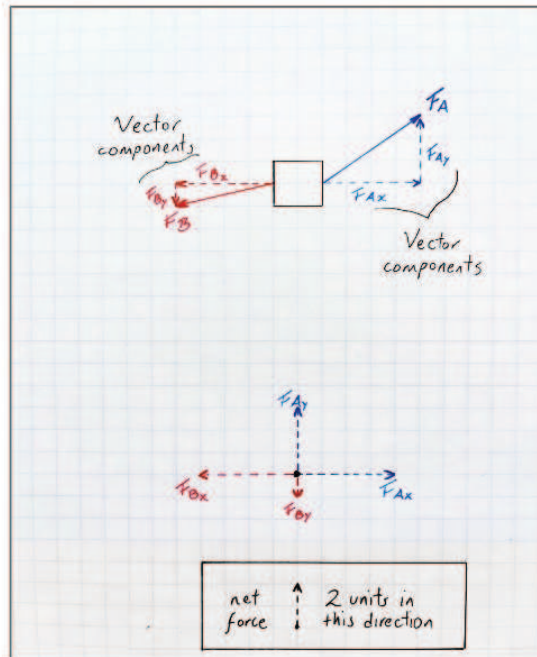
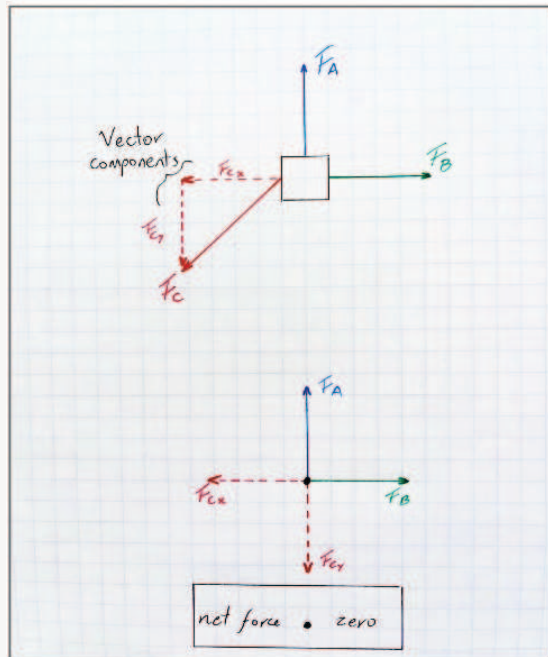
Cutting out the arrows for the *Free-Body Manipulatives* will be time-consuming. Consider providing each group in your first class with a pair of scissors, the handout, and a clear sandwich bag so they can cut them out themselves. After that, the arrows can be reused by subsequent classes.

Ask students to share their findings. Listen for the following:

- The magnitude of the horizontal force squared added to the magnitude of the vertical force squared equals the magnitude of the force that is at an angle.
- You can form a right triangle using the smaller two force vectors as the legs and the larger force as the hypotenuse.

Explain that any force represented as an angled vector can be broken down into two parts--a horizontal part and a vertical part--similarly to how any angled line on a coordinate can be visualized as having a slope made of a rise and a run. *

Draw an example in which 2-3 forces result in a net force of zero, and a second example in which 2-3 forces result in a nonzero net force; see the examples below. State that each part of the two-dimensional vectors you drew is called a *vector component*. For both of your examples, label the two vector components of each force vector, and draw and label the resulting net force.



Connect to work in high school math. Note that in their math classes, students will continue to refine and develop mathematical tools that will enable them to do this analysis of any two-dimensional vector. * Explain that for now, it is sufficient to simply recognize that there are ways to determine the net forces acting on objects, even when those forces are not aligned along the same axis. *

ADDITIONAL GUIDANCE

Vector components will be used again in Lesson 12 as students explore the interactions of gravity and friction on tectonic plate movement.

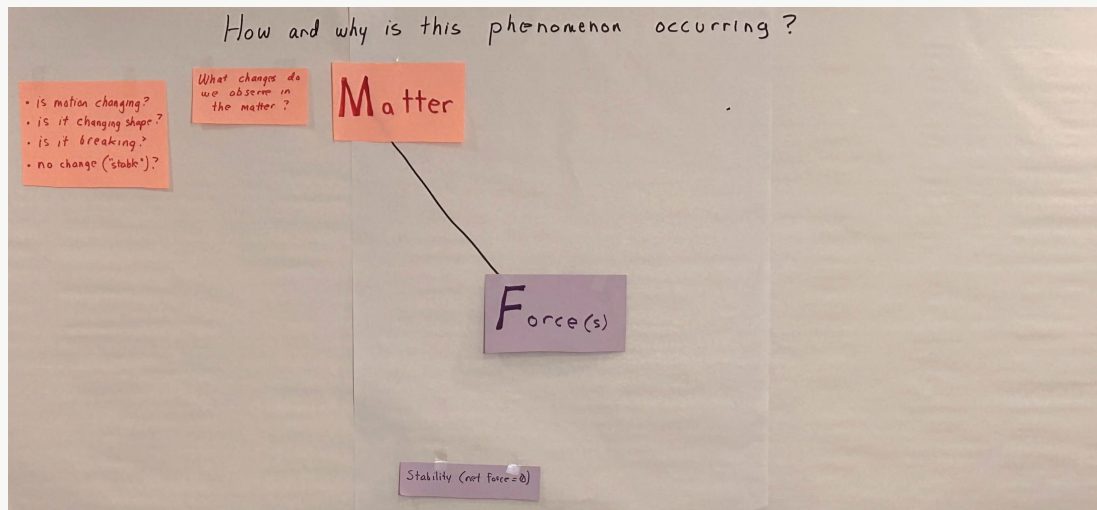
ALTERNATE ACTIVITY

Extension opportunity: For students who are interested in these mathematical extensions or are exploring vectors in their current math class, you can show (or ask them to show) how to do the following:

- **CCSS.MATH.CONTENT.HS.N-V.2 Represent and model with vector quantities.** Find the components of a vector by subtracting the coordinates of an initial point from the coordinates of a terminal point.
- **CCSS.MATH.CONTENT.HS.N-V.4a. Perform operations on vectors.** Add vectors end-to-end, component-wise, and by the parallelogram rule.

Update the M-E-F poster. Suggest that we add a summary statement to the poster, related to what we figured out about how balanced forces or a net force of zero can produce stability in matter.

Add the following annotation to a piece of paper and tape it under the “Force” section of the poster:
Stability (net force = 0)



Point out that on the M-E-F poster, there are three types of matter changes that we also wanted to investigate from a forces perspective.

12 · NAVIGATE: MAKE A PREDICTION

4 min

MATERIALS: None

Make predictions. Present **slide Z**. Have students discuss their predictions for the slide's prompts with a partner:

- How would removing a spring scale from the stable system above affect it?
- Would adding an additional horizontal force to the stable system below produce similar outcomes?

Say, *Let's plan to use the spring scales again to investigate these sorts of conditions in our next class period.*

End of day 2

13 · NAVIGATE: PLAN INVESTIGATIONS C AND D

5 min

MATERIALS: M-E-F poster, M-E-F expansion panels, clear tape, <https://youtu.be/LR1Ui-IVsO4>, computer

Review our progress. Present **slide AA**. Use the M-E-F poster to remind the class that we explained the force conditions that result in a stable system, and that we wanted to continue exploring additional matter changes that we have seen in the unit so far.

Review the investigation procedure. Play the video <https://youtu.be/LR1Ui-IVsO4> to demonstrate how to set up *Investigations C and D*.

Plan the conditions to test. Organize the class into groups of 3-4 students. Distribute the *Investigations C&D* handout to each student.

Instruct groups to plan their investigations according to the directions on the slide:

- Review the directions on the handout. Decide the number of conditions to try to test in 12 minutes for either or both of these investigations:
 - Investigation C: Starting with a stable 4-spring system and removing 1 of the forces.
 - Investigation D: Starting with a stable 3-spring system and adding another force.

Reiterate to students that they have approximately 12 minutes to collect data for either *Investigation C*, *Investigation D*, or both, and to draw free-body diagrams to represent their findings.

14 · CARRY OUT INVESTIGATIONS C AND D

12 min

MATERIALS: Investigations C and D

Carry out the investigation. Display **slide BB**. Distribute lab materials to each group. Use the slide's prompts to orient students to the investigation procedure:

- Document the following for every condition you test:
 - a. Draw a free-body diagram for the foam in its initial stationary condition that you set up.
 - b. Record the force vector you added or removed from that system.
 - c. Record the changes you observed in the system, and any new stable state the system reaches.
 - d. Keep an eye out for whether you think you need to modify your investigation plan as results come in.



Walk through the classroom as students set up their system(s) and collect their data, making sure they are recording their results on the handout. Some groups may also ask to record the outcome using slow-motion video on a camera phone. If they do, encourage them to send you one of the videos they make to share with the class for the next part of the lesson.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Recording data using a **free-body diagram** for each condition, including the **initial force conditions** acting on the stable system, and labeling which **force interaction** was added or removed. (SEP: 3.2; CCC: 4.2; DCI: ESS2.A.1)
- Recording the **dynamic changes** in the system (e.g., how much the object moved, in what direction, and for how long). (SEP: 3.2, CCC: 4.2; DCI: ESS2.A.1)
- Repeated trials or measurements yielding consistent results for several **contact force combinations** to support the reliability of the results. (SEP: 3.2; DCI: ESS2.A.1)
- Following the calibration protocols for gathering accurate results using the spring scales. (SEP: 3.2)
- Record the **new stable state of the system** (where the foam rectangle is in the end and/or the **new interactions on each spring scale**) for each measurement. (SEP: 3.2, CCC: 7.1; DCI: ESS2.A.1)

What to do: Ask students to consider the relationship between the change they made, the change they observed, and the new stable state of the system. Encourage them to think about the forces acting on the object, and whether these forces are balanced or not before, during, and after the change.

See whether students use the scale calibration protocols on their own; if so, this is evidence that they are considering the relationship between data collection and the accuracy of their results. See the *Investigations C&D Key* for how to support data collection and sense making.

Building toward: 2.A.2 Plan and conduct an investigation to determine the **contact force interactions** that result in the observed stability and change in the motion of an object. (SEP: 3.2; CCC: 4.2, 7.1; DCI: ESS2.A.1)

15 · ANALYZE AND INTERPRET DATA

12 min

MATERIALS: *Investigations C&D*, science notebook, <https://youtu.be/LR1Ui-IVsQ4>, M-E-F poster, M-E-F expansion panels, 3x3 sticky note, clear tape



Make sense of the investigation results. Give students a few more minutes to write their answers to the questions on the back of their *Investigations C&D* handout:

1. What was the net force on the object initially, when it was stable?
2. Why did adding or taking away a force make the object move?
3. What, if anything, can you now claim about how the net force on a stationary object and a moving object compare?

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: A free-body diagram for each condition tested:

- Using the results collected as free-body diagrams to explain how force interactions applied to matter would impact the stability and changes within a system. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1)
- Using the free-body diagrams to suggest that this model does not help explain the apparent stability of the Caribbean plate. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1)

What to do: As students set up their stable condition, encourage them to take adequate time to include all the features of the free-body diagram in the example poster before they move on to the next step (actually removing or adding a spring scale). Reassure them that a single well-documented result is more valuable than multiple undocumented results that are hard to reconstruct.

Encourage students to compare the results they recorded in their notebooks when using *Free-Body Placemat* to the results they collected in *Investigations C and D*, and to compare the differences in the net force acting on the object.

Building toward: 2.B.2 Develop and use free-body diagrams (models) to explain and predict how the magnitude of the force interactions applied to matter at different scales would impact the stability and changes within a system. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1)

Identify the changes observed in the investigation. Display slide CC. Discuss the prompt as a class:

- What changes did you observe in the system when you added or removed a force?

Listen for the following ideas:

- The block moved.
- The block (and the springs) moved back and forth.
- The block stopped moving shortly after it moved.

If no students mention the back-and-forth motion, that is OK. If some do, ask the rest of the class whether they saw it. In either case, suggest that we study this system at a different scale to see additional changes in motion.

Display slide DD. Play <https://youtu.be/LR1Ui-IVsO4>. If students sent you a slow-motion video from their investigation, you can show this as well, and ask them to describe the changes in motion they saw in the system.

Facilitate a Building Understandings Discussion. Use what students identified to emphasize the idea that in every case, we set up a system that was stable at first. We then added or removed force and saw that the system changed, and its motion continued to change, but after a short time, it reached a new stable state in which it remained stationary. Suggest that we try to make sense of those three time frames--before, during, and after--from a net force perspective.

Display slide EE. Discuss the prompts and use the follow-up questions shown in the table below.

Suggested prompts	Sample student responses	Follow-up questions
What was the net force on the object initially, when it was stable?	Zero.	How could it be zero in every case, if some people set up 3 spring scales and others set up 4?
Why did adding or taking away a force make the object move?	The net force was no longer zero.	So was the net force on it still zero when the object started moving?

Suggested prompts	Sample student responses	Follow-up questions
What was the net force on the object when it reached a new stable state?	It must have been zero again.	How is it possible that the net force was zero again, if you added or removed a force from the system?

Update the M-E-F poster. Say, *Our evidence suggests that the motion change we saw was the result of a condition in which the net force on an object was not zero.* Add a checkmark to a sticky note on the poster, next to the item that was listed as “change in motion”, to indicate that we have developed a deep understanding of how forces can produce this outcome, as shown below.

Add the following annotation to the piece of paper and tape it under the “Force” section of the poster:
Change (net force $\neq 0$)

Brainstorm prompts to explore matter and forces in a system. Present slide FF. Give students a minute to think on their own about the prompts:

- What question(s) should we ask about the matter in **any** system to identify whether it is stable or not?
- What question(s) should we ask about the forces acting on **any** system to identify whether it is stable or not?

Have them share their responses. Listen for the following ideas:

- Is the shape changing?
- Is the object moving?
- Is the change visible?
- What changes do we observe in the matter?
- What are the forces acting on the system?
- Are the forces acting on the matter balanced or unbalanced?

ADDITIONAL GUIDANCE

If students do not come up with the last three listed responses, you can elicit these ideas with additional prompts, such as, *We found that the net force on an object is either zero or different from zero. What would happen to matter if the net force were not zero?* Listen for students to say that it could cause changes like breaking or moving.

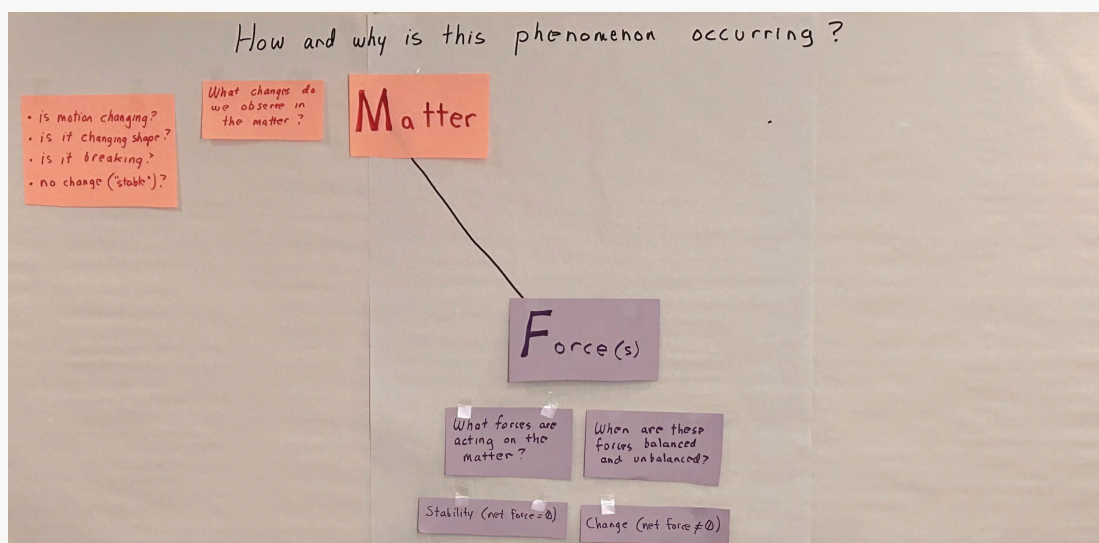
Continue, *Whenever we see matter changing, it's evidence that there are forces acting on the system, so let's keep paying attention to the changes in matter that we see. What information do we need to determine whether the forces are balanced or unbalanced?*

Listen for the following ideas:

- the forces that are acting on the object
- the direction of the forces
- the magnitude of the forces

Add these two panels to the M-E-F poster:

“What forces are acting on the matter?” and “When are these forces balanced and unbalanced?”



16 · DEVELOP AN INITIAL EXPLANATION FOR A LARGER-SCALE PHENOMENON

4 min

MATERIALS: None

Develop an initial explanation. Display slide GG. Give students 5 minutes to talk with a partner and use what we figured out about matter and forces to develop a verbal explanation for why one phenomenon from the larger-scale Earth system happened. Options include (a) an earthquake, (b) the variation in plate motion, and (c) the sudden crack at Afar.

ADDITIONAL GUIDANCE

Consider this discussion a “first draft” explanation of the type of phenomenon that students will eventually explain in far greater depth. This is an opportunity to test-drive the new ideas developed in this lesson about those larger-scale Earth system phenomena. It also primes students for their next Progress Tracker entry, so they are more likely to make those connections in what they write.

17 · ORIENT TO THE NEW PROGRESS TRACKER AND ADD AN ENTRY

8 min

MATERIALS: 3 copies of *Progress Tracker*, loose-leaf paper, science notebook

Recall prior Progress Trackers. Remind students that we kept a Progress Tracker in our last unit. Ask them to share how it helped us put our ideas together over many weeks of figuring things out. Accept all answers.

Prepare notebooks for new Progress Trackers. Have students set aside a section of their notebook for a Progress Tracker to serve a similar purpose in this unit. Distribute three double-sided copies of the *Progress Tracker* handout to each student to add to this new section.

Compare the old and new trackers. Display **slide HH**. Ask students how the structure of this Progress Tracker compares to that in the previous unit. Listen for the following ideas:

- It also has a section for what we figured out.
- It doesn't have a section for how our ideas apply to designing a solution.
- It has new checkboxes related to which of these lenses we use to figure this out.
- It has a section for how using these lenses helped us figure this out.

Remind students that the tracker is not intended to be a record of the “right” answers—it is a record of our changing thinking over the course of a unit, and should be a place where students feel comfortable reflecting on what they do not know or do not yet understand.

Connect to crosscutting concepts. Explain that in every unit, you will introduce a Progress Tracker with a slightly different format, to support a different way of reflecting on how we are figuring things out. Using different ways of tracking our thinking could help us develop more generalizable approaches to figuring things out beyond this unit and even beyond this course. Point out that the lenses section includes some crosscutting concepts that scientists and engineers find useful, not just in physical science and Earth and space science, but in other disciplines as well.

Add a Progress Tracker entry. Give students 6 minutes to fill out one page of their trackers. See the *Progress Tracker Examples* for a sample entry.

Update the Personal Glossary. Display **slide II**. Have students check their entry to see whether they included the ideas/words listed on the slide:

- vector
- vector component
- magnitude
- net force
- balanced forces
- unbalanced forces

If they did not, suggest that they write meanings for the words that are new to them on a sheet of loose-leaf paper. This can be added to the end of the Progress Tracker as their Personal Glossary.

18 · REFLECT ON OUR COMMUNITY AGREEMENTS

3 min

MATERIALS: 1 piece of copy paper or forced copy of the Electronic Exit Ticket (https://docs.google.com/forms/d/1AB7Onbf_9qGMfkD1hgN7sARigc-ssTOjD1wHTY5izfA/copy), Community Agreements poster

Reference and reflect on our Community Agreements. Remind students that these are not static and that over time, we can refine them as well as grow more fluent in them. Emphasize that this can only happen with periodic reflection about what others are doing to help us achieve these agreements and what we can continue to work on doing more of going forward.

Display **slide JJ**. If you are using an Electronic Exit Ticket, see *How to Create Electronic Exit Tickets* from Lesson 4 for how to make a copy of https://docs.google.com/forms/d/1AB7Onbf_9qGMfkD1hgN7sARigc-ssTOjD1wHTY5izfA/copy. Make this copy before the beginning of the period, and share it with the class during this reflection. Otherwise, distribute a piece of copy paper to each student to collect as an exit ticket responding to the slide's prompts:

- *Think back on the past 3 periods of this lesson:*
 - *What was something someone else said that helped move your thinking forward?*
 - *What was something you would like to try to do more of in future lessons to further support one of our Community Agreements?*

ADDITIONAL GUIDANCE

Prepare to share some anonymous responses to the exit ticket's first prompt at the start of Lesson 3. Such public recognition from peers (anonymously) can build a strong sense of gratefulness in those students, who might otherwise never realize that their peers recognize the value they bring to the learning community. This recognition can also emphasize how highly the teacher values peer-to-peer support for elevating each other toward reaching these goals.

19 · NAVIGATE

1 min

MATERIALS: None

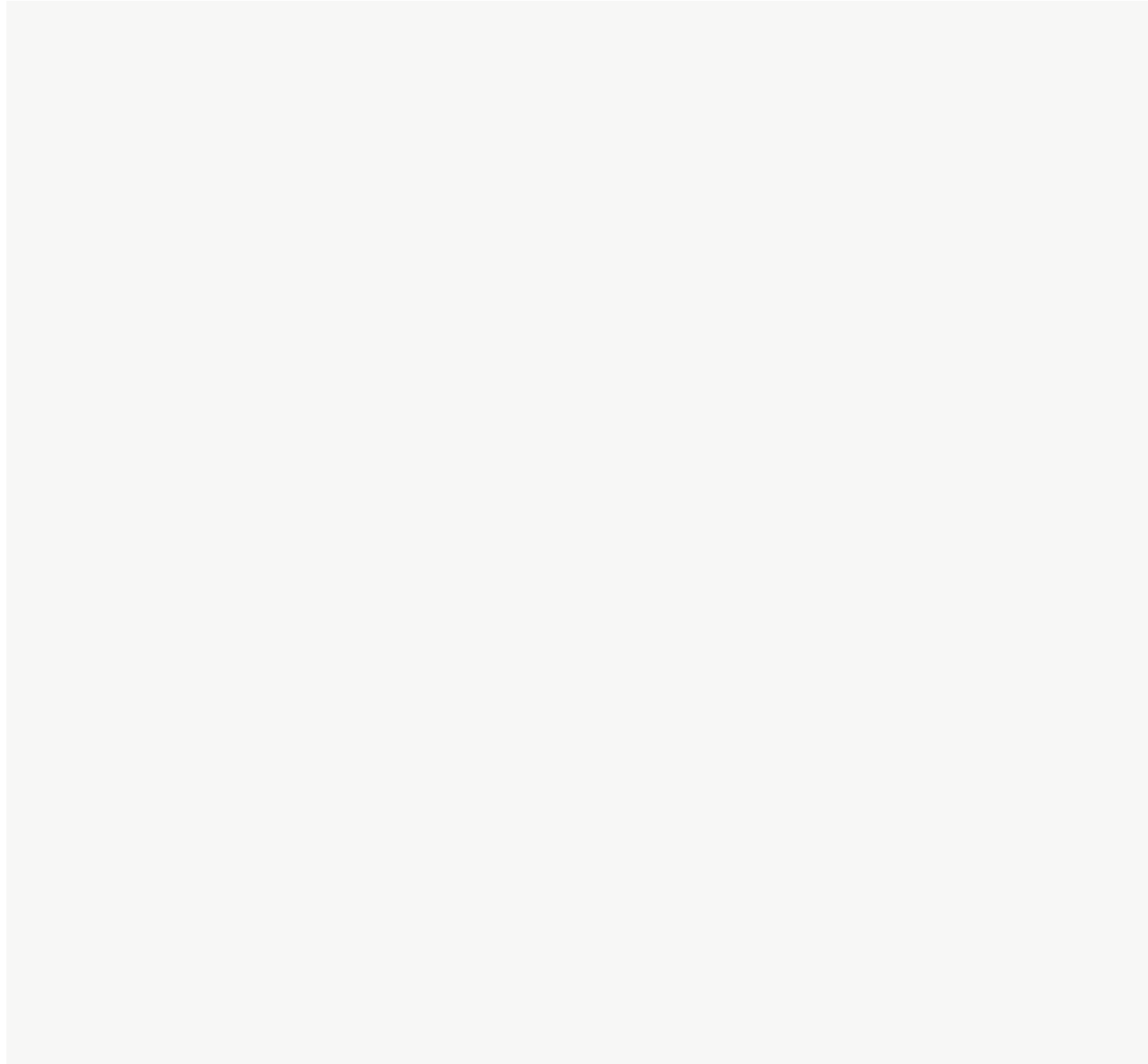
Brainstorm additional outcomes and investigations. Display **slide KK**. Read the top text aloud:

- *In the first set of investigations we carried out, balanced forces on a stationary object appeared to produce no change in its motion. It remained stationary.*

As a class, discuss the slide's prompts as shown in the table below.

Suggested prompt	Sample student response
<i>If we keep increasing the magnitude of these forces acting on a solid object, what do you predict would happen to it?</i>	It could break. It could bend. It could crack.
<i>What additional investigations does this suggest we need to do next time?</i>	We need to apply higher-magnitude forces to something until it starts to bend, break, or crack. We need to measure these sorts of changes at different scales and see how much force it takes to cause this type of change. We need to try to break some rocks.

Say, *Let's plan on doing some of those things and analyzing that sort of data in our next lesson.*



Additional Lesson 2 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

CCSS.MATH.CONTENT.HS.N-VM.1 Represent and model with vector quantities. Recognize vector quantities as having both magnitude and direction.

CCSS.MATH.CONTENT.HS.N-VM.3 Represent and model with vector quantities. Solve problems involving velocity and other quantities that can be represented by vectors.

Additional extension opportunities are also noted in this lesson:

CCSS.MATH.CONTENT.HS.N-V.2 Represent and model with vector quantities. Finding the components of a vector by subtracting the coordinates of an initial point from the coordinates of a terminal point.

CCSS.MATH.CONTENT.HS.N-V.4a Perform operations on vectors. Add vectors end-to-end, component-wise, and by the parallelogram rule.

Students represent external forces acting on an object by using a free-body diagram. Engagement with this type of representation is supported by various tools, including physical cutouts used to identify connections between vector components, and graphical representations used to make sense of the magnitude and direction of vectors.

LESSON 3: What happens to the matter and energy in a system when the magnitude of balanced forces on it increases?

PREVIOUS LESSON

We analyzed plate motion data. We developed a physical model to identify force interactions between plates. We carried out investigations to determine the conditions that result in stability and change in an object's motion when multiple forces act on it. We used free-body diagrams to explain and predict how the magnitude of forces at different scales would impact stability and changes in the matter within the system.

THIS LESSON

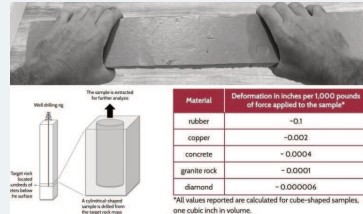
INVESTIGATION

1 day



NEXT LESSON

We will evaluate two models for understanding and explaining earthquakes, elastic deformation, and breaking of solid matter. We will use a computer simulation to investigate how external forces on a solid affect matter changes and energy transfer at the particle level. We will revise our M-E-F and Scale Chart posters to account for the roles of fields on large-scale phenomena and use these ideas to explain volcanic eruptions.



We explore changes in a piece of foam as higher-magnitude forces are applied to it. We develop a model of how unbalanced forces cause the observed changes in matter and energy transfer. We predict whether rock would behave like a piece of foam. We gather information from a reading. We ask questions about the relationship of our new ideas to what is happening in Earth systems.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

3.A Make qualitative claims about how differences in the magnitude of forces (1) acting on different materials (cause) would produce similar effects in their structure (elastic deformation) and (2) acting on a single material would affect the amount of energy transferred into and out of it. (SEP: 6.1; CCC: 2.2, 5.2, 6.2; DCI: PS3.B.2)

3.B Ask questions arising from development of the M-E-F model to clarify (1) additional relationships related to energy transfer and storage in deformed matter and (2) the model's application to various dynamics and interactions occurring in Earth systems. (SEP: 1.2; CCC: 5.2, 7.1; DCI: PS3.B.2, ESS2.A.1)

WHAT STUDENTS WILL FIGURE OUT

- Changes in matter and energy transfers happen together.
- Unbalanced forces transfer energy.
- All solid materials deform elastically when force is applied to them, up to a point.
- When solids deform past their elastic limit, they permanently deform; this includes a permanent change in shape, cracks, and/or breaking into smaller pieces.

Lesson 3 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	2 min		NAVIGATE Review predictions made at the end of the last class.	A	M-E-F poster, M-E-F expansion panels
2	6 min		EXPLORE CHANGES IN A PIECE OF FOAM Carry out two brief explorations with a piece of foam, one as a whole-class demonstration and one in partners.	B-C	M-E-F poster, M-E-F expansion panels, Deforming a Foam Panel
3	8 min		USE A MODEL TO EXPLAIN A FOAM SYSTEM FROM A FORCES AND MATTER PERSPECTIVE As a class, add weight to a foam panel and quickly remove it. Identify where forces on the matter in the system were balanced and unbalanced. Use these ideas to update the M-E-F poster.	D-F	dry erase marker (red), dry erase marker (purple), dry erase marker (green), dry erase marker (black), M-E-F poster, M-E-F expansion panels, chart paper marker, Foam Panel Projectile with a Hanging Weight
4	8 min		EXPLAIN THE SYSTEM FROM AN ENERGY PERSPECTIVE Identify energy transfers into and out of the foam system, and consider their relationship to matter changes. Test the system with a greater mass added and removed. Use these ideas to update the M-E-F poster.	G-H	dry erase marker (red), dry erase marker (purple), dry erase marker (green), dry erase marker (black), M-E-F poster, M-E-F expansion panels, tape, chart paper marker, Foam Panel Projectile with a Hanging Weight
5	4 min		CONSIDER RELATED PHENOMENA Brainstorm other materials that exhibit elastic behavior. Share predictions and identify a question for further investigation about whether solid rock exhibits elastic behavior.	I	M-E-F poster, dry erase marker (red), dry erase marker (purple), dry erase marker (green), dry erase marker (black)
6	11 min		GATHER INFORMATION AND USE IT TO MAKE ADDITIONAL CLAIMS Read about rock sampling and compression testing. Identify ideas in the reading that can help answer our main question, and make claims in response to additional sensemaking questions.	J	<i>Analyzing Rock Behavior</i>
7	6 min		NAVIGATE Use the M-E-F poster to discuss what is happening where two plates meet that could help explain why earthquakes tend to occur near plate boundaries. Update the Personal Glossary.	K-M	2 3x3 sticky notes, permanent marker, <i>Analyzing Rock Behavior</i> , M-E-F poster, Driving Question Board

End of day 1

Lesson 3 • Materials List

	per student	per group	per class
Deforming a Foam Panel materials	indirectly vented chemical splash goggles	1 piece of foam (3" x 12" x ½") - ruler	1 piece of foam (3" x 12" x ½")
Foam Panel Projectile with a Hanging Weight materials	indirectly vented chemical splash goggles		3 pieces of foam (3" x 12" x ½") 3 pieces of string (1'-2' long) 3 paper clips - duct tape or packing tape 2 spring clamps 1 50-g mass 2 2-g soft projectiles - scissors 1 200-g mass - meter stick
Lesson materials	<i>Analyzing Rock Behavior</i> 2 3x3 sticky notes - permanent marker - science notebook		- M-E-F poster - M-E-F expansion panels - dry erase marker (red) - dry erase marker (purple) - dry erase marker (green) - dry erase marker (black) - chart paper marker - tape - Driving Question Board

Materials preparation (30 min 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.

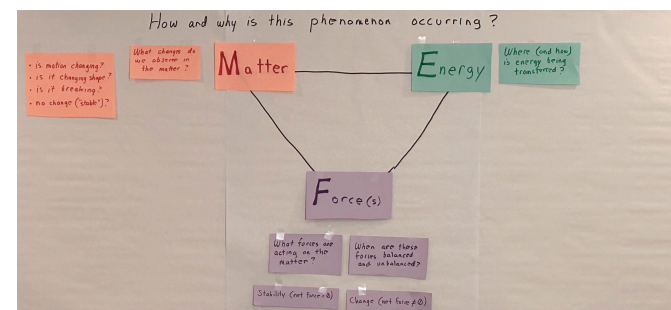
Make copies of the handout for this lesson:

- Analyzing Rock Behavior* - 1 per student

Add these M-E-F expansion panels to the M-E-F poster:

- "Energy"
- "Where (and how) is energy being transferred?"

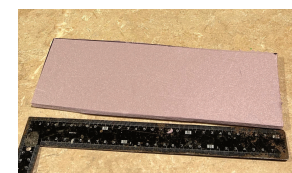
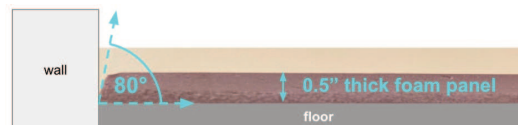
On the poster, draw a black line connecting the "Energy" panel to the "Force(s)" panel. Draw a black line connecting the "Energy" panel to the "Matter" panel. Cover these additions with a blank piece of chart paper; this cover is removed to reveal them to each class at the appropriate point in the lesson. Refer to the *Developing the M-E-F poster* teacher reference for an overview of how this model is developed in this lesson and the next one.



In this lesson, students complete a chart on the whiteboard titled, “Explaining the behavior of the matter in the system.” An example of this chart is shown in the *Explaining Behavior KEY*.

Deforming a Foam Panel

- **Group size:** 2 students.
- **Setup:**
 - Cut 2 pieces of foam (3" x 12" x ½" each) for each pair of students in your largest class. Each pair should only need one, but prepare 3 extras of these to use in the demonstration for slide B and in case of accidental breakage.
 - Make an additional cut along one of the 3" edges of each of these 3 extra panels so that it no longer forms a 90 degree angle between the two largest faces. The new angle should be at about ~80 degree to one of these faces. You are making this cut because the standard 90 degree edge that the panels typically come with will not allow the panel to bend upward when the panel is pressed up against the wall for the demonstration in **slide B**.
 - panels bow upward when they are pressed against the wall as described in the demonstration for **slide B**. To do this, orient the vertex of the ~80 degree angle you made so it is on the **bottom** of the panel when you push it against the wall. This will ensure that the panel bows upward.
- **Safety:** Have students wear indirectly vented chemical splash goggles during this investigation. They need to get close to the foam to observe changes in its shape, and it may snap or their hands may slip when compressing or stretching it.
- **Disposal:** Materials are reusable and do not need to be thrown away, unless the foam breaks.
- **Storage:** Store materials in a cabinet in the classroom.



Foam Panel Projectile with a Hanging Weight

- **Group size:** Whole class.
- **Setup:**
 - Cut 2 pieces of foam (3" x 12" x ½" each). Prepare an extra piece in case of accidental breakage.
 - Cut 3 pieces of string (1'-2' long) per class. Tie one end of each string to a paper clip.
 - Use a piece of duct tape or packing tape to secure the other end of a string to one end of each foam panel. You will replace one of these strings for each class after you cut it in the demonstration.
 - Use a spring clamp to secure each foam panel to the edge of a demonstration table, so both panels are cantilevered off the table and extend from it by the same amount.
 - Find 1 50-g mass and 1 200-g mass. These objects are hung on the paper clips and then drop to the floor when you cut the string.
 - Find 2 similarly shaped masses, ~2 g each, to launch as projectiles. They should have a soft surface (e.g., a ball of clay or an eraser) to avoid any chance of injury.
- **Disposal:** Materials are all reusable and do not need to be thrown away, unless the foam breaks.
- **Safety:** Have students wear indirectly vented chemical splash goggles and stand 10 feet away from the apparatus to avoid possible contact with the projectiles. These should be launched from the foam panels straight up into the air, but they may deviate a bit in their path.



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 ideas (DCIs):

- **ESS2.A.1: Earth Materials and Systems:** Earth's systems, being dynamic and interacting, cause ~~feedback~~ effects that can increase or decrease the original changes. (HS-ESS2-3)
- **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)

A key property of material behaviors in Earth systems is developed in this lesson: all rock that makes up the plates has a dynamic behavior not always visible to the unaided eye--it elastically deforms (up to a point), which enables it to behave like a spring. Students who have completed *OpenSciEd Unit 8.1: Why do things sometimes get damaged when they hit each other? (Collisions Unit)* have previously developed this idea. They have also developed the idea that when external forces acting on any solid material compress, stretch, twist, or bend it past its elastic limit, the material permanently deforms.

This lesson's expanded M-E-F poster looks very similar to the poster created in the OpenSciEd high school Chemistry course. That is initially developed in the second unit, *OpenSciEd Unit C.1: What causes lightning and why are some places safer than others when it strikes? (Lightning Unit)*, and then used across that course. In that unit, students developed the idea that "forces transfer energy." This built upon prior understandings developed in middle school. Students did not qualify that only unbalanced forces do this, as they did not have a phenomenon that necessitated calculating net forces on individual particles or objects.

In this lesson, the class analyzes a phenomenon across two short time periods (less than a second) without the use of a slow-motion video. Visualizing changes in matter happening between stable states across these short timescales builds off the work with crosscutting concepts (CCCs) related to *scale, stability, and change* developed in Lesson 2. In Lesson 4, this thinking will be extended to analyzing what is happening between two stable states at an even smaller physical scale (the particle level) and a shorter timescale.

Students encounter and co-construct ideas around several terms during this lesson, and may decide to add the following words to their Personal Glossaries: *elastic behavior, deformation, elastic limit*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning. At that point, create an opportunity to add new meanings to the Personal Glossary, if desired.

Where We Are NOT Going

In OpenSciEd, we intentionally avoid trying to list or name different "types" or "kinds" of energy. Instead, students focus on how the energy is transferred or where it is stored in the system. We also avoid the term *potential energy*, as it tends to make students think it is energy that could exist or is not real. It obscures the mechanism by which energy is stored in any system--as motion of objects or particles (kinetic or thermal energy) or in the gravitational, electric, or magnetic field between these components (potential energy).

This unit does not target performance expectation HS-PS3-1. But the *L3 Investigation Extension* reference outlines a related optional extension opportunity, which would be relevant to the phenomena in this lesson (and the next): an investigation into how much energy can be transferred into and out of an elastically deformed material.

Though students investigate the properties of elastic materials, they do not explore how the molecular substructure of these materials influences the behavior of solids under forces. In Lesson 4, students will use different models to investigate the changes at the particle level that can help explain these properties.

LEARNING PLAN for LESSON 3

1 · NAVIGATE

2 min

MATERIALS: M-E-F poster, M-E-F expansion panels

Recall predictions from Lesson 2. Display slide A. Read the slide's first prompt aloud:

- *What did we predict would happen if we kept increasing the magnitude of balanced forces acting on a stationary solid object?*

Have students recap some of those predictions. Listen for the following ideas:

- It could break.
- It could bend.
- It could crack.

Use the slide's second and third prompts to follow up on these ideas:

- *Do we have evidence that this could happen to big pieces of land?*
- *How could we use the foam to investigate how forces can cause these changes?*

Listen for students to share the following ideas:

- We have evidence of the land cracking, but we don't have evidence of it breaking and bending.
- We could apply forces to the foam to make it bend or crack.

Use the following questions to elicit ideas about data collection:

- *What would be the independent and dependent variables in this investigation?*
- *What data could we collect?*
- *Which tools could we use to collect data?*

The answers will help students make sense of the upcoming exploration with the foam.

2 · EXPLORE CHANGES IN A PIECE OF FOAM

6 min

MATERIALS: Deforming a Foam Panel, M-E-F poster, M-E-F expansion panels

Present slide B. Recruit a volunteer to work with you for this brief demonstration. Have students put on their safety goggles in preparation for a close-up examination of what happens with the foam. Gather around a wall and carry out the following demonstration:

- Place a piece of foam against the wall, with the vertex of the ~80 degree angle you made on it so it is on the bottom of the panel and up against the wall.
- Have a volunteer push on the other side of the foam (toward the wall), varying the magnitude of their force, without breaking it. This should cause the foam to start to bend upward.



Ask students to describe the changes they see in the matter as the volunteer changes the magnitude of the force being applied to it. Listen for the idea that the harder they push, the more the foam bends. Then ask how we could continue increasing the force on the foam while preventing the material from breaking. Listen for them to suggest applying an additional downward force to it.

ADDITIONAL GUIDANCE

The extra foam pieces are on hand in case the foam breaks in this demonstration. If this happens, reassure the student that this is OK, and ask them to try again with a smaller amount (magnitude) of force.

Launch the partner exploration. Suggest we try another exploration, in which we prevent the foam from changing shape (bowing upward) by applying an additional downward contact force to it.

Display **slide C**. Review the instructions with the class. Refer to the slide's first image to emphasize that during the push exploration, one volunteer pushes down on the top of the foam with only enough force to keep it from bowing upward while the other tries to compress it toward the wall from the end (a perpendicular direction). Refer to the second image to emphasize that during the pull exploration, only one person should attempt to stretch the foam without breaking it.



ADDITIONAL GUIDANCE

Remind students to keep their safety goggles on so they can get up close to the foam to see whether any changes are happening at a relatively small scale.

Distribute 1 foam piece and 1 ruler to each partner pair. Mention that the ruler could be helpful for measuring any really small changes in the matter. Set a timer for 2 minutes to explore each condition.

After the 2 minutes, ask students whether they saw any changes in the foam's length, size, or shape. They should say they noticed very small changes in both conditions (compression and tension).

3 · USE A MODEL TO EXPLAIN A FOAM SYSTEM FROM A FORCES AND MATTER PERSPECTIVE

8 min

MATERIALS: Foam Panel Projectile with a Hanging Weight, dry erase marker (red), dry erase marker (purple), dry erase marker (green), dry erase marker (black), M-E-F poster, M-E-F expansion panels, chart paper marker

Orient students to the system. Present **slide D**. Gather the class around a demonstration table where you have prepared two foam panels cantilevered to it with spring clamps, with a piece of string taped to the end of each panel and a paper clip hanging from each string. Explain that for our next investigation, we will observe changes in matter and forces in a system of a foam panel, hanging mass, and projectile. Place a 2-g soft projectile on top of the end of each panel.

Elicit 1-2 ideas with the slide's prompt:

- *Are the forces on each piece of matter in the system currently balanced (net force of zero) or unbalanced (net force not equal to zero)? How can we tell?*

Listen for the following ideas:

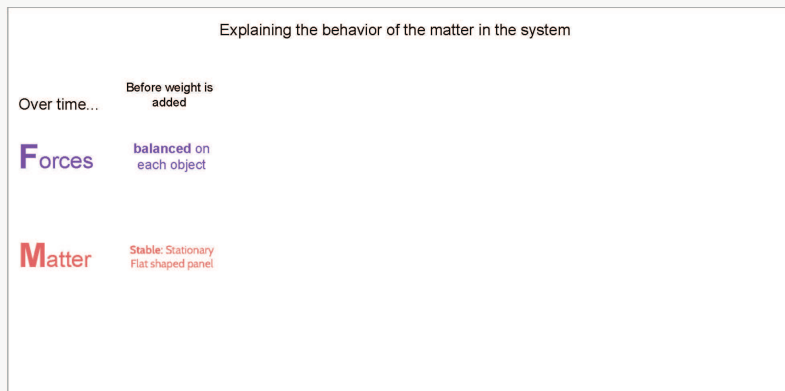
- The forces on each piece of matter are balanced because they are all stationary ("stable").
- The net force on each part of the system (in a free-body diagram) would be zero.

- The matter is not changing.

Say, *Interesting. Let's record some of our ideas about forces and matter together.*



Record students' ideas on the whiteboard, using a red marker for matter and a purple marker for forces. Tell them the different colors are intended to help remind us which lens we are using to explain the system.



Add a downward force to the foam panel. Hang the 50-g mass from one of the paper clips. After letting the system's motion stabilize for a few seconds, ask what applying this force did to the shape of the panel. Students should say it deformed the panel.

Ask again whether the forces on each piece of matter in the system in its current state are balanced (net force of zero) or unbalanced (net force not equal to zero), and how we can tell. Listen for the same ideas as before:

- The forces on each piece of matter are balanced because they are all stationary ("stable").
- The net force on each part of the system (in a free-body diagram) would be zero.
- The matter is not changing.



Point to the M-E-F poster to indicate the link to the idea we figured out in Lesson 2: that balanced forces can keep matter stable.

Record these ideas on the whiteboard, marking off a new section with a dotted line to indicate that the system is now in a new stable state. Leave space between this state and the previous one to add text about what happens in the time period between.

Explaining the behavior of the matter in the system		
Over time...	Before weight is added	When weight is hanging
Forces	...balanced on each object	...balanced forces...
Matter	Stable: Stationary Flat shaped panel	Stable: Stationary, curved shape panel

Describe the time period between each stable state. Present **slide E**. Use the prompts to elicit ideas about changes over time:

- What was the approximate timescale that it took the system to go from the starting stable state to its current stable state?
- If you could watch this transition in slow motion, what changes do you think you would see in the system?
- Were the forces balanced or unbalanced during this transition? How can we tell?

Encourage students to use their hand or arm to represent the behavior of the matter when describing the changes that occurred as the system transitioned from an unstable to a stable state. Listen for the following ideas:

- The period of time between each stable state was less than a second.
- We would see the end of the foam bend downward a bit when the weight was hung on it.
- Maybe it bounced up and down a little before it became motionless again.
- The system was changing, so the forces were probably unbalanced.

Record students' ideas on the whiteboard. Connect these to the idea on the M-E-F poster established in Lesson 2: unbalanced forces cause motion. Say, *Like last time, here again we are proposing that unbalanced forces are the cause of the change we see in the matter during this period of time.*

Add the word "cause" to the poster and underline it.

Explaining the behavior of the matter in the system			
Over time...	Before weight is added	In between (over a very small time scale)	When weight is hanging
Forces	balanced on each object	... unbalanced forces...	... balanced forces...
		<u>Cause</u>	
Matter	Stable: Stationary Flat shaped panel	Changes in motion, shape.	Stable: Stationary, curved shape panel

Make predictions. Present **slide F**. Have students put their safety goggles back on. Ask them to make predictions about what will happen if we quickly remove the downward force on the system from the 50-g mass by cutting the string. Listen for these predictions:

- The foam will move up and down.
- The foam will return to its original shape
- We will hear some kind of sound
- The projectile will fly over.

After students share, cut the string to test the outcome.



After the system has stabilized, pose the slide's second prompt:

- *At this point in time, are the forces on each piece of matter balanced or unbalanced? How can we tell?*

Listen for the same ideas as in the first section. Mark off a new section on the whiteboard with a dotted line and record these ideas.

Pose the slide's third prompt:

- *What happened to the balance of forces and the matter in the time between the previous state and this state?*

Listen for the idea that the forces were unbalanced during this "in between" period of time. Add this to the whiteboard. Point out that we now have a second time period in which we have identified unbalanced forces as the cause of the change in the matter. Add the word "cause" to this time period and underline it.

Explaining the behavior of the matter in the system					
Over time...	Before weight is added	In between (over a very small time scale)	When weight is hanging	In between (over a very small time scale)	After weight is removed
Forces	balanced on each object	...unbalanced forces...	...balanced forces...	...unbalanced forces...	...balanced forces...
		<u>Cause</u>		<u>Cause</u>	
Matter	Stable: Stationary Flat shaped panel	Changes in motion, shape.	Stable: Stationary, curved shape panel	Changes in motion, shape	Stable: Stationary, Flat shape panel

4 · EXPLAIN THE SYSTEM FROM AN ENERGY PERSPECTIVE

8 min

MATERIALS: Foam Panel Projectile with a Hanging Weight, dry erase marker (red), dry erase marker (purple), dry erase marker (green), dry erase marker (black), M-E-F poster, M-E-F expansion panels, tape, chart paper marker

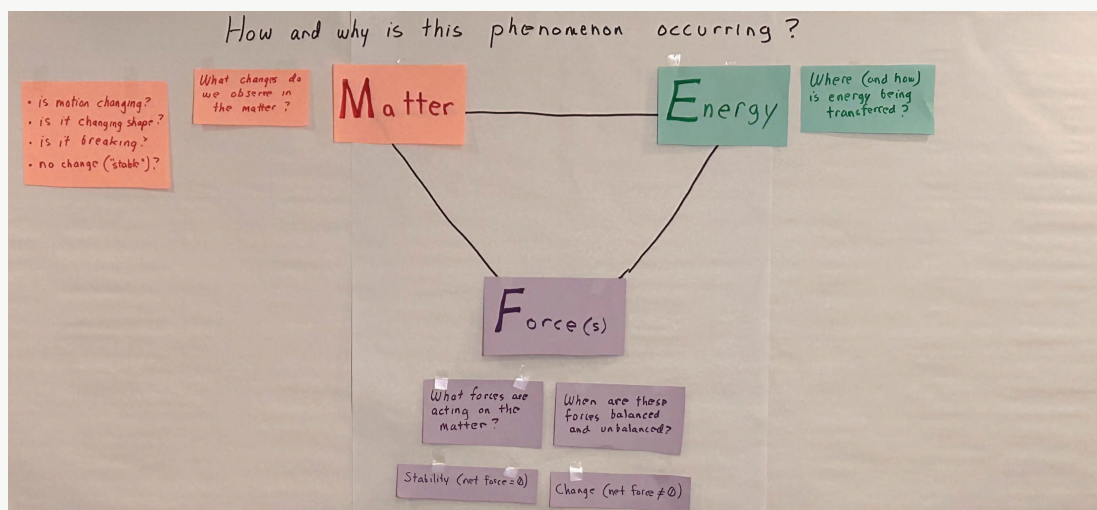
Update the M-E-F poster. Have students return to their seats. Say, *In the (material.p.e.n), we explained many phenomena by thinking about energy transfer through the system. Let's use that lens again to try to explain what is happening in this foam system.*

* SUPPORTING STUDENTS IN ENGAGING IN ARGUMENT FROM EVIDENCE

This is an explicit reference to this crosscutting concept element:

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

The “Energy” corner of the M-E-F poster is now displayed by removing the covering. The panels for “Energy” and “Where (and how) is energy being transferred?” should already be on the poster.



Display **slide G**. Give students 1 minute to turn and talk about the prompts:

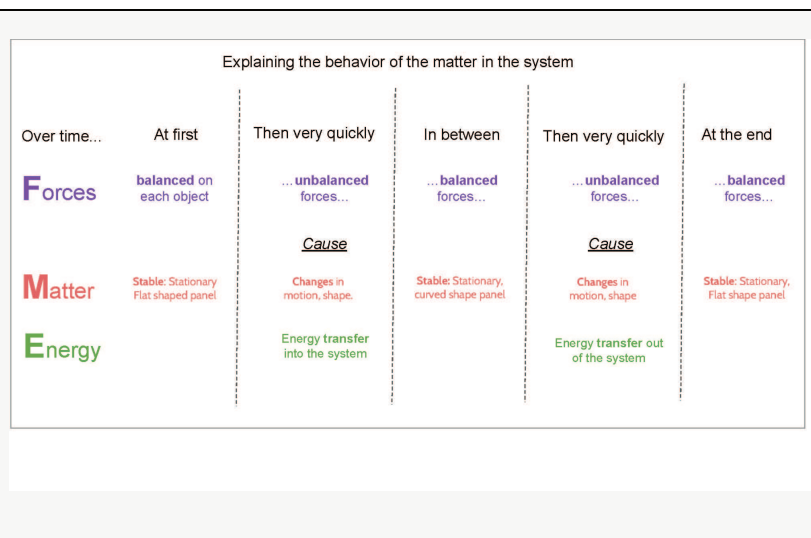
- When did we see evidence of energy being transferred into or out of the system?
- How are matter changes related to the energy transfer we observed in this system?

After 1 minute, have students share out. Listen for these ideas:

- A matter change we observed was that the objects went from being stationary to moving (and back to stationary again at some point).
- Another matter change we observed was the shape of the foam changing.
- An energy transfer we observed was to the projectile when it went from stationary to moving once the string was cut.
- As the foam was bent, energy was transferred into it.
- When we cut the string, the energy stored in the foam was transferred out of it.

Invite students to share their ideas about the slide's second prompt. As they share, reference the five sections of time we divided the system's behavior into, and ask which one showed evidence of energy being transferred out of the system; they should say the fourth section. Add this energy transfer notation to the whiteboard.

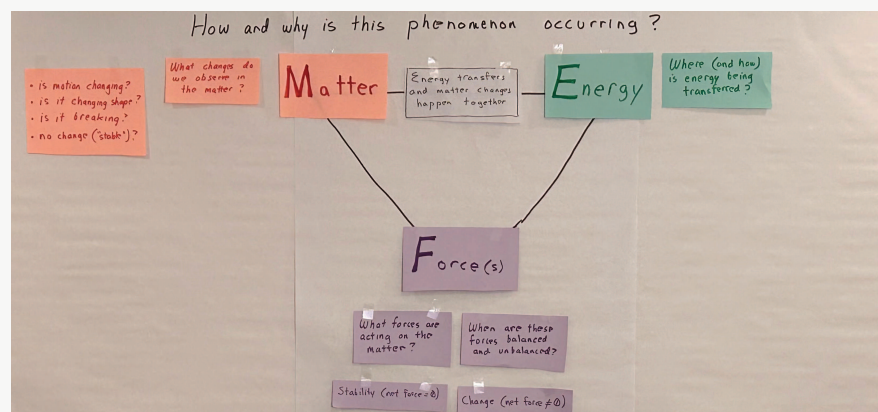
Then ask them to identify which section showed evidence of energy transfer into the system; they should say the second section. Add this energy transfer notation to the whiteboard.



Identify the causal relationships on the whiteboard. Point out that the two sections where we have written “cause” suggest unbalanced forces are causing both matter changes and energy transfers. Ask students to recall what they learned in the last unit--that matter changes and energy transfers happen together, which this chart is showing us again.

Emphasize how forces provide a mechanism for those changes. Say, *Scientists have found that taking a forces perspective can help explain what causes stability and change in any system, because not only are unbalanced forces always what cause changes in matter, they are also the cause of energy transfer.* * Update the M-E-F poster as shown below.

The panel “Energy transfers and matter changes happen together” is added to the poster on the line between the “Matter” and “Energy” panels.



ADDITIONAL GUIDANCE

The Chemistry course for OpenSciEd developed the idea that “Forces transfer energy”. This idea built upon prior understandings developed in middle school in (material.cf) and [material.df]. Students did not qualify that only unbalanced forces do this, as they did not have a phenomenon that necessitated calculating net forces on individual particles or objects.

It won't be until *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)* that the class will modify the statement just added to the M-E-F poster, qualifying it with one additional word so it becomes “Unbalanced forces *can* transfer energy.” This qualification won't be uncovered until students encounter a phenomenon that provides evidence requiring its revision: namely, the circular motion of some orbits.

Make a prediction. Say, *Let's use this cause-and-effect relationship to make a prediction.* Display **slide H**. Take a quick class poll with a show of hands about the slide's question:

- *Would changing the amount of weight that we hang from the foam panel affect these two things? (Yes / No)*

Point out any controversy that has emerged in the class. If no controversy exists, ask students how we could test their ideas. Then suggest we carry out a test of our predictions, looking for evidence to support or refute them along the way.

Set up the test. Have students gather around the demonstration table and put their goggles back on. Place a 2-g projectile on top of the end of each foam panel. Hang the 50-g mass from the panel that still has a string with a paperclip. Tape a new string and paper clip to the other panel and hang the 200-g mass. Ask the class to compare the amount of change in the matter in the two systems.

- If all students agree that we can see the 200-g mass deforms the foam more than the 50-g mass does, then move on.
- If students don't agree that the foam deforms more with the 200-g mass, or if they say we need a measurement to be certain, ask what we should measure and then carry that out.



ADDITIONAL GUIDANCE

A typical comparative measurement that students tend to suggest in such cases is to use a ruler to determine the amount of downward dip in the end of each foam panel. This is easy to do using a meter stick touching the floor and held upright, perpendicular to the end of the panel. Students might also suggest subtracting the foam panel's height from the floor when a weight is hanging on it from the panel's height from the floor when no weight is hanging on it.

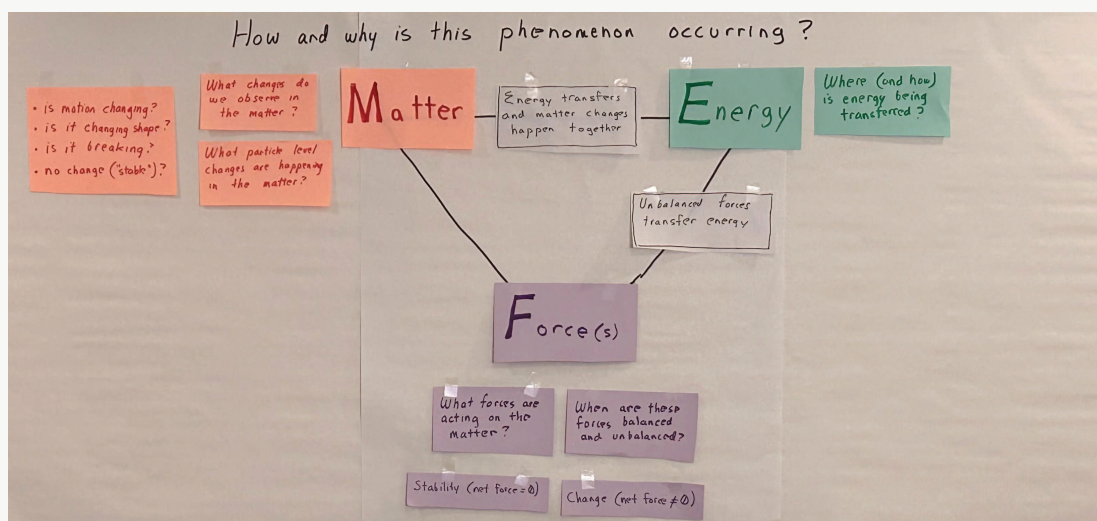
Take this opportunity to explore the advantages and disadvantages of each measuring method for producing accurate, reliable data, as well as the limitations on the precision of the data generated by each method. Use these ideas to decide as a class which measuring method aligns with the classroom criteria.

If students completed *OpenSciEd Unit 8.1: Why do things sometimes get damaged when they hit each other? (Collisions Unit)*, they will notice that this way of measuring deformation is nearly identical to the method for measuring deformation of a suspended beam developed in their first formal experimental design plan in Lesson 4 of that unit.

Observe and identify outcomes. Cut the string on the system with the 200-g mass to test our predictions. Reference **slide H**. Ask students to identify any changes they observed in the matter or the amount of energy transfer. They may cite more deformation of the foam, greater back-and-forth motion (for longer), a higher/farther launch, and/or a bigger change in speed for the projectile.

Add to the M-E-F poster. Have students return to their seats. Point to the “Force(s)” portion of the poster and say, “We wondered about the effects of changing the magnitude of the unbalanced forces applied to the system. From there, we were able to reason out all the related changes in matter and energy.”

“Unbalanced forces transfer energy” is added to the poster on the line between the “Forces” and “Energy” panels.



5 · CONSIDER RELATED PHENOMENA

4 min

MATERIALS: M-E-F poster, dry erase marker (red), dry erase marker (purple), dry erase marker (green), dry erase marker (black)

Introduce elastic behavior. Display slide I. Read the text at the top aloud:

- Any solid object that changes shape temporarily when forces are applied to it, and then returns to its original shape after those forces are removed, is considered to have elastic behavior (it behaves like a spring).

Give students a minute and a half to turn and talk about the slide's prompts:

- What other materials have you seen exhibit elastic behavior like the foam?
- Does solid rock have elastic behavior?

As they discuss among themselves, write this question on the whiteboard: “Does solid rock have elastic behavior?” Then have students share a few examples for the slide's first prompt. Take a quick class poll (a show of hands for yes/no) for the second prompt.

There is likely to be some controversy around this prediction.

- If there is controversy, suggest that we need to resolve the question “Does solid rock have elastic behavior?” to see whether we can apply our M-E-F poster ideas to the plates' behavior.
- If there is no controversy, suggest that we need evidence to support or refute whether we can apply our M-E-F poster ideas to the plates' behavior.

6 · GATHER INFORMATION AND USE IT TO MAKE ADDITIONAL CLAIMS

11 min

MATERIALS: *Analyzing Rock Behavior*

 **Assign the reading.** Display slide J. Distribute a copy of *Analyzing Rock Behavior* to each student. Explain that this reading can help with our questions about the elastic behavior of rocks.

Orient the class to the reading task with the slide's prompts:

- Highlight any ideas in the reading that can help answer our central question: *Does solid rock have elastic behavior?*
- Answer the four additional sensemaking questions throughout the reading.

Tell students that you will collect this handout as a formative assessment at the end of the period. Give them about 9 minutes for this task, and reserve 2 minutes to share a few key ideas as a class.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment and what to do: See the *Analyzing Rock Behavior Key* to assess Questions 1, 2, and 3 (LLPE 3.A) and Question 4 (LLPE 3.B.1) on the *Analyzing Rock Behavior* handout.

Building toward: 3.A Make qualitative claims about how differences in the magnitude of forces (1) acting on different materials (cause) would produce similar effects in their structure (elastic deformation) and (2) acting on a single material would affect the amount of energy transferred into and out of it. (SEP: 6.1; CCC: 2.2, 5.2, 6.2; DCI: PS3.B.2)

Building toward: 3.B.1 Ask questions arising from development of the M-E-F model to clarify (1) additional relationships related to energy transfer and storage in deformed matter and (2) the model's application to various dynamics and interactions occurring in Earth systems. (SEP: 1.2; CCC: 5.2, 7.1; DCI: PS3.B.2, ESS2.A.1)

7 · NAVIGATE

6 min

MATERIALS: 2 3x3 sticky notes, permanent marker, *Analyzing Rock Behavior*, science notebook, M-E-F poster, Driving Question Board

Connect to phenomena from the anchor. Say, *Now that we've figured out that the plates' material would exhibit elastic behavior, let's consider how the M-E-F relationships we've developed can help us better explain some of the phenomena we explored in the anchor.*

Display slide K. Give students 2 minutes to turn and talk about the prompts:

- Most earthquakes happen near plate boundaries.
- Afar's earthquake and some other earthquakes do not.
- Use the ideas from the reading and the M-E-F poster to help explain either of these phenomena.

Distribute 2 sticky notes and a permanent marker to each student during this discussion.

 Display slide L. Have students take a moment to record any new questions. Remind them to write one question per sticky, in marker, with their initials on the back in pencil. Ask them to place their stickies onto their *Analyzing Rock Behavior* handout to turn in at the end of class.

Before collecting these materials, have students share some questions from their stickies or their response to Question 4 on the handout. Emphasize that these seem to indicate we need some additional ways to investigate our questions next time.

ALTERNATE ACTIVITY

You could collect new questions digitally, and then if you have a physical Driving Question Board, you could print them out and add them to the DQB.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Questions that clarify differences in the relationship between changes in matter, forces acting on the system, and energy transfer occurring along plate boundaries and in other plate locations. (SEP: 1.2; CCC: 5.2, 7.1; DCI: PS3.B.2, ESS2.A.1)

Some examples of such questions:

- How strong (what is the magnitude) of the forces acting on the plates?
- How much can a plate elastically stretch or compress before breaking?
- How much energy is transferred into a plate (or between plates) before an earthquake occurs?
- What is causing an imbalance in forces in the plates before an earthquake?
- Is the elastic limit of a plate different along plate boundaries than in the middle of the plate?
- Is the material in the plate below Afar different from the material in plates in other locations?
- Is an earthquake always the result of unbalanced forces in the matter?
- How is the same thing happening to the matter in the plate at Afar as at plate boundaries?
- Where is the energy actually stored in the matter when you elastically deform it?
- How much energy can be stored in a plate?
- How much energy can be stored in a rock when it is compressed, before it breaks?

What to do:

- **To support students:** If you notice they develop questions that don't directly connect to ideas developed in this lesson, emphasize that all questions are productive. Encourage them to use their second sticky note to consider another question related to a specific Earth system phenomenon that also connects to one or more ideas we developed in the M-E-F poster. You can do this at the start of Lesson 4, after you have reviewed student questions collected at the end of this lesson.
- **To support navigation into the next lesson:** The last three questions listed above are about energy storage in matter. This is a new idea that students may raise, and it is intended to be foregrounded in the navigation at the start of the next lesson. Make sure to incorporate some of these questions in **slide A** of Lesson 4. If no students ask energy storage questions yet, that is OK. Guidance will be provided on how to elicit these questions using ideas about energy conservation established in the previous unit.

Collect the handouts and the questions on the sticky notes, as you will need them to prepare for the next class.

Building toward: 3.B.2 Ask questions arising from development of the M-E-F model to clarify (1) additional relationships related to energy transfer and storage in deformed matter and (2) the model's application to various dynamics and interactions occurring in Earth systems. (SEP: 1.2; CCC: 5.2, 7.1; DCI: PS3.B.2, ESS2.A.1)

Update the Personal Glossary. Display **slide M**. Give students time to update their Personal Glossary. You can suggest words such as the terms listed on the slide:

- *elastic behavior*
- *deformation*
- *elastic limit*

ALTERNATE ACTIVITY

Extension opportunity: This is designed to serve as an optional opportunity to plan and carry out an investigation and develop a mathematical relationship from the data collected.

Have students look back at their response to Question 2 on *Analyzing Rock Behavior*. Ask them whether they would be interested in designing and carrying out an investigation to support or refute their claim. Tell students who are interested in this extension opportunity to circle Question 2 before turning in their handout.

This opportunity was developed as a differentiation option for students who have demonstrated either prior fluency or high interest in the related science and engineering practices (SEPs) it would require, particularly related to developing mathematical models from experimental data. Though such work was a focus of the first unit of the prior Chemistry course, *OpenSciEd Unit C.1: How can we slow the flow of energy on Earth to protect vulnerable coastal communities? (Polar Ice Unit)*, it has not yet been a focus in this course. Such mathematical modeling approaches will be introduced for the first time in this course in Lesson 8. They will become a larger focus of students' work in the next two units: *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)* and (material.pg).

This optional extension opportunity is outlined in greater detail in *L3 Investigation Extension*.

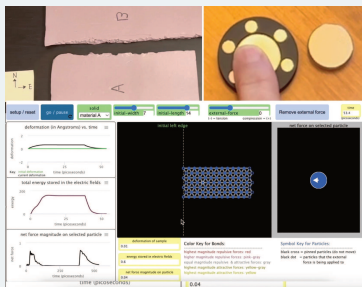
LESSON 4: What is changing in the matter at a particle level before an earthquake, and when a solid elastically deforms or breaks?

PREVIOUS LESSON We explored changes in a piece of foam as higher-magnitude forces were applied to it. We developed a model relating unbalanced forces to changes in matter and energy transfer. We predicted whether rock would behave like a piece of foam. We gathered information from a reading and asked questions about the relationship of our new ideas to what is happening in Earth systems.

THIS LESSON

INVESTIGATION

2 days



We evaluate the merits and limitations of two models (foam panels and inverter magnets) for understanding and explaining earthquakes, elastic deformation, and breaking of solid matter. We use a computer simulation to investigate how external forces on a solid affect matter changes and energy transfers at the particle level. We revise our M-E-F and Scale Chart posters to account for the roles of fields on large-scale phenomena, and use these ideas to explain volcanic eruptions in an Electronic Exit Ticket.

NEXT LESSON We will wonder what could be happening in Earth's interior to cause unbalanced forces on the crust. We will analyze seismic velocity data to determine the structure of Earth's interior and establish that local heterogeneity in Earth's mantle explains certain surface features. We will revise our model of Earth's layers to include a heterogeneous mantle and add to our Progress Trackers.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

4.A Evaluate the merits and limitations of different models using a crosscutting lens (*stability and change, thinking across scales, and/or cause and effect*) for understanding and explaining different phenomena (earthquakes) and mechanisms (elastic deformation, cracking/breaking). (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2)

4.B Use a computational model to explore stability and change and cause-and-effect relationships between the magnitude of external forces acting on a solid, the changes in matter given its mass (number of particles), and the changes in energy in the system across different scales. (SEP: 2.3; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS3.B.2, PS2.B.3, ESS2.B.2)

WHAT STUDENTS WILL FIGURE OUT

- External forces applied to or removed from a solid create a temporary imbalance of forces between particles. In elastic deformation, those particles rearrange until they reach a place in the system where the forces on them are balanced.
- All changes in matter (bending, breaking, state change) are changes in motion, either macroscopic or at the particle level.
- If unbalanced forces deform a solid too much, some of the particles in it move far enough apart that their bonds break.
- Matter produces various fields (electric, magnetic, gravitational); fields exert forces that act across a distance on other particles.
- Energy can be transferred to, transferred from, and stored in fields.

Lesson 4 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	4 min		NAVIGATE Review questions from Lesson 3 and create a list of phenomenon categories that these questions can help answer. Reflect on this lesson's focal Community Agreement.	A-B	selected questions generated by students at the end of Lesson 3 (on this lesson's slide A), Community Agreements poster
2	10 min		DISCUSS MODEL 1 Use a video and its captions to evaluate how two foam panels can simulate the plate interactions that produce earthquakes.	C-E	<i>Evaluating Models</i> , https://www.youtube.com/watch?v=uVM4t2QXtLo , Scale Chart poster, M-E-F poster, M-E-F expansion panels
3	6 min		IDENTIFY ADVANTAGES AND LIMITATIONS OF MODEL 1 Individually record advantages and limitations of the foam model on the handout. Identify points in the foam panels where slips originate or breaks occur, and discuss why it is happening there.	F-G	<i>Evaluating Models</i> , Scale Chart poster, M-E-F poster, M-E-F expansion panels
4	8 min		MAKE SENSE OF MATTER CHANGES AND RECALL PRIOR PARTICLE-LEVEL MODELS OF MATTER Recall prior experiences with simulating and visualizing particles and particle-level interactions. Identify the force interactions between similarly and oppositely charged particles (protons and electrons) that make up atoms.	H-L	<i>Evaluating Models</i> , M-E-F poster, M-E-F expansion panels
5	6 min		DISCUSS MODEL 2 Use a video and its captions to evaluate how two inverter magnets simulate force interactions between bonded atoms.	M	<i>Evaluating Models</i> , https://youtu.be/K3m2x6Vtj4I
6	3 min		IDENTIFY ADVANTAGES AND LIMITATIONS OF MODEL 2 Individually record advantages and limitations of the inverter magnet model.	N	<i>Evaluating Models</i> , Scale Chart poster, M-E-F poster, M-E-F expansion panels
7	3 min		BRAINSTORM FEATURES OF A SIMULATION Brainstorm what parts and interactions we would want in a particle-level simulation, and what we would want to be able to change, visualize, and measure in it.	O	<i>Evaluating Models</i>
8	5 min		INTRODUCE THE SIMULATION AND PLAN INVESTIGATIONS Watch the orientation video for the simulation. Complete Part 1 of the investigations handout in small groups.	P-Q	<i>Particle Investigations</i> , <i>Evaluating Models</i> , https://youtu.be/D8QZMCO5_oc
End of day 1					
9	15 min		NAVIGATE: USE THE SIMULATION TO CARRY OUT A SERIES OF INVESTIGATIONS In small groups, carry out a four-part investigation using a computer simulation of deformation and breaking.	R	<i>Particle Investigations</i> , computer with access to https://opencscied-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html
10	3 min		PREPARE FOR A SCIENTISTS CIRCLE Share and compare findings in partners.	S	<i>Particle Investigations</i>

Part	Duration		Summary	Slide	Materials
11	13 min		UPDATE THE M-E-F POSTER Gather in a Scientists Circle. Use a demonstration to discuss changes in the system from a matter, energy, and forces perspective. Add to the M-E-F poster.	T-AA	<i>Particle Investigations</i> , M-E-F poster, M-E-F expansion panels, Scale Chart poster, 3x5 sticky notes, clear tape, chart paper markers, Breaking Foam Panels
12	12 min		ASSIGN THE ELECTRONIC EXIT TICKET Apply what we have figured out so far to an Electronic Exit Ticket about a new phenomenon: volcanic eruptions.	BB	copy of https://docs.google.com/forms/d/1d7mdn_MMObL_bFfLV3eRkazg-AETeohRiBhXX7Z7sDE/copy made before class
13	2 min		NAVIGATE Conclude that we can not fully explain what is happening at Afar and need more information/data.	CC	

End of day 2

Lesson 4 • Materials List

	per student	per group	per class
Breaking Foam Panels materials			2 double V-notched foam pieces (3" x 12" x ½")
Lesson materials	<i>Evaluating Models</i> <i>Particle Investigations</i> - science notebook	computer with access to https://openscienced-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html	- selected questions generated by students at the end of Lesson 3 (on this lesson's slide A) - Community Agreements poster https://www.youtube.com/watch?v=uVM4t2QXtLo - Scale Chart poster - M-E-F poster - M-E-F expansion panels https://youtu.be/K3m2x6Vtj4I https://youtu.be/D8QZMCO5_oc 3x5 sticky notes - clear tape - chart paper markers - copy of https://docs.google.com/forms/d/1d7mdn_MMObL_bFfLV3eRkazg-AETeohRiBhXX7Z7sDE/copy made before class

Materials preparation (30 min 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.

Include copies/images of some of the questions developed at the end of Lesson 3 in the boxes on **slide A** and **slide K**. Select questions that focus on matter, energy, and/or forces and use these lenses to compare Afar and places near plate boundaries. Here are several examples:

- Is the matter at Afar similar to the matter near plate boundaries?
- How strong are earthquakes in Afar compared to earthquakes near plate boundaries?
- How often do earthquakes happen in Afar compared to earthquakes near plate boundaries?
- How much energy do earthquakes near plate boundaries have compared to earthquakes in Afar?
- How does the magnitude of the forces acting on Afar compare to the forces acting near plate boundaries?
- Where do the forces causing earthquakes come from? Are these forces the same in Afar and plate boundaries?
- How do the places not near plate boundaries where earthquakes happen compare to Afar?

Make copies of the handouts for this lesson:

- Evaluating Models* - 1 per student
- Particle Investigations* - 1 per student

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

Position the M-E-F poster from Lesson 3 so you can add the M-E-F expansion panels on day 1. On day 2, bring the poster to the Scientists Circle to do this.

Before class, make a copy of the Electronic Exit Ticket found at the following link: https://docs.google.com/forms/d/1d7mdn_MMObL_bFfLV3eRkazg-AETeohRiBhXX7Z7sDE/copy. Share the link to the **copy** with students, **not** the link provided here; if you share the original link, that will create a new copy for each student, and you will not have access to their responses. See the reference *How to Create Electronic Exit Tickets*.

Review the preparation and demonstration videos of the foam and inverter magnets:

- Plate interaction and earthquake demonstration: <https://www.youtube.com/watch?v=uVM4t2QXtLo>
- Inverter magnet demonstration: <https://youtu.be/K3m2x6Vtj4I>

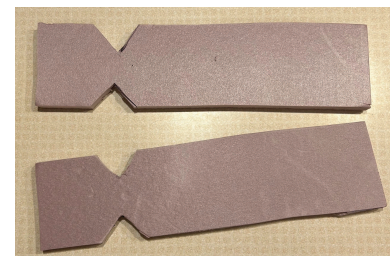
Test the simulation orientation video and the simulation link itself for use on day 2:

- Orientation video to Apply and Remove External Force on a Solid Simulation: https://youtu.be/D8QZMCO5_oc
- Apply and Remove External Force on a Solid Simulation: <https://openscienced-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html>

Reserve enough computers so each pair of students has one computer to share on day 2.

Breaking Foam Panels

- **Group size:** Whole class.
- **Setup:** Cut 2 pieces of 3" x 12" x ½" foam. Cut a V-notch approximately 1" deep and 1" wide into each side at a location 3" from the smaller edge. These pieces are referred to as double V-notched foam (3" x 12" x ½").
- **Safety:** Have students wear indirectly vented chemical splash goggles during this demonstration, because pieces of the foam will fly off when you break it.
- **Disposal:** Panels that break are not reusable and must be thrown away. Unbroken panels can be reused.
- **Storage:** Store unbroken panels in a cabinet in the classroom.



Lesson 4 • Where We Are Going and NOT Going

Where We Are Going

In this lesson, students continue developing the matter, energy, and forces lenses by investigating how materials stretch and break at the particle level. Using the forces lens, they explore whether and how materials deform in response to internal and external forces. Through the matter lens, they develop the idea that electric forces between particles change as a result of external forces acting on the material, changing its shape. Finally, the particle-level models used in the investigations support sensemaking about the way energy is transferred and stored in electric fields in a solid when forces act on it.

This lesson is designed to coherently build ideas related to the following disciplinary core ideas (DCIs):

- **ESS2.B.2: Plate Tectonics and Large-Scale System Interactions.** 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. ~~Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust.~~
- **PS2.B.3: Types of Interactions.** 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.~~
- **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)
- **PS3.A.4: Definitions of Energy.** 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.~~

In this lesson, students recall the following ideas from prior experience in their High School OpenSciEd Chemistry course, rather than inventing them. These ideas are briefly discussed:

- **From OpenSciEd Unit C.2: What causes lightning and why are some places safer than others when it strikes? (Electrostatics Unit):**
 - Charged particles (electrons and protons) and their interactions.
 - Any qualitative (or quantitative) reference to force versus distance relationships from Coulomb's law.
 - Electric fields as a part of a system.
- **From OpenSciEd Unit C.3: How could we find and use the resources we need to live beyond Earth? (Space Survival Unit):**
 - Bonds are stable states in which the attractive forces on two atoms from each other and their shared electrons are balanced.

Students evaluate different models through self-selected crosscutting concept (CCC) lenses on day 1. Two of these were established in Lesson 2: *stability and change* and *scale*. A third was expanded in Lesson 3: *cause and effect* in M-E-F relationships.

Students encounter and/or co-construct ideas around several terms during this lesson, and may decide to add the following words to their Personal Glossaries: *bond, electric field, pressure, compression, tension, nucleus, protons, electrons, magnetic field*. **Do not** ask students to define or keep track of any words until after your class has developed a shared understanding of their meaning.

Where We Are NOT Going

In OpenSciEd, we intentionally avoid trying to name different “types” or “kinds” of energy. Instead, students focus on how energy is transferred or where energy is stored in a system. We also avoid the term *potential energy*, as it tends to lead students to think it is energy that could exist or is not real. It also obscures the mechanism by which energy is stored in any system--as motion of objects or particles (kinetic or thermal energy) or in the gravitational, electric, or magnetic field between objects or particles.

Students are told that the simulation represents force interactions between particles as electric forces. However, no attempt is made to address how changing electric forces can cause magnetic forces, which was a focus of the prior unit and will be a focus of *OpenSciEd Unit P.5: How do we use radiation in our lives and is it safe for humans? (Microwave Unit)* of this course.

Students evaluate the merits and limitations of two models of matter, energy, and force interactions to select design criteria for a model that can help explore these relationships at the particle level. However, they do not revise these models to better fit the evidence.

Students may use words like *stress* or *strain* to explain what is happening in the matter during this lesson. Although they may encounter these words in scientific literature, particularly in the context of material sciences, describing what these ratios are is not this lesson's focus. Alternate guidance is provided in the last Consensus Discussion in case students introduce these words.

LEARNING PLAN for LESSON 4

1 · NAVIGATE

4 min

MATERIALS: selected questions generated by students at the end of Lesson 3 (on this lesson's slide A), Community Agreements poster

Review questions from last class. Present **slide A**. This slide should now include some of the questions generated at the end of Lesson 3.

Have students consider the prompt:

- *How might answering these questions help us understand why most earthquakes appear to happen near plate boundaries, while others, like what happened in Afar in 2005, do not?*

Give them a moment to review the questions. Elicit responses and accept all answers.

Foreground categories of phenomena. Say, *Let's see whether we can apply our ideas about matter, energy, and forces to make progress on these questions by using different models to explain the phenomena you referenced in your questions. Some of those phenomena are related to earthquakes, some to cracks, and some to the elastic behavior of matter.* Write these three categories of phenomena on the board:

- earthquakes
- cracking
- elastic behavior of all matter

If students suggest an additional related category (e.g., volcanic eruption or plate motion), add it to this list.

Frame the Community Agreement of "Moving Our Thinking Forward." Present **slide B**. Say, *We have made significant progress, thanks to everyone's contributions.* Reference the Community Agreements poster. Suggest that the work of connecting different perspectives is challenging, and we will need to lean on each other to push our thinking forward.

Say, *At the end of the period tomorrow, I'm going to ask you to name one student who helped push your thinking forward in a specific way. I'll share those shout-outs with the class later in the unit.*

Then give students a moment to quietly reflect on the prompt on the slide:

- *What do you want to try to do in your discussions over the next two days that could really help push both your thinking and others' thinking forward? **

* ATTENDING TO EQUITY

Building classroom culture: Though the focal Community Agreement for this lesson is "Moving Our Thinking Forward," making time in subsequent lessons for public celebration of specific student contributions that are recognized and valued by their peers is one way to measure progress toward the agreement of being *equitable*. This strategy can also be used to reinforce the agreement of being *committed to our community*.

2 · DISCUSS MODEL 1

10 min

MATERIALS: *Evaluating Models*, <https://www.youtube.com/watch?v=uVM4t2QXtLo>, Scale Chart poster, M-E-F poster, M-E-F expansion panels

Compare structures of plate boundaries. Present **slide C**. Read the text at the top aloud:

- *Let's prepare to use a model to simulate the interactions we think are happening between two plate boundaries.*

Elicit 1-2 ideas related to the images on the slide with the prompt:

- *How do the edges of the foam in image A better represent the structure of the plates along their edges than image B?*

Listen for students to suggest that the foam panels in image A better represent matter along plate boundaries because the plate edges along boundaries are irregularly shaped, rather than being flat or straight as in image B.

Foreground that today's main practice is related to modeling. Refer to picking one foam model over another (for irregular edges versus straight edges) as an example of identifying an advantage in using one part of a model versus another to explore a phenomenon. Emphasize that we will focus on that type of thinking for the rest of the lesson to consider how different models may better explain some aspects of the listed phenomena.

Distribute the *Evaluating Models* handout to each student, and tell them they will use it to track that thinking. Display **slide D**. Read the text at the top aloud:

- *Every model has advantages and limitations. Understanding these can help us move more flexibly between different types of models for explaining how and why phenomena occur. **

Instruct students to record the phenomenon categories of interest in response to the first prompt:

- *Record the phenomena that we are trying to explain (listed on the board) on the top of your handout.*

Say that we are about to identify changes in matter, using the two foam panels as our first model of matter interactions at plate boundaries.

Cue the class with the second prompt:

- *Come up with a name for the first model you are preparing to use, and record it.*

Employ a crosscutting concept to evaluate models by saying that in each row on the handout, students should summarize the model's advantages and limitations, starting with the foam panels. Read the third prompt aloud:

- *Decide and record which lens you want to use to evaluate this first model.*

Have students pick one of the crosscutting concepts listed on the handout--referred to here as *lenses*--to make this evaluation. These lenses are:

- stability and change over time or space
- thinking at/across different scales
- cause-and-effect M-E-F relationships

Reference the related posters in the room that have helped us keep track of our thinking related to these lenses, including the Scale Chart poster and M-E-F poster.

Identify matter changes in the system. Present **slide E**. Open <https://www.youtube.com/watch?v=uVM4t2QXtLo> and display it to the class. Turn the captions on. This video shows what happens when two foam panels with irregular edges are in contact and moving perpendicularly to each other, with force of increasing magnitude applied to their movement. Pause the video when each of the following prompts is displayed:

- Consider whether we would see motion at a smaller scale if we were to zoom into any part of the matter. Imagine you can observe in a zoomed-in location along the plate boundary as they do this again, and the magnitude of the external force on plate B slowly increases.

* SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

This text is also on the top of the *Evaluating Models* handout. It is emphasized here and on **slide D** to make these elements of the modeling practice explicit.

You could start using the word *merits* as a synonym for advantages. You may, however, want to continue using *advantages*, as it tends to be the word that more students use in everyday language.

- 1:06 - What changes would you expect to see along the plate boundary as the magnitude of the forces on each plate increases?
 - While this prompt is displayed, consider restating the question as: What would you see happening to the matter at these locations?
- Consider why these particular pieces of foam would have cracked and broken off from the larger piece of material they were attached to.
 - 2:05 - What, if anything, was different about the matter at the locations where the matter broke off versus where it did not? What, if anything, was different about the forces acting on the matter at those locations?

Have students turn and talk about each prompt before discussing it as a class. Rewind and replay any section that you think supports this discussion.

3 · IDENTIFY ADVANTAGES AND LIMITATIONS OF MODEL 1

6 min

MATERIALS: *Evaluating Models*, Scale Chart poster, M-E-F poster, M-E-F expansion panels

Evaluate Model 1. Present **slide F**. Have students reflect on the slide's first prompt:

- *First take a moment to consider how Model 1 helps us explain how/why any of our listed phenomena occur.*

Give them 3 minutes to record their response to the second prompt on *Evaluating Models*:

- *Then evaluate the model's advantages and limitations for helping explain these phenomena through the particular lens you selected.*

Transition to the next slide by saying, *We should always try to evaluate the advantages and limitations of any model in terms of what phenomena it can explain. Let's discuss a few of those related to earthquakes.*

Focus on points in matter where slips or breaks occur. Display **slide G**. Read the text at the top:

- *Plates can suddenly slip along where they are in contact with each other. The video claimed that this is the cause of many earthquakes along plate boundaries.*

Discuss the slide's two questions as a class, as shown in the table below. Use the follow-up questions to foreground the role of scale in considering matter changes in the system.

Suggested prompts	Sample student responses	Follow-up questions
<i>What must be happening to the matter at points of contact between the plates right before this occurs?</i>	It is elastically deforming. It is getting compressed or bent at those points.	<i>Why would such changes be hard to detect in any solids interacting in this way unless we changed scales to zoom in and/or to slow down time?</i>
<i>Why, in most cases, would breaking, fracturing, or cracking tend to occur at points along the edge of the plate, instead of farther back, away from the edge?</i>	There are stronger (higher-magnitude) forces on the matter along the plate edge than in the middle. There are small pieces of matter in contact along the plate edge, but larger amounts of matter farther away from the edge.	<i>Why would differences in the amount of matter along the plates' points of contact affect where the matter breaks?</i>

In students' responses to the follow-up questions, listen for the following ideas:

- It is hard to detect changes in solids, because the amount of elastic deformation is relatively small compared to the amount of force for most solids.
- Smaller pieces are more affected by forces than larger pieces, because they have less matter.
- There are fewer particles in that part of the matter.

4 · MAKE SENSE OF MATTER CHANGES AND RECALL PRIOR PARTICLE-LEVEL MODELS OF MATTER

8 min

MATERIALS: *Evaluating Models*, M-E-F poster, M-E-F expansion panels

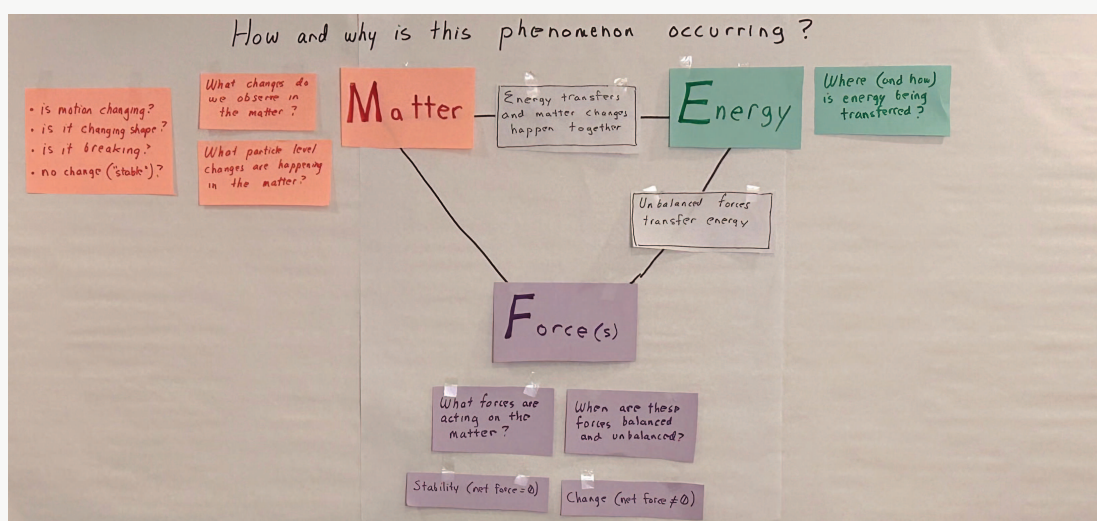
Recall prior models of particles. Say, *As we are now considering the changes happening in smaller parts of the plate, let's see what thinking about even smaller scales can help us understand about this system.* Present **slide H**. Elicit 1-2 ideas in response to the prompt:

- *How did thinking about the particles in the system help us better explain a phenomenon in our prior unit?*

Listen for students to recall their experiences from *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)* with electrons moving through wires to help explain energy transfer through a circuit.

Update the M-E-F poster. Say, *Paying attention to changes at the particle level helped us understand phenomena better in the past, so let's add a question to our M-E-F poster to remind us of that going forward.*

The “What particle-level changes are happening?” panel is added to the upper left “Matter” corner of the M-E-F poster.



Review types of particles. Present **slide I**. Read the text at the top, and elicit 1-2 ideas with the prompt:

- *Particles is a general name for the smallest pieces of matter represented in a model we develop or use.*
- *What names have we used to refer to those particles in our prior modeling work in science class?*

Listen for students to mention atoms, molecules, electrons, and protons.

ADDITIONAL GUIDANCE

If students mention things like grains of sand or rock, ask them to identify the more fundamental particles making up those materials. Encourage them to recall their prior Chemistry units and to consider particles that are not visible to the unaided eye and have distinct properties and interactions.

Consider particle-level interactions. Display **slide J**. Have students turn and talk for a minute about the prompt:

- *What is happening at the particle level within a solid that helps explain either of these behaviors of matter? (You pick.)*
 - *All solids elastically deform up to a point.*
 - *Pieces of a solid can break off when the matter reaches its elastic limit.*

Compare models of bonds. Say, *In Chemistry, you probably would have used the term “bonds” to describe what holds atoms or molecules in a solid together.* Present **slide K**. Read all of the slide aloud:

- *Bonds between atoms or molecules are often used to help explain some of the properties of matter. What does your own model suggest about what the bonds between these particles in a solid are like?*
 - *They are like strings.*
 - *They are like springs.*
 - *They are like rigid sticks.*
 - *They are like _____.*

Explain that the blank option is included because these models are all analogies, which are useful in some ways but limited in others, and they may think a different model would be a more useful analogy. Give students a few moments to think on their own about which of the listed options is closest to their own model of the bonds in a solid. Then poll the class about these options with a show of hands.

After the poll, validate that scientists represent bonds in many ways, such as those on the slide, and these representations help explain some properties of matter but not all. Say, *If you asked scientists whether bonds are actually solid physical structures, like a string, spring, or stick, they’d say they are not, and that bonds are actually stable states that emerge from the electric forces between the charged particles making up atoms and molecules.*

Recall charge interactions. Present **slide L**. Read the text on the top:

- *Smaller particles make up atoms. Some have a charge.*

Discuss the prompts as a class to review how charged particles interact, as shown in the table below.

Suggested prompt	Sample student response
<i>Which of these particles would repel each other?</i>	Particles with the same charge repel each other. Electrons (negatively charged particles) push each other away. Two protons (positively charged particles) repel each other.
<i>Which of these particles would attract each other?</i>	Particles with different charges attract each other. Electrons and protons would be attracted.

ADDITIONAL GUIDANCE

Slides K-L are designed to help students quickly recall their prior models for these particles and their interactions. If they have taken OpenSciEd Chemistry, they have developed and used several models that could apply here. Eliciting these ideas supports making sense of the behavior of the magnets in the next model.

5 · DISCUSS MODEL 2

6 min

MATERIALS: *Evaluating Models*, <https://youtu.be/K3m2x6Vtj4I>

Introduce Model 2. Say, *The second model we're going to evaluate uses magnets to simulate the interactions between the nucleus of an atom and the electrons that produce bonds between atoms in a solid. As with Model 1, we'll use a video to orient to Model 2 and discuss what is happening through any lens that you choose.*

Present **slide M**. Open <https://youtu.be/K3m2x6Vtj4I> and display it to the class. Turn the captions on. This video shows particle-level interactions, using magnets of different sizes to represent the nucleus and electrons of an atom. It includes the following prompts:

- *What relationships do you notice between the distance between the magnets and the forces acting on them?*
- *Predict what you think the net force will be on these parts as we bring them together.*
- *What does this tell us about the magnitude of the repulsive versus attractive forces acting on the magnets at this point in the system?*

Pause the video when each prompt is displayed, and have students turn and talk about it before discussing it as a class. Rewind and replay any section that you think supports this discussion.

6 · IDENTIFY ADVANTAGES AND LIMITATIONS OF MODEL 2

3 min

MATERIALS: *Evaluating Models*, Scale Chart poster, M-E-F poster, M-E-F expansion panels

Evaluate Model 2. Present **slide N**. Give students a moment to consider how Model 2 helps us explain how/why any of our listed phenomena occur. Then cue them to record the model's advantages (merits) and limitations on their handout, as well as the lens they are using to evaluate it.

7 · BRAINSTORM FEATURES OF A SIMULATION

3 min

MATERIALS: *Evaluating Models*

Brainstorm about a simulation. Say, *To prepare to use a third model, which is a particle-level computer simulation, let's specify what we think it should have or do, based on our model evaluation work so far.* Present **slide O**. Discuss the prompts as a class, as shown in the table below.

Suggested prompt	Sample student response
<i>What parts and interactions would we need/want in a particle-level simulation to make progress on our questions?</i>	We need atoms or molecules that can move when forces are acting on them. Bonds between particles.
<i>What characteristics of the matter could affect some of these interactions?</i>	Its size (dimensions). The type of material. Temperature.

Suggested prompt	Sample student response
What would we want to be able to visualize or measure in this simulation?	A measure of the amount of energy transferred. I would like to see a representation of the forces. Particle movement.
Say, Let's compare the features we specified to the simulation I have for us, and consider how we could use it to design investigations to help answer some of our questions.	

8 · INTRODUCE THE SIMULATION AND PLAN INVESTIGATIONS

5 min

MATERIALS: *Particle Investigations*, science notebook, *Evaluating Models*, https://youtu.be/D8QZMCO5_oc

Orient to the simulation. Present **slide P**. Play the video https://youtu.be/D8QZMCO5_oc to introduce the simulation's assumptions, representations, and variables. Distribute the *Particle Investigations* handout.

ALTERNATE ACTIVITY

Extension opportunity: For those who are interested, the simulation has an information tab that describes the model's rules further, as well as a code tab that lets students inspect, modify, and recompile the code for the model.

No attempt is made to explain the simulation's underlying code, which emulates the effect of electric forces between particles by using an equation that calculates the combined effect of repulsive forces (e.g., between positive nuclei) and attractive forces (between nuclei and shared electrons). The code uses a twelfth-order potential energy equation known as the Lennard-Jones potential (LJ potential) to derive the net force versus distance relationships. Understanding this relationship is not a target DCI for high school.

Prepare for the investigation. Present **slide Q**. Assign students to groups of 2-3. Read the task instructions aloud:

- *Decide which independent variable each person will investigate.*
- *Record this on Part 1 of your handout.*



Have students store *Particle Investigations* in their science notebooks. Collect *Evaluating Models* before the end of the class period.

ASSESSMENT OPPORTUNITY

What to look for/listen for:

- Use evidence generated by the model to discuss the mechanism(s) the model helps explain in terms of matter changes and/or M-E-F interactions. (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2)
- Use a crosscutting lens (stability and change, thinking across scales, and/or cause and effect) to discuss the advantages and limitations of the model to further explain or test plate changes, breaking, and elastic deformation. (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2)

See the *Evaluating Models Key* for sample responses.

What to do: If students need additional practice, return the *Evaluating Models* handout toward the end of the next class period, and tell them to use the row for Model 3 to evaluate the advantages (merits) and limitations of the simulation we used.

Building toward: 4.A Evaluate the merits and limitations of different models using a crosscutting lens (stability and change, thinking across scales, or cause and effect) for understanding and explaining different phenomena (earthquakes) and mechanisms (elastic deformation, cracking/breaking). (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2)

End of day 1

9 · NAVIGATE: USE THE SIMULATION TO CARRY OUT A SERIES OF INVESTIGATIONS

15 min

MATERIALS: science notebook, *Particle Investigations*, computer with access to <https://opencied-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.htm>



Carry out investigations. Present slide R. Distribute a computer with access to <https://opencied-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html> to each group. Instruct them to take out the investigation plans they previously wrote on their *Particle Investigations* handouts and follow the instructions on the slide:

- Review your investigation plan.
- Carry out Investigations 1-4 and record your results.

Give them 14 minutes to complete the investigations and document the results. *

ASSESSMENT OPPORTUNITY

What to look for/listen for: See the *Particle Investigations Key*. It includes a brief explanation of the goal of each investigation (1-4) and what to look for in student responses.

What to do: Encourage students to consider how their findings provide additional insight into how/why different phenomena happen that we have been trying to explain (earthquakes, elastic deformation of solid matter, and cracks/breaking).

Building toward: 4.B.1 Use a computational model to explore stability and change and cause-and-effect relationships between the magnitude of external forces acting on a solid, the changes in matter given its mass (number of particles), and the changes in energy in the system across different scales. (SEP: 2.3; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS3.B.2, PS2.B.3, ESS2.B.2)

* ATTENDING TO EQUITY

Universal Design for Learning: Provide multiple means of representing these findings. In Investigation 1, students can record both qualitative and quantitative data. They can also use tables or graphs. If they record only quantitative data, encourage them to write a conclusion summarizing their findings. If they include only qualitative data, encourage them to support their ideas with a couple of data points. For Investigations 2-4, which are brief, encourage students to record several observations at the very least.

Adjust the simulation speed using the setting located at the top. Some students with disabilities might benefit from using a lower speed to more easily track changes in the system.

10 · PREPARE FOR A SCIENTISTS CIRCLE

3 min

MATERIALS: *Particle Investigations*

Share results with a partner. Present **slide S**. Ask students to share with a partner how the changes in their independent variable affected the outcomes in the simulation. It is OK if they only get to discuss their results from Investigation 1; this is enough to prepare them to share all their findings in the Scientists Circle.

11 · UPDATE THE M-E-F POSTER

13 min

MATERIALS: Breaking Foam Panels, *Particle Investigations*, M-E-F poster, M-E-F expansion panels, Scale Chart poster, 3x5 sticky notes, clear tape, chart paper markers

Facilitate a Consensus Discussion in a Scientists Circle. Display **slide T**. Have students bring their *Particle Investigations* handout to a Scientists Circle. Tell them explicitly, *As in all Consensus Discussions, my role is to give everyone time to consider each proposed idea and weigh in on those ideas. Today we'll consider additions to our M-E-F poster. I'll need everyone to weigh in on those before we add anything to it.* *

SCIENTISTS CIRCLE



Having students sit in a circle facing one another is a key structure in building a sense of shared mission and a community of learners working together. This is also a good opportunity to have them briefly recap the logistics for forming a Scientists Circle. Challenging the class to see how smoothly and quickly this transition can be achieved in each subsequent gathering can refine its timing. After another round or two of attending to this goal, it becomes something that can take fewer than 30 seconds to carry out.

Discuss macroscopic changes. Use the foam panel with a narrow middle section for a demonstration to establish the relationship between changes in external forces applied to a system and macroscopic changes in its matter. This supports considering differences in particle-level forces at different parts of the system. Say, *Let's use some of the M-E-F prompts and our ideas from all three models to see how particle-level thinking can help us better explain the changes in matter that we've observed.*

Hold up a double V-notched foam piece (3" x 12" x ½"). Compress it with your hands from both ends until it is in a slightly bowed shape, before it starts cracking. Ask, *What changes do we see in this matter right now?* Listen for the following observations:

- The foam is bending.
- The foam is changing shape.



Discuss how forces acting on the system affect the matter. Say, *We saw in the simulation that paying attention to changes in particles helped us explain changes in shape. Let's consider what's happening at the particle level here.*

Present **slide U**. Use the prompts to elicit ideas about the demonstrated changes in the foam:

- Consider whether forces acting on particles are balanced or unbalanced in the following conditions:
 1. No external forces are acting on the foam.
 2. Forces start bending the foam.
 3. Forces stop bending the foam, but keep it bent.
 4. Forces continue bending the foam, and cracks appear.
 5. The foam breaks into two pieces.
- What is happening to the particles along this sequence?

The class discussion may play out as shown in the table below.

* STRATEGIES FOR THIS CONSENSUS DISCUSSION

As this is early in the unit, it is helpful to be explicit now about your role in a Consensus Discussion, so when you say "consensus" in future lessons and units, students will recognize the goal of the work and your role in it.

Encourage student-to-student talk with a focus on representing how all their group's ideas compare to the ideas others have shared. Emphasize first restating what others said, before adding to it or saying whether there is agreement. Students can also use head nods or hand signals to show they had a similar idea.

Similarly to how we have developed the M-E-F poster so far in this unit, use student ideas to incrementally add annotations to it after class-wide agreement is established for a related set of ideas or ways of thinking/questioning.

* SUPPORTING STUDENTS IN DEVELOPING AND USING ENERGY AND MATTER

One purpose of the prompts in the M-E-F poster is to assist students in making sense of changes in energy within a system. By being prompted to observe macroscopic changes in matter and in the net force acting on a system, they begin to identify how interactions among the system's

Suggested prompt	Sample student response
<i>What is happening at the particle level as I change the shape of this foam?</i>	The particles move. The distance between particles increases and/or decreases.
<i>As the shape of the foam changes, are the forces on its particles balanced or unbalanced?</i>	Unbalanced.
<i>When I stop pushing but hold the foam bended, are the forces on its particles balanced or unbalanced?</i>	Balanced.
<i>What will happen if I continue bending the foam?</i>	It will break. It will crack.
<i>When cracks start to form, what will happen to the forces on the particles along where the cracks form?</i>	The forces will be unbalanced because particles will start moving. The bonds will break.
<i>So in both cases, breaking and elastic deformation, the motion changes happening at the particle level are due to unbalanced forces on the particles?</i>	Yes.

Discuss particle-level changes in the system. Present slide V. Lead students to summarize the role of unbalanced forces with the prompt:

- *What causes all changes in motion, whether the motion is at the particle level or macroscopic?*

They should say that unbalanced forces cause all changes in motion. Point out that we have seen unbalanced forces cause several types of changes: motion, shape change, and breaking. Suggest we use this insight to simplify the entire set of changes listed under the “Matter” section on the M-E-F poster, as these are all changes in motion.

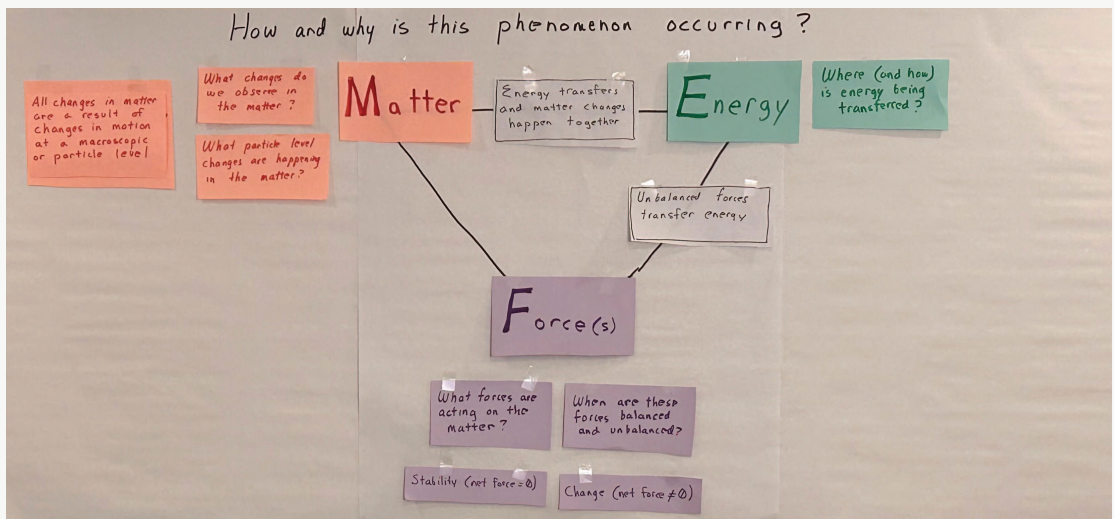
components help explain the changes in matter and energy, both macroscopically and at the particle level.

*** SUPPORTING STUDENTS IN DEVELOPING AND USING ENERGY AND MATTER**

You may want to ask for additional examples of phenomena from students' prior work in Chemistry that involved explaining energy changes in terms of kinetic energy of particles and/or energy stored in fields. Examples they may cite:

- In *OpenSciEd Unit C.1: How can we slow the flow of energy on Earth to protect vulnerable coastal communities?* (*Polar Ice Unit*): The phenomenon was melting polar ice caps and sea level rise due to changes in atmospheric composition. The particles were molecules making up water, land, and air, and their motion was related to temperature changes in the system.
- In *OpenSciEd Unit C.2: What causes lightning and why are some places safer than others when it strikes?* (*Electrostatics Unit*): The phenomenon was lightning. The particles were displaced electrons in the air, clouds, ground, and metal, and the positive nuclei left behind. The fields were electric fields between places where excess charges accumulated.
- In *OpenSciEd Unit C.5: How can chemistry help us evaluate fuels and transportation options to benefit the Earth and our communities?* (*Fuels Unit*): The design problem was related to alternate fuels for energy. The particles were atoms and shared electrons in bonds within molecules (for combustion reactions or batteries) or protons and neutrons (for fission reactions). The fields were electric for the former, and fields from strong nuclear forces for the latter.

The panel “Checklist of different matter changes” is covered with the panel “All changes in matter are a result of changes in motion at a macroscopic or particle level” in the top left corner of the M-E-F poster.



Emphasize that we will continue to use this idea as a way of explaining all changes we observe in matter. *

Discuss how the amount of matter affects the forces acting on it. Present slide W. Continue the discussion with the prompts, as shown in the table below.

Suggested prompt	Sample student response
Where do we think the foam will break?	It will break in the narrow middle section.
How do the number of particles across this section compare to the rest of the sample?	There are fewer particles here.
Why would this lead to a higher magnitude of internal force per particle in this section, compared to other parts of the matter?	(Accept all answers.)

Introduce a term used to describe forces on particles. Say, *When scientists consider the average amount of force per particle, they sometimes refer to this as “pressure.”* Ask for another example of hearing the term *pressure* referring to this sort of force. Students who completed *OpenSciEd Unit C.5: How can chemistry help us evaluate fuels and transportation options to benefit the Earth and our communities? (Fuels Unit)* may provide examples of force on a piston surface due to particle collisions in a combustion engine.

ADDITIONAL GUIDANCE

Supporting emergent multilingual learners: If students use words like *stress* or *strain* to refer to what was happening in the simulation outcomes, it may be helpful to reinforce that scientists sometimes describe matter changes in this way. Help all students use a common understanding, and increase the *relevance* of these words at this point, by mapping the use of the words to (1) everyday language and to (2) the M-E-F ideas.

Start by asking for an example of seeing someone use a strainer in food preparation to separate something. Reference the “Matter change” corner of the M-E-F poster, and say that the scientific measure of *strain* has a similar meaning, as it is a measure of how much the matter in a solid separates. Specifically, it is the ratio of the amount of deformation to the original length of the sample.

Then note that “pressure” or “stress” is used in everyday language about people’s feelings. Ask for examples of external things that can cause those feelings. Reference the “Matter force” corner of the M-E-F model, and say that the scientific measure of *pressure* or *stress* is similar, as it is a measure of the internal forces within a section of a solid, often in response to external forces. Specifically, it is also a ratio—either the ratio of force to area (of matter) or force per particle.

Keep in mind that these terms are not needed in future lessons, so they do not need to be entered in students’ Personal Glossaries.

Present **slide X**. Slowly bend the foam to its breaking point, asking students to pay attention to what they see happening. The foam will snap, and pieces may fly off. Turn the broken faces of the foam toward the class and point along it when you ask the questions shown in the table below.

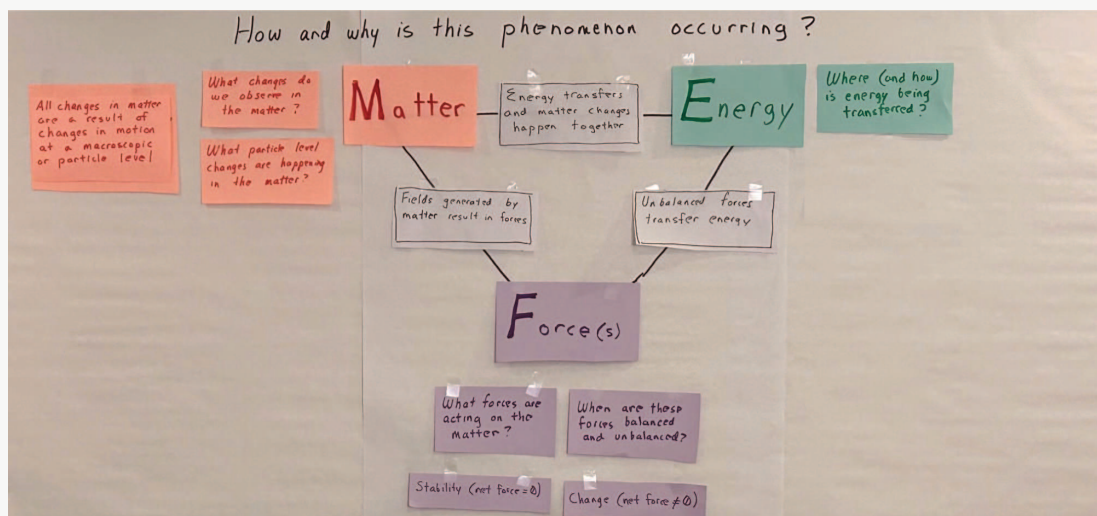
Suggested prompt	Sample student response
<i>What kept the matter from breaking apart along where it cracked before we reached the elastic limit?</i>	The bonds between the neighboring particles.
<i>What types of forces between protons and electrons produce those bonds?</i>	Electric.
<i>Do those same types of forces help explain why all solids, including the plates, could elastically deform up to a point?</i>	Yes.

ADDITIONAL GUIDANCE

The next couple of minutes foreground two aspects of energy thinking. This is necessary to help upend (or at least call into question) prior ways students may have encountered for conceptualizing or referring to potential energy. Keep the discussion focused on the distance between particles and changes in their motion to make sense of energy transferred and energy stored in and out of the system.

Identify the role of fields. Say, *We have argued that electrons and protons produce electric fields. So, because all atoms have these particles, we can say that all matter produces fields. In a solid, these electric fields produce forces that act on neighboring particles in ways that explain all sorts of macroscopic behavior.* Update the M-E-F poster.

The “Fields generated by matter result in forces” panel is added between the “Matter” and “Force(s)” panels on the line connecting them on the M-E-F poster.



ALTERNATE ACTIVITY

You might want to invite students to suggest updates to the M-E-F poster to reflect the ideas developed during this discussion. Ask questions such as:

- What components and interactions connect “Forces” and “Energy”?
- How are fields related to matter, energy, and forces?

Say, *Let’s see how this idea of fields can also be used to help explain how energy is transferred and stored in the system.*

ADDITIONAL GUIDANCE

You may want to emphasize the limitations of using the term *potential energy* to describe the energy stored in a system, especially if students are already familiar with it. You can say something like: *Scientists sometimes refer to the energy stored in systems like this as “potential energy.” But this term can be problematic, because it doesn’t help in tracking the energy or identifying what part of the system it’s stored in. The phrase “potential energy” also doesn’t have any explanatory power, because it’s often isolated from thinking about unbalanced forces--which we’ve discovered is the mechanism behind all energy transfer.*

Connect to prior discussions. Continue by saying, *When the foam is being held in this stable bent shape, there’s no measurable energy increase in the system, like increased kinetic energy or temperature. So, we need to find a way to describe exactly where the energy is being stored; otherwise, we won’t be able to account for conservation of energy--something that we know should occur in every process. When changes in the distance between objects or between particles acting on each other through fields affect the amount of energy stored in the system, scientists say the energy is being transferred into or out of, or stored in, the fields.*

Discuss matter and energy relationships. Present slide Y. Continue the discussion with the prompts, as shown in the table below. Encourage students to refer to their *Particle Investigations* as needed.

Suggested prompt	Sample student response
<i>What was the relationship between changes in the distance between particles and changes in the energy stored in the electric field(s) in the simulation?</i>	Greater changes in distance result in greater amounts of energy being stored in the electric fields.
<i>Can we store unlimited amounts of energy in those electric fields, or was there a limit?</i>	There was a limit. When the material breaks, we can't store more energy in it.

Use our new ideas to explain earthquakes. Present slide Z. Discuss the prompts, as shown below.

Suggested prompt	Sample student response
<i>How does the scale of a plate, and the number of particles that make up its matter, affect the amount of energy that can be stored in the electric fields between the particles before part of the plate reaches an elastic limit?</i>	Plates have a lot of mass, which means they have a lot of particles, so they have more electric fields between particles that can store energy.
<i>We know the motion of the plates is relatively slow. What does that tell us about why there are periods of apparent stability between earthquakes in any given region?</i>	It takes a long time for the amount of energy stored in the system to build up. It takes a long time for the system to be deformed enough (again) to reach another elastic limit.

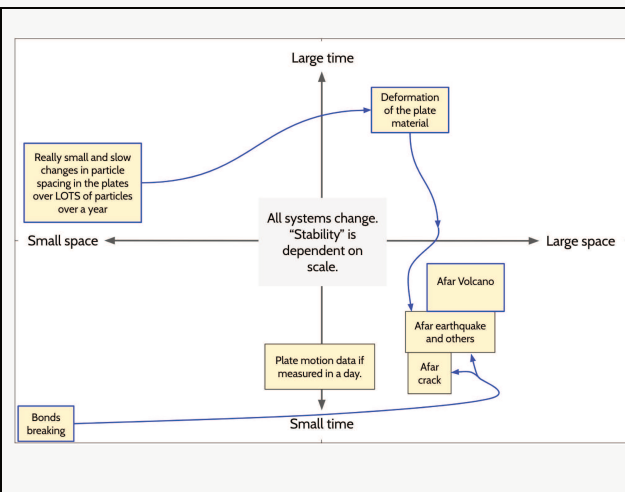
Revise the posters. Present slide AA. Emphasize that we can now say that what happens at a very small scale--the particle level--can explain changes in the plates at a much larger scale, including earthquakes and cracks. Part of the explanation is related to the amount of elastic deformation in the system, which steadily increases over time.

Note: Use yarn, string, or crafting wire and tape on paper arrowheads to add the following connections to the Scale Chart poster temporarily, so they can be removed before your next class--until your last class, when you can add these connections with a chart paper marker.

Add a sticky note for "Really small and slow changes in particle spacing in the plates for lots of particles over a year" on the left side.

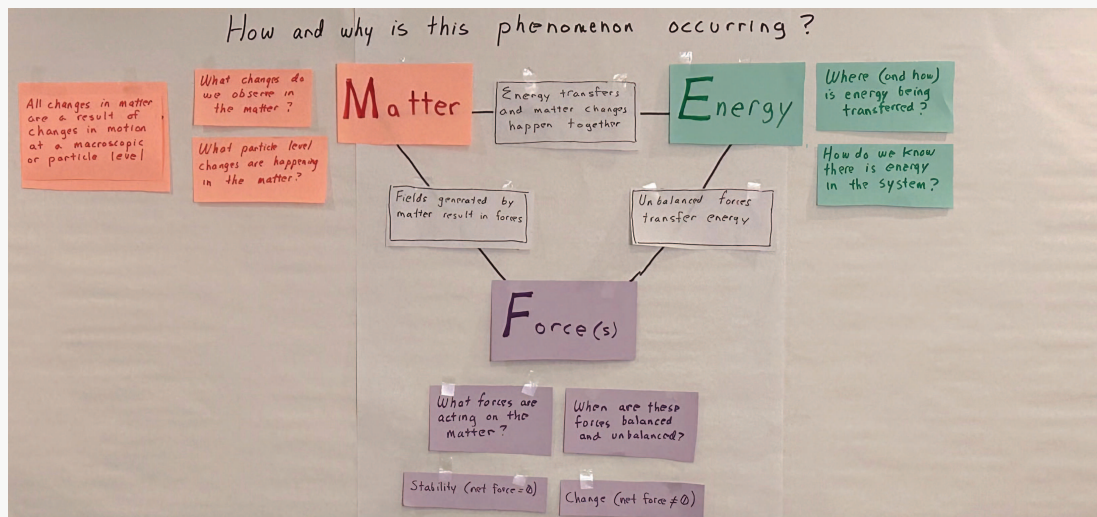
Add "Deformation of the plate material" to the first quadrant. Connect these with an arrow, and add another arrow to the Afar earthquakes and others.

Add "Bonds breaking" to the bottom left corner. Connect this to the Afar earthquakes and others, and to the Afar crack, with arrows.



As you update the M-E-F poster, ask how we knew whether electricity was transferring energy through the system for the electricity-powered devices in *Electricity Unit*. Students should say heat, light, and maybe sound coming from those devices. Validate these responses.

The “How do we know there is energy in the system?” panel is added to the top right corner of the M-E-F poster.



Summarize the relationship between particle-level changes and energy stored in matter. Point out that we are considering how energy is stored in systems in a new way, related to elastic deformation. Note that this involves thinking about the motion of particles in matter and the energy stored in the fields based on their relative positions in space.

Emphasize that in our prior unit, we also thought about electricity in terms of particle motion and fields transferring energy, though we didn't focus on how fields can store energy. Ask students to recall what particles we studied in that system, and what types of fields transferred energy from the generator through space to the wires. They should say electrons in wires, and electric and magnetic fields.

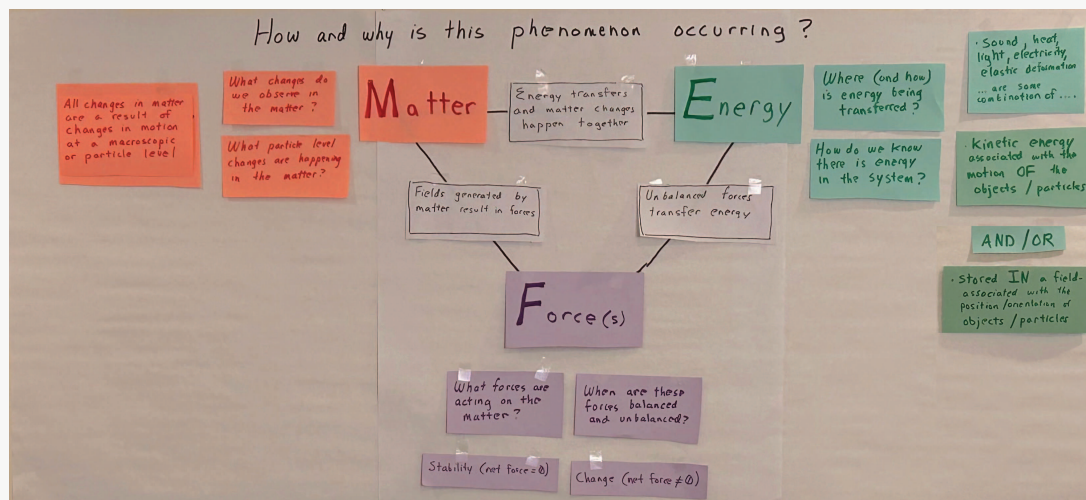
Summarize how to account for energy changes in a system. Point out that it is not only elastic deformation and electricity that can be broken down into a combination of one or two things that describe where energy is in the system and how it is transferred. We can also think in this way about the kinetic energy of objects (generators, magnets, plates) or particles (electrons, atoms, molecules) and the energy in fields (electric, magnetic).

Challenge students to keep this lens in mind going forward--we can, if needed, account for all changes in energy as a combination of changes in kinetic energy and changes in energy stored in fields, even if the everyday name we give to the transfer of that energy is “sound” or “heat”. *

Use these ideas to update the M-E-F poster.

The remaining 4 panels are added to the right side of the M-E-F poster:

- “Sound, heat, light, electricity, elastic deformation ... are some combination of:”
- “Kinetic energy associated with the motion of objects or particles”
- “and/or”
- “stored in a field associated with position/orientation between the objects /particles”



Emphasize that we just applied our M-E-F thinking to two Earth science phenomena, and going forward, we should recognize that we can now explain any Earth science phenomenon from a particle-level perspective. Point to the Scale Chart poster and its sticky note for volcanic eruption, and forecast that we will apply our thinking to this phenomenon in the upcoming Electronic Exit Ticket.

12 · ASSIGN THE ELECTRONIC EXIT TICKET

12 min

MATERIALS: copy of https://docs.google.com/forms/d/1d7mdn_MMObL_bFfLV3eRkazg-AETeohRiBhXX7Z7sDE/copy made before class

 **Assign the Electronic Exit Ticket.** Before class, make a copy of https://docs.google.com/forms/d/1d7mdn_MMObL_bFfLV3eRkazg-AETeohRiBhXX7Z7sDE/copy. Share the link to the copy with students (do not share the original link, as that will create a new copy for each student, and you will not have access to their responses). Present slide BB. Give them 10-12 minutes to complete the Electronic Exit Ticket individually.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Use the *Electronic Exit Ticket Key* to assess student work.

What to do: The Electronic Exit Ticket addresses 3D elements associated with a lesson-level performance expectation (LLPE) for Lesson 4. This assessment is designed to make it easy to gather information about where students are still struggling to put the pieces together.

Building toward: 4.B.2 Use a computational model to explore stability and change and cause-and-effect relationships between the magnitude of external forces acting on a solid, the changes in matter given its mass (number of particles), and the changes in energy in the system across different scales. (SEP: 2.3; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS3.B.2, PS2.B.3, ESS2.B.2)

MATERIALS: None

Navigate into Lesson 5. Present **slide CC**. Ask students to raise their hand (yes or no) in response to the prompt:

- *Can we fully explain what is happening at Afar, or do we need more information/data?*

Establish agreement that because the Afar events didn't happen at a plate boundary, something must be going on there that is different from what we think is happening for most earthquakes, or for the volcanic eruption in the Electronic Exit Ticket, which did occur near a plate boundary. We need some additional data/information to figure out the case sites that appear to be exceptions.

ALTERNATE ACTIVITY



Extension opportunity: You can assign home learning if you want to provide students with additional practice in engaging with *developing and using models*. Present **slide DD**, and suggest they identify the simulation's advantages and limitations by filling in the last row of the *Evaluating Models* handout.

The second prompt encourages students to add new meanings to their Personal Glossaries. Use it if you think some students might benefit from this.

Additional Lesson 4 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

CCSS.ELA-LITERACY.SL.11-12.1 Initiate and participate effectively in a range of collaborative discussions (one-on-one, in groups, and teacher-led) with diverse partners on grades 11-12 topics, texts, and issues, building on others' ideas and expressing their own clearly and persuasively.

Four discussions are integrated into this lesson: two with different pairings of students for video analysis on day 1, one in small groups to compare investigation findings, and one whole-class Consensus Discussion on day 2. These provide multiple opportunities to engage in this speaking and listening standard. This lesson's focal Community Agreement further foregrounds the importance of student contributions that are recognized and valued by their peers; the last question on the Electronic Exit Ticket has students reflect on this as well.

LESSON 5: How do we investigate the connection between matter in Earth's interior and surface features above?

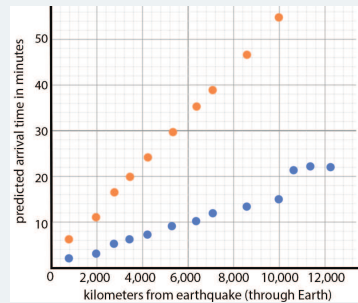
PREVIOUS LESSON

We evaluated two models for understanding and explaining earthquakes, elastic deformation, and breaking of solid matter. We used a computer simulation to investigate how external forces on a solid affect matter changes and energy transfers at the particle level. We revised our M-E-F and Scale Chart posters to account for the roles of fields on large-scale phenomena, and used these ideas to explain volcanic eruptions in an Electronic Exit Ticket.

THIS LESSON

INVESTIGATION, PUTTING PIECES TOGETHER

3 days



We wonder what could be happening in Earth's interior to cause unbalanced forces. We learn that energy transfers differently through different types of matter, and that scientists use this to collect indirect evidence about Earth's interior. We analyze seismic wave data and notice wave speed anomalies that suggest Earth's interior is not entirely solid. We analyze a model of Earth's layers and use a simulation to test our predictions about seismic energy transfers at plate boundaries. We zoom in to a local scale to investigate the connection between mantle matter properties and surface features at locations across the globe. We revise our model of Earth's layers to include a heterogeneous mantle and add to our Progress Trackers.

NEXT LESSON

We will develop a predictive model of the mantle movement. We will analyze a video of a tank containing a mixture of liquid and plastic pellets simulating the matter in the mantle to figure out what happens to the matter when heat is added. We will observe convection in the tank and develop a model to represent it.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

5.A Analyze mathematical representations of indirect data to reveal anomalies in the pattern of arrival times for seismic waves to support a claim about the relationship between wave speed and the medium through which the wave is passing in Earth's interior. (SEP: 4.1, 5.2; CCC: 1.4, 3.2; DCI: PS4.A.1, ESS2.A.2)

5.B Analyze seismic velocity anomaly data at multiple scales and evaluate the impact of this data on our working model of Earth's interior to provide evidence for a causal link between local matter variation in Earth's mantle and surface features, such as mountains, volcanoes, and cracks. (SEP: 4.1, 4.5; CCC: 1.1, 1.2; DCI: ESS2.A.2, PS4.A.4)

WHAT STUDENTS WILL FIGURE OUT

- The speed of a wave through matter depends on the matter through which it is passing.
- Seismic velocity data provide evidence that Earth is composed of layers.
- Earth has a solid inner core, a liquid outer core, a mantle, and a crust.
- Differences in matter in the mantle cause unbalanced forces in different locations, which is why some regions have different kinds of surface features than others.

Lesson 5 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	5 min		NAVIGATE Review explanations from Lesson 4 to consider what causes most earthquakes.	A-C	Initial Class Consensus Model (from Lesson 1)
2	15 min		READ ABOUT INVESTIGATING EARTH'S INTERIOR Read <i>How Do Scientists Explore Earth's Interior?</i> in partners using a close reading protocol. Answer the questions and be ready to discuss as a class.	D	<i>How Do Scientists Explore Earth's Interior?</i>
3	5 min		BUILD UNDERSTANDING ABOUT SEISMOLOGY Conduct a Building Understandings Discussion structured by the questions in the reading. Establish that energy travels in seismic waves and that the waves' speed is affected by the medium they are passing through.	E-F	<i>How Do Scientists Explore Earth's Interior?</i> , Scale Chart poster
4	5 min		BUILD UNDERSTANDING ABOUT P-WAVES AND S-WAVES Continue the Building Understandings Discussion. Establish how seismic waves move through matter, and notice patterns in seismic data.	G-I	<i>How Do Scientists Explore Earth's Interior?</i> , M-E-F poster
5	5 min		TEST OUR IDEAS AND MAKE INFERENCES Analyze and interpret graphs of seismic arrival times to reveal anomalies that suggest a heterogeneous Earth.	J-L	<i>How Do Scientists Explore Earth's Interior?</i>
6	10 min		NAVIGATE Discuss a model of Earth's layers in partners. Complete an exit ticket about the layers.	M-N	<i>How Do Scientists Explore Earth's Interior?</i> , <i>Earth's Interior Model</i> , loose-leaf paper
End of day 1					
7	5 min		NAVIGATE Review what we figured out about P-waves and S-waves in Earth's liquid outer core. Reflect on a crosscutting idea.	O	
8	10 min		TEST OUR IDEAS WITH A SIMULATION Observe seismic waves in a simulation passing through Earth, with S-waves dissipating and P-waves slowing down. Make sense of the energy transfer, in particular that energy from S-waves must be absorbed and reflected at the mantle-core boundary, in a Building Understandings Discussion.	P-Q	device with access to http://ds.iris.edu/seismon/swaves/index.php?lat=34.2&lon=-118.5&depth=17&mag=6.7&title=Northridge%201994&date=1994-01-17T12:30Z&w_terrain=false&wiki=https%3A%2F%2Fearthquake.usgs.gov%2Fearthquakes%2Fstates%2Fevents%2F1994_01_17.php
9	15 min		READ ABOUT EARTH'S MANTLE Read about Earth's mantle and answer Making Sense questions. Consider a closer look at the mantle.	R-S	<i>Earth's Interior Model</i> , <i>The Mantle and the Moho</i>

Part	Duration		Summary	Slide	Materials
10	10 min		USE A DIGITAL TOOL TO COMPARE THE MANTLE BENEATH AFAR TO OUR REGION Use the SubMachine web tool to generate models of mantle cross sections beneath the Afar region and our region. Record observations of seismic wave anomalies on a local scale.	T-U	<i>Investigating Cross Sections of the Mantle</i> , colored pencils, device with access to https://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section
11	5 min		UPDATE THE PERSONAL GLOSSARY Add new words to Personal Glossaries.	V	<i>How Do Scientists Explore Earth's Interior?, The Mantle and the Moho</i>
End of day 2					
12	8 min		NAVIGATE AND RETURN TO THE DRIVING QUESTION BOARD Consider which questions on the DQB might be addressed by investigating properties of the mantle on a local scale.	W	
13	13 min		INVESTIGATE ADDITIONAL MANTLE CROSS SECTIONS Use SubMachine to investigate cross sections of Earth's mantle in pairs. Investigate three locations and record any observed patterns on the handout.	X	<i>Investigating Cross Sections of the Mantle</i> , device with access to http://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section , <i>Longitude and Latitude Coordinates for Mantle Cross Sections</i> , colored pencils
14	13 min		BUILD UNDERSTANDING ABOUT THE MANTLE Identify patterns in the types of anomalies beneath various categories of surface features in a Building Understandings Discussion. Revise our model of Earth's mantle to include local-scale heterogeneities.	Y-AA	<i>Investigating Cross Sections of the Mantle, Earth's Interior Model</i>
15	11 min		NAVIGATE AND UPDATE THE DRIVING QUESTION BOARD AND PROGRESS TRACKER Revisit the Scale Chart poster, return to the DQB, and add to the Progress Tracker. Consider different temperatures in the mantle as an exit ticket.	BB-DD	<i>Progress Tracker</i> , sheet of loose-leaf paper, Scale Chart poster, Driving Question Board, chart paper markers
End of day 3					

Lesson 5 • Materials List

	per student	per group	per class
Lesson materials	• <i>How Do Scientists Explore Earth's Interior?</i> • science notebook • <i>Earth's Interior Model</i> • loose-leaf paper • <i>The Mantle and the Moho</i> • <i>Investigating Cross Sections of the Mantle</i> • colored pencils • <i>Progress Tracker</i> • sheet of loose-leaf paper	• device with access to https://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section • <i>Longitude and Latitude Coordinates for Mantle Cross Sections</i> • colored pencils	• Initial Class Consensus Model (from Lesson 1) • Scale Chart poster • M-E-F poster • device with access to http://ds.iris.edu/seismon/swaves/index.php?lat=34.2&lon=-118.5&depth=17&mag=6.7&title=Northridge%201994&date=1994-01-17T12:30Z&w_terrain=false&wiki=https%3A%2F%2Fearthquake.usgs.gov%2Fearthquakes%2Fstates%2Fevents%2F1994_01_17.php • device with access to https://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section • Driving Question Board • chart paper markers

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 handouts so they can be added to students' science notebooks.

Make copies of the handouts for this lesson:

- *How Do Scientists Explore Earth's Interior?* - 1 per student
- *Earth's Interior Model* - 1 per student
- *The Mantle and the Moho* - 1 per student
- *Investigating Cross Sections of the Mantle* - 1 per student
- *Longitude and Latitude Coordinates for Mantle Cross Sections* - 1 per student pair

Before using SubMachine with students, make sure you know how to generate cross sections. View <https://youtu.be/mcJl6fyBwCk?si=ALTxOY6cfiK-RUh4> for further guidance.

For the investigation using SubMachine on day 2, be prepared with the coordinates of your location.

Follow these steps to get the coordinates of a location:

1. Open Google Maps: <https://www.google.com/maps>
2. Enter the search term of the place or area you are exploring and press "Search".
3. Right-click the name of the place or area on the map, which opens a pop-up window. At the top of the pop-up window are two numbers that correspond to the latitude and longitude of that location.

Introduce the coordinates in SubMachine:

1. Open the SubMachine tool website https://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section in a different tab.
2. Enter the first value obtained in Google Maps in the Latitude 1 and Latitude 2 fields.
3. For longitude, subtract 10 from the second value obtained in Google Maps and enter that in Longitude 1. Add 10 to the second value obtained in Google Maps and enter that in Longitude 2.

Lesson 5 • 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):

- **PS4.A.1: Wave Properties.** ~~The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing. (HS-PS4-1)~~
- **PS4.A.4: Wave Properties.** Geologists use seismic waves and their reflection at interfaces between layers to probe structures deep in the planet. (secondary to HS-ESS2-3)
- **ESS2.A.2: Earth Materials and 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. (HS-ESS2-3)

For the first Wave Properties DCI, the ideas struck out about the type of wave will be developed in *OpenSciEd Unit P.5: How do we use radiation in our lives and is it safe for humans? (Microwave Unit)*. For the Earth Materials and Systems DCI, the ideas struck out about changes to Earth's surface will be covered later in the unit as we look for clues about what happened at Afar in the past and what will happen in the future.

This lesson addresses ideas that are fundamental to the performance expectation HS-ESS2-1:

- Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.

These ideas are not necessarily well articulated in DCIs. They include mantle heterogeneity at multiple scales as well as the connection between surface features and activity in Earth's interior. In Lesson 6, students will make the connection between heterogeneity and convection, building toward the following DCI:

- **ESS.3: Plate Tectonics and Large-Scale System Interactions.** Plate movements are responsible for most continental ~~and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust.~~ (HS-ESS2-1)

ESS2.B.3 is only partially covered. Students consider how the things we have figured out about the mantle might explain plate motions we observed in earlier lessons. They will continue to grapple with this idea in future lessons, and layer on ideas about friction and mid-ocean ridges. For this reason, it is not claimed in this lesson, even though we are building toward it.

This lesson is designed to support students toward the Next Generation Science Standards (NGSS) Nature of Science Understanding titled **Scientific Knowledge Is Based on Empirical Evidence** (Appendix H). The relevant understanding element is:

- Science includes the process of coordinating patterns of evidence with current theory.

Students encounter and/or co-construct ideas around several terms, and may decide to add the following words to their Personal Glossaries during this lesson: *seismic waves*, *Moho*, *anomaly*, *heterogeneous*, and *homogeneous*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

Students notice that Earth is heterogeneous, but they do not use evidence to fully construct a model of the interior. Instead, they are introduced to a model, and they need to decide whether it matches the evidence they have.

LEARNING PLAN for LESSON 5

1 · NAVIGATE

5 min

MATERIALS: Initial Class Consensus Model (from Lesson 1)

Navigate by reviewing what causes most earthquakes. Present **slide A**. Pose the questions on the slide:

- *What did we figure out about what causes most earthquakes?*
- *How does this explanation also help us understand volcanic eruptions?*

Encourage students to describe some of the interactions they saw when they worked with the foam. Listen for ideas about the edges or boundaries of plates (or pieces of foam). Students may say that earthquakes happen at plate boundaries, or when two chunks rub together or collide.

Revoice these ideas in M-E-F language by saying, *I hear you telling me we found a connection between two plates meeting, a plate boundary, and earthquakes or volcanoes. The force interactions at these boundaries transfer the energy that we then experience as earthquakes or, as in the Electronic Exit Ticket, volcanic activity.*

Problematicize Afar not being at a plate boundary. Present **slide B**. Say, *But we noticed in Lesson 1 that the events in East Africa that we thought were connected to the Afar region didn't appear to be along an established plate boundary, right?*

Give students a moment to consider this gap in our current model. Then point to the class consensus model and pose the question on the slide:

- *Looking back at our consensus model, what ideas did we have that could explain where the forces come from to cause earthquakes, volcanic eruption, and breaking in the Afar region?*

Listen for ideas about magma, lava, the mantle, or anything else beneath Earth's crust. If these do not surface quickly, ask, *Could there be something underneath the crust that might be applying forces?* Listen for students to agree that it would be worth looking into.

Talk about how to investigate beneath Earth's surface. Present **slide C**. Have students turn and talk for a minute about the prompt:

- *What data could we use to investigate the matter below Earth's surface to explain where the forces might be coming from to cause earthquakes, volcanic eruption, and breaking where there are no clear plate boundaries?*

Elicit 2-3 ideas. Listen for students to suggest data taken from digging into Earth's crust or retrieving samples, from lava that comes out of volcanoes, seismic data, X-rays, or sonograms. Accept all ideas, but highlight ideas about seismic waves (if they come up) and obtaining samples by drilling/digging.

Say, *It's very tricky to get data about Earth's interior. In fact, we have more direct evidence for what makes up the surface of Mars, millions of miles away, than for what's a few miles beneath our feet! Let's read more about why it's so hard to gather data about Earth's interior, and what kind of evidence we can collect.*

2 · READ ABOUT INVESTIGATING EARTH'S INTERIOR

15 min

MATERIALS: *How Do Scientists Explore Earth's Interior?*

Do a close reading in partners. Present **slide D**. Distribute the *How Do Scientists Explore Earth's Interior?* handout to each student and direct their attention to the close reading protocol. Read the instructions aloud and allow time for clarifying questions:

1. *Read once for understanding. Underline words or ideas that are new or confusing.*
2. *Share your ideas with a partner. Discuss the questions we have as a class with your partner before reading again.*

3. Read a second time. As you read, highlight information that might help us answer our questions.
4. Respond to the Making Sense questions with a partner. Be ready to discuss with the class.

Give students 15 minutes to read the handout and respond to the questions in partners. If they do not have time to record their responses, tell them it is more important to discuss their ideas with their partner and be ready to share with the class. These questions are not intended to be assessed.

3 · BUILD UNDERSTANDING ABOUT SEISMOLOGY

5 min

MATERIALS: *How Do Scientists Explore Earth's Interior?*, Scale Chart poster

Discuss Earth's scale and the handout's first question. Present slide E. Ask a student to read the excerpt from the reading at the top of the slide, and ask another student to translate by explaining it in different words. They might say something like, "Earth is too big for us to observe with our eyes or collect samples from the inside, so we have to figure out what's inside of it in different ways."



Pose the slide's prompt, directing students to Making Sense Q1:

- *What other systems have we learned about that cannot be studied directly, and why? **

See the assessment callout below for expected responses.

ASSESSMENT OPPORTUNITY

What to look for/listen for:

- Students should list examples of **systems at various scales**, such as the solar system, the electrical grid, tectonic motion, or an atom.
- Students should recognize and explain that **scale affects our ability to collect empirical evidence. If something is too large, too small, or on too long a timescale, it is very difficult to observe directly.** (CCC: 3.2)

What to do: Provide examples if students are having trouble making this connection. Ask them to look across these systems, then ask, *What makes them so hard to observe?* Once the idea of too big and/or too small is on the table, give them a second chance to come up with examples of systems or phenomena.

Building toward: 5.A.1 Analyze mathematical representations of indirect data to reveal anomalies in the pattern of arrival times for seismic waves to support a claim about the relationship between wave speed and the medium through which the wave is passing in Earth's interior. (SEP: 4.1, 5.2; CCC: 1.4, 3.2; DCI: PS4.A.1, ESS2.A.2)

Discuss seismic waves and Making Sense Q2. Present slide F. Ask a student to read the excerpt at the top of the slide, and ask another student to translate as before. They might say something like, "The vibrations that come from an earthquake travel at different speeds, and scientists use that information to figure out the kind of matter the vibrations are passing through." If they struggle to articulate something complete, do not worry right now; we will spend time making sense of this later.

Then pose the slide's prompt, directing students to Making Sense Q2:

- *What evidence have we seen that vibrations can travel through solid matter?*

They may say that the particles in the matter in the simulation from earlier lessons exhibited vibrations when external forces were applied and removed. They also saw the springs and foam vibrate back and forth when they changed the net force applied to the system.

* SUPPORTING STUDENTS IN DEVELOPING AND USING SCALE, PROPORTION, AND QUANTITY

At this moment, students consider connections across disciplines by discussing other systems we have learned about. Help them see that scale affects how we collect data about a system. Examples they might come up with include the solar system, the electrical grid, tectonic motion, or an atom. If the opportunity arises, note that some systems are also difficult to study because of their temporal scale, and point to the Scale Chart poster from earlier in the unit. Examples might be natural selection and adaptation, climate change, or the life cycle of the sun.

4 · BUILD UNDERSTANDING ABOUT P-WAVES AND S-WAVES

5 min

MATERIALS: *How Do Scientists Explore Earth's Interior?*, M-E-F poster

Use an animation to build understanding. Present **slide G**. Say, *The reading described two kinds of seismic waves. I found an animation of P-waves that we can observe and make sense of.* Move through the slides' prompts with the class, as shown in the table below.

Suggested prompt	Sample student response
What do we know about P-waves that can help explain what is going on here?	They are basically sound waves, so they compress the matter, and then they expand again, which pushes on the particles around them, making them compress, and transferring energy.
If lines in the animation represent bonds between particles, where are the particles, and how are they moving?	They are at the intersections of the bonds. They are moving back and forth. *
What is actually traveling through the solid if it is not the particles themselves? *	Energy is moving through the solid.

KEY IDEAS

Listen for the following key ideas before moving on:

- Matter might vibrate or move back and forth in a wave, but it does not travel from one place to another.
- In a wave, energy transfers through the motion of matter.

Discuss P-waves, S-waves, and Making Sense Q3. Present **slide H**. Ask a student to read the excerpt at the top of the slide. Then pose the prompt, pointing students to Q3:

- Which type of wave should reach the seismic measurement stations first?

Students should say the P-waves should reach the stations before the S-waves. *

Identify and interpret patterns in the graph of arrival times. Present **slide I**. Remind students that when we see a new graph or other kind of data representation, it can be helpful to annotate it by first identifying patterns, without making any guesses about what those patterns mean. Then we can start to interpret them. Elicit observations of patterns using the slide's first prompt:

- What patterns can you identify on the graph?

Students may say the lines go up. Listen for someone to point out that the orange line stops and the blue line goes wonky after 10,000 km. Do not press if these ideas do not come up, as you can elicit ideas about anomalies on the next slide. Then pose the second prompt:

- What does each of the patterns that you identified mean?

Listen for students to explain that the lines go up because as the waves travel farther and farther, it takes longer and longer for them to arrive. They may or may not have an explanation for the anomalies right now. If a student suggests that these anomalies are due to differences in the state of the matter that the waves must pass through, say, *That's a really interesting idea. Let's keep it in mind as a strong hypothesis, and see whether we can reason through some additional evidence to support it.*

* SUPPORTING STUDENTS IN DEVELOPING AND USING ENERGY AND MATTER

Students might say that motion, compression, or vibration is moving through the solid. Point to the M-E-F poster developed earlier in this unit to prime them to think about matter-energy relationships. Use probing questions to help them clarify their thinking, and layer the appropriate scientific vocabulary onto their ideas if necessary. Questions you might ask include:

- When matter changes its motion, what is transferring through it, according to our M-E-F triangle?
- When you say "vibration," what do you mean? Is a vibration something that moves, or is it evidence of something else that is moving or transferring?

* ATTENDING TO EQUITY

Universal Design for Learning: Watch for students to move their hands back and forth, even if they are not articulating back-and-forth motion in words, and highlight this by saying, *It looks like you're moving your hands back and forth like this.* Allowing students to express their ideas using multiple modalities (such as gesturing) supports their ownership of their learning by giving them choice, access, and control in navigating their understanding around science ideas. It also supports students who are emergent multilingual learners.

* SUPPORTING STUDENTS IN DEVELOPING AND USING SYSTEMS AND SYSTEM MODELS

To support students in using ratio reasoning to understand data and make predictions, a logic they will apply over this course, follow

up by asking, *For this station that looks like it's twice as far away as this one, how much longer should it take the S-waves to arrive?* If you have time, give students a chance to discuss this with partners and make predictions. They should say that it should take twice as long. Sketch a line graph to illustrate that as the ratio of the distances increases, so does the distance between the data points of the arrival times of P-waves and S-waves.

5 min

5 • TEST OUR IDEAS AND MAKE INFERENCES

MATERIALS: *How Do Scientists Explore Earth's Interior?*

Motivate applying computational reasoning to test our ideas. Present slide J. Pose the first question:

- *Where do the data appear to be different from what we would expect (an anomaly)?*

Pause for a moment to make sure students have noticed the new word (anomaly) and can infer a definition from the question (where the data are different from what we expect). Consider recording this at the front of the room, or giving students a chance to record it in their Personal Glossaries. They will have a more formal chance to add to their glossaries at the end of the lesson.

Determine that there is a place on the graph where there is a break in the P-wave data, and the S-wave data disappears. If you are projecting on a whiteboard or interactive board, draw a line up the 10,000 km mark on the *x*-axis. Pose the slide's second question:

- *What could we do to test whether the data matches what we expect?*

Accept all reasonable ideas, but listen for students to suggest using the numbers in the reading. Say, *Let's see whether these data points are anywhere near the numbers we'd expect to get if the waves travel at the speeds given in the reading.*

Test data points to quantify the anomaly. Present slide K. Say, *One way we can test whether this is really an anomaly is by checking the speed that each wave was traveling. Remember, speed is just a measure of how far something goes in a certain amount of time, expressed as distance over time, like miles per hour or kilometers per second.*

Model the calculation first with the dot at 2,000 km. The P-wave appears to arrive at about 3 minutes, and the S-wave appears to arrive at about 11 minutes.

$$2,000 \text{ km} / (3 \times 60 \text{ seconds}) = 11.1 \text{ km/s}$$

$$2,000 \text{ km} / (11 \times 60 \text{ seconds}) = 3 \text{ km/s}$$

Have students check the reading to confirm that these speeds are roughly accurate. Then explain that we are going to test additional data points. Split the class down the middle, tell one half to choose another data point from Part 1 of the graph, and tell the other half to choose an anomalous data point from Part 2. Give students time to work out the math, and then ask them to share their findings with a show of hands, as shown in the table below. *

Suggested prompt	Student response
<i>Let's take a show of hands. For those who tested a data point that matched our expectations, how many got speeds that were very close to the numbers in the reading?</i>	(Look for students to raise their hands.)

* SUPPORTING STUDENTS IN ENGAGING IN ANALYZING AND INTERPRETING DATA

Follow up on outliers by asking which data point was tested. Demonstrate the math at the front of the classroom, and help students see that a slight deviation from the expected number is normal, as long as it is within 10%. If there is time, do the calculation to show that at about 12,000 km, the speed would be 13.3 km/s, which is 2 km/s away from the known speed of P-waves in a solid (11 km/s), a difference of almost 20%. On the other hand, the values in Part 1 should be within 10% (11 km/s).

* SUPPORTING STUDENTS IN THREE-DIMENSIONAL LEARNING

This is an opportunity to help students see that "...the speed of travel of [a] wave... depends on the...medium through which it is passing." This is part of the DCI element associated with the performance expectation HS-PS4-1: "Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media." This performance expectation and the associated DCI are addressed primarily in [material:pr], when students derive the relationship between frequency, wavelength, and wave speed. But

Suggested prompt	Student response
For those who tested an anomalous data point in Part 2, how many got speeds that matched the numbers in the reading?	(Look for students to not raise their hands.)

the important idea that wave speed is affected by the medium is established first in this unit.

Say, *It looks like, in general, the numbers matched up for the first half of this graph, but not for the second half. This appears to support our claim that something weird is going on with these dots over here.*



Make inferences about Earth's structure. Present slide L. Pose the question:

- What can we infer from each part of the graph about the states of matter that make up Earth's structure? *

KEY IDEAS

Listen for the following key ideas before moving on:

- S-waves only travel through solids, so they are probably hitting a liquid or even a gas.
- P-waves move slower through liquids and gases, so when they slow down, they are probably hitting a liquid or even a gas.

Use probing questions to help students clarify their thinking as they make connections between the patterns they identified and the reality of seismic waves moving through matter. Examples include:

- Which pattern are you explaining right now? Can you point to the pattern on the slide?
- What about this pattern right here? What does that tell us about the speed of the seismic wave for waves that pass all the way through Earth's center?
- What information can we draw from the reading that could help us explain that pattern? Take a moment to look back at the section on seismic waves.
- I hear you say that the waves must be moving through a liquid (or a gas). Can you point to some evidence that P-waves slow down in a liquid (or a gas)?

Use talk moves to get students responding to one another's ideas. Examples include:

- Can someone restate that idea in different words?
- I hear you say that _____. Does anybody have a different idea?
- Great idea. Can someone else point to evidence that supports that idea?

ASSESSMENT OPPORTUNITY

What to look for/listen for:

- Students should recognize that the data points representing observed arrival times depart significantly from the expected times at this point, with arrivals later than expected for P-waves and none at all for S-waves. (SEP: 4.1; CCC: 1.4)
- Through discussion, the class should make a connection between this pattern and the reading, which explains that wave speeds are affected by the media through which they pass. (DCI: PS4.A.1)
- Students should make and defend the claim that in Part 2 of the graph, the pattern of speed anomalies indicates that the seismic waves have encountered matter that is not a solid. S-waves do not travel through liquid or gas, which is why they disappear. P-waves slow down in a liquid or a gas, which is why they arrive later than expected. (SEP: 5.2; CCC: 1.4)

What to do: If students recognize the anomaly but struggle to interpret it, give them more time to read. Have them specifically look for information that could explain why P-waves might travel more slowly and S-waves might not travel at all. Have them record these questions at the top of their handout to refer back to. Then bring the class back together and try again.

Building toward: 5.A.2 Analyze mathematical representations of indirect data to reveal anomalies in the pattern of arrival times for seismic waves to support a claim about the relationship between wave speed and the medium through which the wave is passing in Earth's interior. (SEP: 4.1, 5.2; CCC: 1.4, 3.2; DCI: PS4.A.1, ESS2.A.2)

6 • NAVIGATE

10 min

MATERIALS: science notebook, *How Do Scientists Explore Earth's Interior?*, *Earth's Interior Model*, loose-leaf paper

Discuss a model of Earth's layers in partners. Present slide M. Distribute the *Earth's Interior Model* handout to each student. Instruct them to work in partners to make sense of the model using the questions on the slide. These questions also set them up for the exit ticket.



Assign an exit ticket. Present slide N. Read the prompts aloud:

- Which layers cause P-waves to slow down?
- The speed of P-waves through liquid iron is ~9 km/s. Use this to support your claim with evidence and reasoning.

Have students respond on loose-leaf paper. Draw attention to their *How Do Scientists Explore Earth's Interior?* handout as a resource. Assign the exit ticket and move around the classroom to support students who might be intimidated by doing calculations. * Collect the exit ticket at the end of class to review and provide math support if necessary.

* SUPPORTING STUDENTS IN THREE-DIMENSIONAL LEARNING

This is an opportunity to make explicit that the process we are practicing, by coordinating patterns in the evidence with a current model, is one that scientists often use to build theory. This lesson supports students toward the Next Generation Science Standards (NGSS) Nature of Science Understanding titled **Scientific Knowledge Is Based on Empirical Evidence** (Appendix H). The relevant understanding element reads:

- Science includes the process of coordinating patterns of evidence with current theory.

ASSESSMENT OPPORTUNITY

What to look for/listen for:

- Students should make the claim that the liquid outer core causes P-waves to slow down and S-waves to disappear. (DCI: ESS2.A.2)
- Students might choose to use the speed provided on the slide (~9 km/s) to test at least one anomalous data point from the graph in the *How Do Scientists Explore Earth's Interior?* handout. For example, to test the dot at about 12,200 km, they can divide the x-value (12,200 km) by the y-value (22 minutes = 1,320 seconds) to get 9.2 km/sec. Then they compare that number to the speed on the slide and find it is roughly equal; it should be a little off, because the waves are not passing exclusively through liquid iron. They can use this to support their claim that the liquid core causes the slow-down pattern in the P-wave data. (SEP: 4.1, 5.2; DCI: PS4.A.1)
- Alternatively, students may choose to support their explanation without doing the calculations but still applying mathematical reasoning. For example, they might argue that because 9 km/s is slower than 11 km/s, it makes sense that the P-waves arrive later than expected. They might also point out that these data points move in an odd pattern, going up and then back down. This implies that at some point, the waves are no longer moving through as much liquid iron and may be moving through a more solid inner core, reducing the lag. (SEP: 4.1, 5.2; DCI: PS4.A.1)

What to do:

- If you think your students will be intimidated by this math, consider letting them discuss and work out the math in pairs before responding.
- Consider encouraging students to work through mathematical reasoning without doing the math.
- Move around the classroom and provide support for students who have trouble organizing the resources available. Point to the graph on the handout and ask them to choose a dot corresponding to a P-wave moving slower than expected. Then ask them how they could figure out that wave's speed from the information on the graph. They should recognize that speed is distance over time, or the x-value over the y-value.

Building toward: 5.A.3 Analyze mathematical representations of indirect data to reveal anomalies in the pattern of arrival times for seismic waves to support a claim about the relationship between wave speed and the medium through which the wave is passing in Earth's interior. (SEP: 4.1, 5.2; CCC: 1.4, 3.2; DCI: PS4.A.1, ESS2.A.2)

End of day 1

7 · NAVIGATE

5 min

MATERIALS: None

Reorient to P-waves and S-waves in the outer core. Present slide O. Say, *Last time, we figured out that Earth's interior is heterogeneous (that is, not all the same).* Have students turn and talk about the slide's prompts:

- How does the energy in P-waves transfer through the solid mantle versus through the liquid outer core?
- How does the energy in S-waves transfer through the solid mantle versus through the liquid outer core?
- How did graphing and math support your reasoning?



Highlight ideas about how P-waves slow down in the liquid outer core and S-waves stop, dissipate, or reflect. Do not play guess-what's-in-my-head. If students are still not ready to make inferences about the speed of waves through matter, or why S-waves might disappear when passing through the core, they will have a chance to make observations in a simulation.

Reflect on a crosscutting idea. Elicit 2-3 ideas about the third question on the slide to enable students to see how indirect empirical evidence and mathematical representations helped them identify patterns and anomalies in seismic velocities to support their reasoning.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Use this as a quick check-in to make it explicit that *by organizing the data as a graph, we could see patterns that might not have been clear, and that by applying mathematical reasoning, we could quantify how anomalous certain patterns were and highlight patterns* that helped us figure out what might be going on deep inside our planet. (CCC: 1.4)

What to do: Revoice students' ideas about how the graphing and math helped us figure things out. Then make the idea explicit by saying, *Scientists rely on mathematical representations like graphs and equations to identify patterns. Without these tools, we might not be able to pick out interesting patterns in a bunch of numbers.*

Building toward: 5.A.4 Analyze mathematical representations of indirect data to reveal anomalies in the pattern of arrival times for seismic waves to support a claim about the relationship between wave speed and the medium through which the wave is passing in Earth's interior. (SEP: 4.1, 5.2; CCC: 1.4, 3.2; DCI: PS4.A.1, PS4.A.4, ESS2.A.2)

8 · TEST OUR IDEAS WITH A SIMULATION

10 min

MATERIALS: device with access to http://ds.iris.edu/seismon/swaves/index.php?lat=34.2&lon=-118.5&depth=17&mag=6.7&title=Northridge%201994&date=1994-01-17T12:30Z&w_terrain=false&wiki=https%3A%2F%2Fearthquake.usgs.gov%2Fearthquakes%2Fstates%2Fevents%2F1994_01_17.php

Observe a simulation of seismic waves. Present slide P. Say, *Let's look at a simulation to test our ideas about what might be happening with these waves to produce these anomalies.* Project http://ds.iris.edu/seismon/swaves/index.php?lat=34.2&lon=-118.5&depth=17&mag=6.7&title=Northridge%201994&date=1994-01-17T12:30Z&w_terrain=false&wiki=https%3A%2F%2Fearthquake.usgs.gov%2Fearthquakes%2Fstates%2Fevents%2F1994_01_17.php. Make sure to select the "shadow zone" settings, and then press play. *

ALTERNATE ACTIVITY

This can be done as a class, but if there is time, you can also have students observe the simulation in small groups.

Have students turn and talk about the question at the bottom of the slide:

- What do you notice about the P-waves and S-waves when they pass through Earth's liquid core?

* ATTENDING TO EQUITY

The simulation has the option to choose from a wide variety of historical earthquakes. The default is the 1994 Northridge Earthquake in Southern California. If your area has a history of large earthquakes, click "Load new quake" and look for one that is interesting and relevant. Connecting phenomena to place supports students in seeing connections between science content and their own lives.

Elicit ideas. Listen for students to notice that the S-waves do not pass through the core and the P-waves slow down. Remind them that seismic waves spread out in every direction from one point rather than traveling in a straight line, to help them understand that this visualization lets us see where the front of all the P-waves and S-waves is at any given moment. ✱

Make sense of the simulation's energy transfer. Present **slide Q**. Pose the first question to start a Building Understandings Discussion:

- *Does the simulation support our model for what happens to the energy transferring in P-waves and S-waves when they pass through Earth's liquid outer core?*

Listen for consensus that the simulation generally supports our model. Pose the second question:

- *What can we infer about where the energy transfers when S-waves arrive at Earth's liquid outer core?*

Students might suggest that it gets absorbed or reflected, or talk about transferring thermal energy in the surrounding matter. Remind them that energy cannot disappear; it must transfer elsewhere.

9 · READ ABOUT EARTH'S MANTLE

15 min

MATERIALS: science notebook, *Earth's Interior Model*, *The Mantle and the Moho*

Motivate the reading. Present **slide R**. Have students take out their *Earth's Interior Model* handout. Problematicize a homogeneous mantle by asking whether the model explains why the forces are stronger in the Afar region than in regions like ours. They should say no, not really.

Point out that the speed of seismic waves told us about changes in Earth's matter. Ask, *Could we use the same kind of evidence to figure out what's happening under the crust at a local scale?*

Read about the mantle and the Moho. Present **slide S**. Ask, *Do these questions represent what we're wondering about?*

- *What might be different about the mantle rock under the Afar region?*
- *How do you think the mantle rock under the Afar region might compare to the mantle rock under the region where we live?*

Suggest that we read about the mantle to help answer our questions. Distribute *The Mantle and the Moho* to each student. Then ask, *What else do you hope we'll figure out from the reading?* Accept all ideas.

Give students about 10 minutes to read the handout and answer the Making Sense questions (the same as on **slide S**). If they do not get to those, that is fine. The questions are meant to navigate into the SubMachine investigation.

Motivate using the SubMachine tool. Use the last question on the slide to motivate a closer look at the mantle under Afar and comparison to the mantle under our region. Briefly ask for 1-2 responses to the previous question:

- *What might be different about the mantle rock under the Afar region?*

Then say, *I have a digital tool we can use to investigate the mantle in both places to answer that question.*

10 · USE A DIGITAL TOOL TO COMPARE THE MANTLE BENEATH AFAR TO OUR REGION

10 min

MATERIALS: *Investigating Cross Sections of the Mantle*, colored pencils, device with access to https://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section

Introduce SubMachine. Say, *This tool lets us generate a model of seismic wave anomalies over a much smaller scale and in greater detail, at any location within Earth's mantle. We can use it to "see" under the surface and find out whether the speed of energy transfer through the mantle in that specific part of the world is above average, below average, or close to average.*

Continue by saying, *This image shows one such model.* Present **slide T**. Distribute the *Investigating Cross Sections of the Mantle* handout and colored pencils to each student. Project the tool at https://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section. Use the slide to help them make connections between the various representations depicted in SubMachine.

As the class discusses the prompts, annotate the diagram on the slide and have students annotate the image on their handout (Question 1) with the following labels:

- negative velocity anomaly
- positive velocity anomaly
- crust
- mantle
- Earth's surface
- Earth's interior

Pose the slide's first prompt:

- *What do you notice about the images shown by this tool?*

Students should mention colors, the red-blue color scale labeled "seismic velocity anomaly," the map, the cross section, and the location dots and lines. Continue by saying, *Let's focus on these colors first. What do the different colors represent?* They should suggest that the colors show seismic velocity anomalies. Invite students to look back at the meaning given for the word *anomaly* on **slide J**.

Say, *We know that an anomaly is when we see data that are different from what we expect. In this case, we expected seismic waves would travel at a certain speed through the mantle, based on the assumption that the mantle's material is the same at any depth; however, the value we obtained was different. The colors show how different the actual seismic velocity is from the expected value.*

Point out that these colors also represent a relationship in temperature between the sections of mantle. Ask students to turn and talk to a partner about Question 2 on their handouts. Then elicit ideas about what these colors correspond to.

Guide students to determine that the seismic velocity anomalies correspond to temperature anomalies. The color scale is designed to make that apparent. Have students label the positive and negative seismic velocities in the boxes that indicate temperatures on page 1 of the handout.

Identify geographical correspondence between images. Point to the images on the slide. Say, *Let's look at the location on Earth that these images represent. How are the images related to each other? Do they have any features in common?*

Students should mention the dots following a curved line. Make sure they understand the connection between the dots and the cross section. The lines connect the black and green dots to corresponding locations on the planet, showing that the cross section's upper edge corresponds to the surface. The cross section represents locations or a planar section of Earth's interior that is not visible on the map.

Label the crust, mantle, surface, and interior on both the map and the cross section.

Explore Afar with SubMachine. Present **slide U**. Say, *We're trying to explain what happened to the crust in Afar, and what's going on beneath the surface might be important. Let's generate a model of Earth's interior beneath that region. What surface features did we observe that might be evidence for unbalanced forces in the mantle?*

Listen for students to mention things they observed in the anchor, such as cracks, volcanic eruption, and broken rocks in the Afar region. Tell them these ideas and observations from the anchor can be recorded in the "Surface observations" column of Question 3 in *Investigating Cross Sections of the Mantle*.

Use the following inputs in the tool to generate a cross section beneath the Afar region:

- latitude - 1: 10
- latitude - 2: 10
- longitude - 1: 30

- longitude - 2: 50

Ask students to record their observations of the seismic velocity anomalies by coloring or shading in the cross section diagram, and describing what they see in the final column of Question 3. At minimum, look for them to notice a large, extreme negative seismic velocity anomaly in the upper part of the mantle (the asthenosphere) beneath Afar.

Compare the Afar cross section to our location. Ask, *How do you think the mantle beneath where we live might compare to the mantle in Afar?* Accept all responses. Students may suggest that the anomalies would be smaller or nonexistent, because our region is not cracking in the same way Afar is; or, they may suggest a large positive seismic velocity anomaly in contrast to Afar's negative anomaly. Ask them to explain their thinking, but do not evaluate the accuracy of their predictions.

Use the predetermined coordinate ranges for your location to generate a SubMachine model. Have students record observations and ideas individually. Discuss what looks different or similar between the mantle below your location and the mantle below Afar, as shown in the table below. During the discussion, prompt students to record their answers to Question 4 if they have not already done so.

Suggested prompt	Sample student response
<i>What differences do you notice in the mantle models for these two locations?</i>	They have different colors/a different mix of colors. The blobs of color are different sizes. The seismic velocity anomalies are stronger in some places than in others.
<i>What is unique about the mantle under Afar compared to where we are?</i>	The mantle at Afar has a bigger red part. The mantle at Afar has a large high-temperature zone. The mantle at Afar has a larger negative seismic velocity anomaly.

11 · UPDATE THE PERSONAL GLOSSARY

5 min

MATERIALS: science notebook, *How Do Scientists Explore Earth's Interior?*, *The Mantle and the Moho*

Identify terms for Personal Glossaries. Present slide V. Ask students to look back with a partner at what they underlined in the readings, or to think about any other new words used in this lesson. Suggestions you can make include *heterogeneous*, *anomaly*, *homogeneous*, *Moho*, and *mantle*.

End of day 2

12 · NAVIGATE AND RETURN TO THE DRIVING QUESTION BOARD

8 min

MATERIALS: None

Navigate and return to the DQB. Present slide W. Pose the slide's first question:

- *How did observing seismic waves on a local scale help us understand more about the matter in Earth's mantle?*

Listen for ideas about how seismic waves travel at varying speeds, indicating a change in matter. Then pose the second question:

- *What questions on the DQB might we be able to make progress on by changing from a global scale to a more local scale to investigate the mantle?*

Highlight questions that get at smaller-scale variations in Earth's properties or behavior, such as surface features or earthquakes. Move these to a new spot to revisit at the end of the lesson.

13 · INVESTIGATE ADDITIONAL MANTLE CROSS SECTIONS

13 min

MATERIALS: science notebook, *Investigating Cross Sections of the Mantle*, device with access to https://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section, *Longitude and Latitude Coordinates for Mantle Cross Sections*, colored pencils

Investigate mantle cross sections. Present **slide X**. Have students take out their *Investigating Cross Sections of the Mantle* handout and find a partner to work with. They are to investigate at least three more locations using a map program and a provided list of coordinates, and then respond to the questions on the handout.

Distribute an internet-connected device, *Longitude and Latitude Coordinates for Mantle Cross Sections*, and colored pencils to each pair. The reference gives instructions for how to use SubMachine to generate models of Earth's mantle at specific locations. Direct students to https://users.earth.ox.ac.uk/~smachine/cgi/index.php?page=cross_section. As they work to complete the chart for Question 6 on the handout, walk around to help with technical and conceptual questions.

After investigating three locations, student pairs should respond to Question 7, describing any patterns they see in their own observations.

ADDITIONAL GUIDANCE

The purpose of this investigation is to illuminate potential connections between processes in Earth's interior and features on Earth's surface. Most continental and ocean-floor features on the surface are created by the motion of tectonic plates. Seismic velocity anomalies in the mantle correspond to locations where the properties of mantle material cause tectonic activity.

At this point, it is not necessary to connect specific surface features or events to characteristic mantle properties or plate boundary types. The broad pattern students should see is that when there is a more significant mantle anomaly, either in size or magnitude, there is more likely to be a geologically significant surface feature on the crust above. Locations with surface features such as volcanoes, mountains, ridges, rifts, and so forth have red or blue (more anomalous) mantle models. Locations that are relatively "featureless" (e.g., flat, not earthquake-prone) have more neutral-colored mantle models.

The reference list includes three categories of earthquake case locations. The first four (Hawaii, Japan, Chile, and Denver) have visible volcanic and/or mountainous features caused by various types of tectonic activity. The second group of four (Atlantic Ocean, Libya, Russia, and Antarctica) does not have prominent tectonic features. The third group is all the case studies from Lesson 1. It will be beneficial to investigate all these locations across the class, and for all students to see a variety of location types. You may decide to assign locations to different pairs, or allow them to choose their own if the class is large.

When students view the surface using Google Maps or Google Earth, consider encouraging them to zoom in or out to view the region at various geographic distance scales to help them see and identify various surface features.

14 · BUILD UNDERSTANDING ABOUT THE MANTLE

13 min

MATERIALS: science notebook, *Investigating Cross Sections of the Mantle, Earth's Interior Model*

Lead a Building Understandings Discussion. Present **slide Y**. Say, *Over the last two classes, we've modeled mantle properties beneath many surface locations. Let's talk about the new ideas that have come from these smaller-scale models.* Discuss the slide's prompts as shown in the table below. Tell students they should write down all the patterns the class identifies in the Question 8 box on their handout.

Suggested prompt	Sample student response
<i>What mantle patterns did you notice beneath volcanoes?</i>	Red sections near the surface. Negative velocity anomalies. Hotter temperatures. Except it was blue and cooler under the volcano in Japan, Mt. Fuji.
<i>What mantle patterns did you notice beneath locations with earthquakes, or the case study locations?</i>	They tend to have stronger anomalies/darker colors. It doesn't seem like the color is consistent. Sometimes it's very red (hotter), sometimes it's very blue (colder).
<i>What mantle patterns did you notice beneath mountains?</i>	Blue sections near the surface, especially for mountains that aren't active volcanoes. Positive velocity anomalies. Cooler mantle temperatures.
<i>What mantle patterns did you notice beneath other surface features, or in other locations?</i>	Beneath things like deserts, oceans, and rivers, the mantle did not have strong colors near the surface. There didn't tend to be seismic velocity anomalies or temperature anomalies in these places.

Revise our model to include local differences in the mantle's matter. Give students 5 minutes to respond to Questions 9-10 on the handout, if they have not already, before they share their ideas.

Present **slide Z**. Pose the first two questions:

- *What have we figured out that can help explain the plate motions we observed?*
- *How should we revise our Earth's Interior Model to reflect our new understandings about the mantle?*

Highlight ideas about smaller-scale differences in the mantle. Listen for recognition that mantle heterogeneity can help explain differences in forces, features, or behavior of the crust. Support speculation about cause-and-effect relationships between properties of matter in Earth's interior and phenomena observed on the surface. Remind students that our existing model shows a homogeneous mantle of solid rock (magnesium iron silicate), which does not account for the local differences we observed in the tomography data.

* STRATEGIES FOR THIS BUILDING UNDERSTANDINGS DISCUSSION

As students respond, push for them to talk about the rock's temperature. For example, say, *I heard you say there was a lot of red rock. What does that mean in terms of temperature?* If they struggle to identify patterns, ask them to focus on the colors in the mantle models closer to the surface (at the top of the cross section). Remind them to record the patterns identified by the class on their handout in the Question 8 box.



Present **slide AA**. Have students get out their *Earth's Interior Model* handout. Give them about 5 minutes to revise their models on their own, following the directions on the slide:

- Add labels, symbols, drawings, and/or annotations to your model of Earth's interior to reflect our new understandings about the mantle and its matter.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Look for all students to **add images or words to their global model to indicate that the mantle layer is not all the same; rather, it varies on a relatively local scale.** (SEP: 4.5; CCC: 1.2; DCI: ESS2.A.2, PS4.A.4)
- Some students might include information about temperature or **seismic wave velocities**. They may add surface features corresponding to heterogeneity in the mantle below (e.g., volcanoes above a warmer mantle location). They might also show that these differences create different unbalanced forces in different locations, which is why some regions have different kinds of surface features than others. (DCI: ESS2.A.2, PS4.A.4)

What to do: If students do not know where to begin, have them look back at the handout *Investigating Cross Sections of the Mantle*, Questions 7-10. Help them explain to you how the cross sections they created show a small slice of the mantle in the model. Ask whether those cross sections are represented in their models, and help them brainstorm how to fill that gap.

Building toward: 5.B.1 Analyze seismic velocity anomaly data at multiple scales and evaluate the impact of this data on our working model of Earth's interior to provide evidence for a causal link between local matter variation in Earth's mantle and surface features, such as mountains, volcanoes, and cracks. (SEP: 4.1, 4.5; CCC: 1.1, 1.2; DCI: ESS2.A.2, PS4.A.4)

15 · NAVIGATE AND UPDATE THE DRIVING QUESTION BOARD AND PROGRESS TRACKER

11 min

MATERIALS: science notebook, *Progress Tracker*, sheet of loose-leaf paper, Scale Chart poster, Driving Question Board, chart paper markers

Foreshadow convection by focusing on scale and change. Present **slide BB**. Pose the first question:

- *How does the scale of these mantle anomalies compare to the scale of the anomalies we used to figure out Earth's layers?*

Call students' attention to the Scale Chart poster. Have them compare the scale of the velocity anomalies that told us about Earth's layers to those that told us about mantle matter differences. Then ask them to consider the timescale. They should realize that although we know these anomalies occur on both global and local scales, we don't know where they would go temporally on the chart.

Say, *We don't know where to put these on the y-axis, because we don't know on what timescales these anomalies exist. Are they forever? Do they change over time? And if so, on what timescales?* Use this to motivate the second question on the slide:

- *Could these anomalies change over time?*

Elicit student responses. Accept all ideas, and suggest that we keep this question in mind.



Return to the DQB. Remind the class of the DQB questions we identified earlier. Ask, *Which of these questions can we answer, or do we have ideas about?* As students identify the questions that we have answered, put a checkmark on that sticky note and move it to the side. Leave any unanswered questions on the DQB.

Update the Progress Tracker. Give students a few minutes to record their ideas in their Progress Trackers. They may record something like: "The mantle has different temperatures in different places, which means the matter is different. This could create different unbalanced forces in different locations, which is why some regions have different kinds of surface features than others."

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Look/listen for students to start answering DQB questions **about specific surface features** (such as volcanoes) and events (such as earthquakes) **by describing seismic anomalies in the mantle at a regional scale that were added to our working model of Earth's interior.** (SEP: 4.5; CCC: 1.1; DCI: ESS2.A.2, PS4.A.4)
- Look for students to describe in their Progress Trackers how **scaling down from a global to a regional grain size allowed us to see the patterns of differences** in mantle matter that were important for understanding surface features. (CCC: 1.2)
- Students still have a significant gap in the causal chain connecting surface features to mantle matter, because they have not yet connected temperature variation to convection, and thus to plate movement. This will be developed over the next several lessons. Do not look for students to be able to make that connection here.

What to do: If students do not feel ready to answer questions on the DQB because of the gap in the causal chain, do not push them. They will have the opportunity to go back to the DQB several more times in the unit.

Building toward: 5.B.2 **Analyze seismic velocity anomaly data at multiple scales and evaluate the impact of this data on our working model of Earth's interior to provide evidence for a causal link between local matter variation in Earth's mantle and surface features, such as mountains, volcanoes, and cracks.** (SEP: 4.1, 4.5; CCC: 1.1, 1.2; DCI: ESS2.A.2, PS4.A.4)

Navigate with an exit ticket. Pose the prompt on slide DD as an exit ticket:

- *What do we know about how flowing matter of different temperatures interacts that could explain how the mantle might change over time?*

You do not need to collect these exit tickets. They will be used at the start of Lesson 6 to motivate a closer look at convection.

Additional Lesson 5 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

These are the CCSS for ELA/Literacy-related ideas that are used to support sensemaking in this lesson:

- **CCSS.ELA-LITERACY.11-12.RST.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.

This standard shows up because students synthesize information from two readings, a simulation, and tomography models to develop a coherent understanding of Earth's interior and how scientists use evidence from seismic waves to investigate it.

- **CCSS.ELA-LITERACY.11-12.RST.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.

This standard shows up because students determine the central ideas from two readings and use the Making Sense questions and class discussions to paraphrase the important ideas.

**SUPPORTING
STUDENTS IN
MAKING
CONNECTIONS IN
MATH**

CCSS.MATH.CONTENT.HS.A-CED.2 Create equations that describe numbers or relationships: Create equations in two or more variables to represent relationships between quantities; graph equations on coordinate axes with labels and scales.

On day 1 of this lesson, students analyze a linear graph. They use an equation (mathematical model) to test several data points in order to identify anomalous patterns in seismic wave velocities. They respond to a reflection question during navigation into day 2 on how mathematical representations helped them identify patterns and anomalies in seismic velocities to support their reasoning.

LESSON 6: How is temperature related to the behavior of the matter in the mantle?

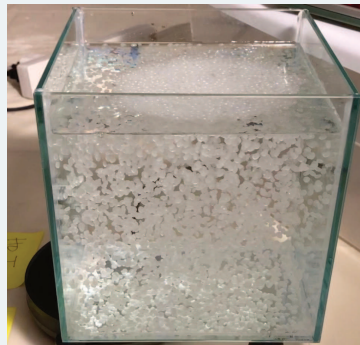
PREVIOUS LESSON

We analyzed seismic velocity anomalies to infer that Earth's interior is not entirely solid. We used a model of Earth's layers and a simulation to make sense of our observations. Then we zoomed in to a local scale to investigate the connection between mantle matter properties and surface features across the globe. Finally, we revised our model of Earth's layers to include a heterogeneous mantle and added to our Progress Trackers.

THIS LESSON

INVESTIGATION

2 days



We look back at our tomography data and create a predictive model of the movement of the mantle. We analyze a video of a tank containing a mixture of liquid and plastic pellets simulating the matter in the mantle to figure out what happens to the matter when heat is added. We utilize the M-E-F triangle to create a model to explain the thermal convection in the mantle.

NEXT LESSON

We want to know where the heat comes from that drives mantle convection, so we will jigsaw a series of articles that answer this question from forces, matter, and energy perspectives. We will develop a cause-effect model to explain how radioactive decay results in heat in Earth's mantle.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

6.A Develop a model to explain the relationship between energy transfer and the motion of matter in a solid material via thermal convection and the motion of particles. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)

WHAT STUDENTS WILL FIGURE OUT

- Increasing the temperature of matter in the mantle causes particles to move faster and farther apart, occupying a larger volume that results in a lower density.
- In different parts of the mantle, the relationship between the gravitational force and the pushing force from the matter beneath explains the cycling of matter in Earth's interior through convection.

Lesson 6 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	4 min		NAVIGATE Revisit the Lesson 5 exit ticket. Discuss the role of temperature in the mantle and its effect on matter changes.	A-B	exit ticket from Lesson 5
2	6 min		DEVELOP EXPLANATORY MODELS OF THE MANTLE UNDER AFAR Use the <i>Afar Mantle Model</i> handout to create an explanatory model of mantle movement using tomography data.	C-D	<i>Afar Mantle Model</i>
3	6 min		INTRODUCE THE MANTLE TANK Discuss how a tank filled with matter could serve as a scaled-down model of the mantle. Consider how it could be used to test our models of what is happening in the mantle under Afar.	E-I	
4	13 min		ANALYZE VIDEO FROM THE MANTLE TANK Analyze the video of the mantle tank investigation as a class.	J	<i>Mantle Tank Model</i> , https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOHtsy
5	6 min		USE M-E-F PERSPECTIVES TO EXPLAIN THE MANTLE TANK Create an explanatory model of the mantle tank using a matter, energy, and forces perspective.	K	<i>Mantle Tank Model</i> , M-E-F poster made in Lessons 2-4
6	10 min		NAVIGATE AND COMPARE MANTLE TANK MODELS Compare models of the mantle tank with a classmate who used the same M-E-F perspective, and then with a classmate who used a different perspective.	L-M	<i>Mantle Tank Model</i>
End of day 1					
7	5 min		REFLECT ON OUR COMMUNITY AGREEMENTS Reflect on the Community Agreements in a Scientists Circle.	N	Community Agreements poster
8	20 min		DEVELOP A CONSENSUS MODEL ABOUT MOVEMENT IN THE MANTLE TANK Meet in a Scientists Circle to discuss ideas about how temperature influences the structure of matter and the forces that cause convective motion.	O	<i>Mantle Tank Model</i> , M-E-F poster, Model of Movement in the Mantle poster, chart paper markers, Community Agreements poster
9	10 min		USE THE MANTLE TANK CONSENSUS MODEL TO TEST/REVISE AFAR MANTLE MODELS Compare the parcel within the tomography data from Afar to the mantle tank. Use lava lamps to consider non-uniform convection and its manifestations in the mantle.	P-R	<i>Afar Mantle Model</i> , <i>Mantle Tank Model</i> , https://youtu.be/l2HLRgpIJsQ
10	5 min		REVISIT THE DRIVING QUESTION BOARD Revisit the Driving Question Board and add any new questions.	S	3x3 sticky notes, permanent marker
11	5 min		UPDATE THE PROGRESS TRACKER Add an entry to the Progress Tracker.	T	<i>Progress Tracker</i>
End of day 2					

Lesson 6 • Materials List

	per student	per group	per class
Lesson materials	- science notebook - exit ticket from Lesson 5 <i>Afar Mantle Model</i> <i>Mantle Tank Model</i> 3x3 sticky notes - permanent marker <i>Progress Tracker</i>		https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOhtsy - M-E-F poster made in Lessons 2-4 - Community Agreements poster - M-E-F poster - Model of Movement in the Mantle poster - chart paper markers https://youtu.be/I2HLRgpIJsQ

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 handouts so they can be added to students' science notebooks.

Make copies of the handouts for this lesson:

- Afar Mantle Model* - 1 per student
- Mantle Tank Model*- 1 per student

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

- Model of Movement in the Mantle

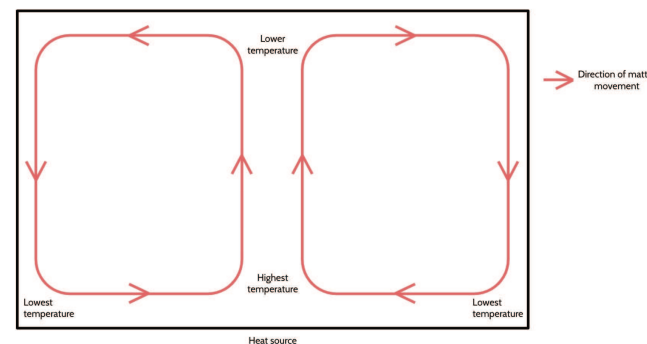
Make sure the M-E-F poster developed in previous lessons is readily visible in the classroom.

Test the following links:

- Mantle Tank Investigation Video, <https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOhtsy>
- Optional particle simulation, <http://bit.ly/heating-and-cooling>
- Note: the Mantle Tank Investigation Video shows condition A and references a condition B, but there is no condition B in this lesson.

On day 2, if a clear, shared understanding of what happened in the tank does not easily develop, draw a base descriptive model on the board. This might look like the image on the upper right.

Another option to help students make sense of temperature in the tank after watching the video is to have them sketch what tomography data would look like for the tank. This might look like the image on the lower right.



Lesson 6 • Where We Are Going and NOT Going

Where We Are Going

This lesson works toward building the following disciplinary core idea:

- **ESS2A.1: Earth Materials and 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.

The lesson only addresses the last sentence of this element, as students figure out that the motions of the mantle are caused by convection in its matter. They model the movement of energy and matter in the mantle. They also begin to consider the forces involved in various sections of the mantle due to convection: both gravity and the pushing forces from beneath the matter.

If students have experienced *OpenSciEd Unit C.1: How can we slow the flow of energy on Earth to protect vulnerable coastal communities? (Polar Ice Unit)*, they may already have a basic understanding of density-driven convection currents in water, with warmer but more dense salt water present at the bottom of bays while less dense water from glaciers cycles via convection currents.

Students encounter and/or co-construct ideas around several terms during this lesson, and may decide to add the following word to their Personal Glossaries: *convection*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

In this lesson, the mechanism of convection is only developed as needed to continue building a conceptual model of what is happening in the mantle. This exploration and discussion will continue in Lesson 7 as students figure out more about how convection in the mantle affects interactions between the mantle and crust. They will not figure out the source of the heat that causes this convective motion until Lesson 7.

Though a lava lamp model is used to explain the non-uniform convection in the mantle, no attempt is made in this unit to explain differences in the type of matter within the mantle. This will be revisited in *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)* when students learn about Earth's history, the collision that created the moon, and the possible effects on the components of Earth's interior.

LEARNING PLAN for LESSON 6

1 · NAVIGATE

4 min

MATERIALS: science notebook, exit ticket from Lesson 5

Review the Lesson 5 exit ticket. Display **slide A**. Remind the class that at the end of Lesson 5, we were thinking about the mantle and how there are different temperatures of rock. We recognized that the mantle moved, and we were trying to explain how matter having different temperatures might affect the flow in Earth's interior. Finally, we had an exit ticket with the question on the slide:

- *What do we know about how flowing matter of different temperatures interacts that could explain how the mantle might change over time?*

Have students turn and talk about their exit tickets for 1-2 minutes, then ask a few to share out. Accept all ideas. Highlight ideas about heat rising and cold sinking, analogies to boiling water, and the introduction of words like *convection*. Validate these, but if they do not come up, simply move on.

Present **slide B**. Say, *Let's work on connecting these ideas to the mantle and our understanding of how it moves. We've been moving between scales to explain matter, energy, and forces. Let's start at the particle scale again, and build our explanation from there.* Pose the first two questions on the slide:

- *When flowing matter is heated, what changes at the particle level?*
- *How do these changes at the particle level affect what we observe about matter at the macro scale?*

Listen for suggestions that the particles move more (have higher kinetic energy) as the temperature rises. Students might also note that these particles apply more forces to particles around them because they are moving more.

Guide the class to remember that the velocity anomalies identified in Lesson 5 correlated to different temperatures in the mantle. Suggest that hereon, we refer to these areas of different temperatures as parcels of mantle material.

ADDITIONAL GUIDANCE

The term *parcels* was chosen because it is how students referred to sections of matter in convective cycles in middle school, such as when discussing the atmosphere in *OpenSciEd Unit 6.3: Why does a lot of hail, rain, or snow fall at some times and not others? (Storms Unit)*. Take a moment to ensure that students have an intuitive understanding of a parcel as a fixed quantity of something. This will be important when the class begins to discuss how temperature changes in the mantle cause density changes within the fixed quantity of matter in a parcel.

Ask students to consider what would be different between a parcel with a higher temperature versus a lower temperature. They should determine that the higher-temperature parcel would have particles with a higher average kinetic energy, and a parcel with a higher kinetic energy would be less dense than a parcel with a lower average kinetic energy. They may also have the idea that the matter in the parcels pushes on other matter in the mantle.

ADDITIONAL GUIDANCE

Students may need a refresher on what temperature is a measure of. If they do not remember from middle school that temperature is the average kinetic energy of a sample, consider pulling up a simulation that allows you to manipulate a sample's temperature in a particle-level view. Many such simulations exist; for example, <http://bit.ly/heating-and-cooling> utilized in *OpenSciEd Unit 6.2: How can containers keep stuff from warming up or cooling down? (Cup Design Unit)*. Oscillate between different temperatures and have students make observations about the particles' behavior. This simulation can also be used to consider differences in the density of mantle parcels.

Once students determine there would be a difference in the average kinetic energy and the density of these parcels, ask them to consider the slide's third question:

- *How might this affect how matter flows in Earth's mantle?*

Elicit responses. Remind the class that this would mean that parcels of different densities would be interacting within the mantle. Then ask how this interaction would affect the movement of these larger sections. Point to the image of parcels and have students consider how a more dense parcel and a less dense parcel might be moving relative to the others. Accept all responses.

ALTERNATE ACTIVITY

If students have not yet had the opportunity to make sense of the relationship between density and objects floating or sinking, consider conducting an experiment in which they can measure the mass and volume of objects, such as density cubes, to see that less dense objects float and more dense objects sink.

2 · DEVELOP EXPLANATORY MODELS OF THE MANTLE UNDER AFAR

6 min

MATERIALS: *Afar Mantle Model*



Create an explanatory model using tomography data. Project slide C. Say, *Last time, we looked at tomography data to give us an idea of how what was happening in the mantle affected the surface. Let's shift to consider what might cause the motion of the parcels of mantle material.*

Distribute the *Afar Mantle Model* handout. Ask students to use what we know about particles and samples of matter (such as parcels) at different temperatures, as well as the tomography data, to predict why and how the mantle is moving. Direct them to draw the motion directly on the data in the handout, and to use the circles to consider what we would see happening at the particle level.

As students work, take the opportunity to walk around the classroom and collect formative data about how students currently view the mantle's movement and the mechanisms for that movement.

ASSESSMENT OPPORTUNITY

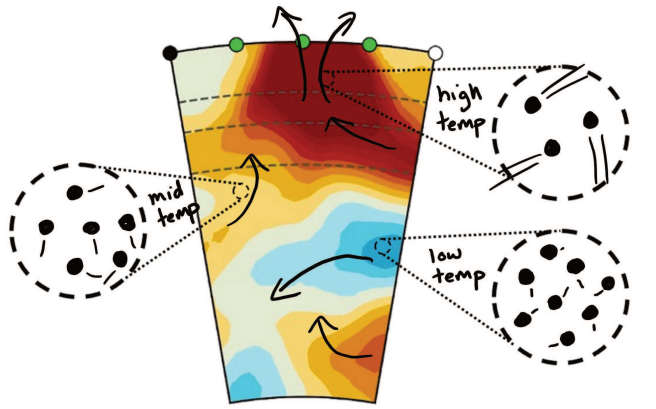
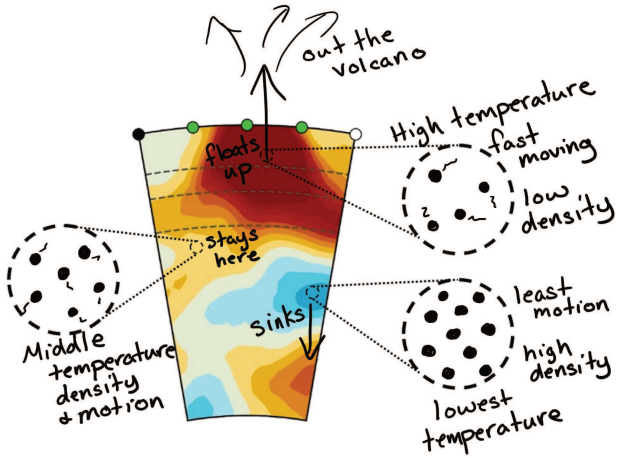
What to look for/listen for in the moment:

- Look for all models to **predict the relationship between the particle nature of the parcels of different temperatures and their movement in the mantle.** (SEP: 2.3; DCI: PS3.A.4)
- Models should include **particle-level interactions** at various locations in the mantle system. (DCI: PS3.A.4)
- Models should include **changes in the matter related to the energy transferred in the mantle parcels.** (CCC: 5.4)

What to do:

- At this point in the lesson, the model does not need to be accurate. It is meant for formative assessment purposes and can inform instruction at future steps in this lesson, including the consensus model at the beginning of day 2. Students also have one more chance to revisit this model at the end of day 1. Do not press for specific right answers at this point. Instead, use the following sections as guidelines for helping students consider a new perspective or idea.
- If particle differences are missing or limited:
 - Direct students to consider what differences exist between particles of the same matter sample in the same state at two temperatures. Have them consider this movement and how it would affect the density of the sample.
- If the movement of the sample and/or changes in matter due to energy transfer are missing or limited:
 - Direct students to consider how that density difference would affect movement if the samples were two vastly different densities, such as a more or less dense pool toy in water. Ask them to consider how this difference might affect the movement of parcels in the mantle, and how those blobs interact with blobs of different densities.
- Some students may include Earth's core as an energy source. Though this is an important component of the model of Earth's interior, it is not necessary to include at this time. By the end of the lesson, students will converge on the idea that thermal convection occurs in the mantle, but they will not have evidence of the mechanism. This will provide a segue into Lesson 7.

Building toward: 6.A.1 **Develop a model to explain the relationship between energy transfer and the motion of matter** in a solid material via **thermal convection and the motion of particles.** (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)

 SubMachine	 SubMachine
Student who is thinking about kinetic energy differences between the parcels of mantle material and the flow of matter.	Student who is thinking about kinetic energy and density differences between the parcels of mantle material and how those might manifest on the surface.

Bring the class back together and have a few students share elements of their models. Accept all ideas. Say, *It seems we have a lot of ideas about what might be happening with the movement of these blobs in Afar. Thank you for sharing. Let's consider how we can test our models.*

Remind students that in our models, we are trying to show rock moving like a thick fluid. We know that this phenomenon takes millions of years, but we don't have millions of years to investigate it.

Recall ways to test predictions of events over different time scales. Project slide D. Say, *Is there a way we can investigate fluids moving at a rate we can observe in the classroom, to test our predictions?*

Allow students to respond, and accept all ideas. Have them hone in on the idea of changing the rate by asking the question on the slide:

- *What have we done in the past to increase or decrease the speed at which a phenomenon happens?*

Elicit a few ideas. Listen for students to suggest simulations, videos, or models of the same mantle substance, or using a faster-moving fluid.

3 · INTRODUCE THE MANTLE TANK

6 min

MATERIALS: None

Consider the usefulness of the mantle tank. Present **slide E**. Say, *I have a video of a model that was created to visualize how matter in the mantle moves when parcels of it have different temperatures. Let's consider how the model might be used to test our models.*

Present **slide F**. Ask students to turn and talk about the slide's list of tank elements and the prompt:

- *What purpose might each element of this model serve, and how can we use it to test our models?*

Have pairs share out. Listen for these ideas:

- comparisons of the tank's mixture of liquid and pellets with the rock mixture in the mantle, and specifically, that both are similar throughout and can flow
- mentions that the pellets might allow us to see the motion of the liquid
- ideas about heating parts of the tank to create temperature differences and then making observations

Use probing questions or suggestions to help students explore these ideas if they do not develop them on their own.

ADDITIONAL GUIDANCE

The plastic pellets are **not** meant to represent particles at the microscopic level. They are used as a way to visualize motion in the surrounding matter when energy is transferred into the system. If students propose the idea of the pellets representing the mantle at the particle level, be sure to discuss how the pellets behave in the liquid and how this is different from particle behavior. For example, the pellets:

- are not vibrating and bouncing off of each other
- stay consistently spaced in the liquid and do not visually show changes in density

It might also help students to better understand the tank model if you propose that the pellets represent smaller parcels of matter in the mantle.

Discuss advantages and limitations of the tank. Present **slide G**. Read the prompt aloud:

- *What advantages and limitations does this model have for testing our models? **

Listen for ideas such as:

- Because rocks move very slowly, maybe we can see changes in matter much faster with the liquid in the tank.
- It is very hard to study the mantle directly, so this will give us evidence of how matter responds to temperature.
- The mantle is made of rock, but this is liquid, so maybe the conclusions we draw from this tank would not apply to the mantle.
- The tank is very small compared to the mantle. Maybe a large-scale system does not behave in the same way as a small system like the tank.
- The tank has walls, but the mantle under Afar isn't blocked off from the rest of the mantle.
- The liquid might not visually show the temperature differences like we see with the tomography data.

Determine how to use the tank to test our models. Present **slide H**. Point out that although it has limitations, the tank still seems like a good representation. Pose the slide's question:

- *How can this mantle tank be used to test the reliability of our drawn models of the mantle under Afar?*

Listen for suggestions that the tank can serve as a representation of the mantle and that it should function like the mantle with a heat source at the core. The tank can be used to compare the movement of mantle parcels of different temperatures, to determine whether the movement is similar in the models we have created.

* SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

In Lesson 4, students evaluated the merits and limitations of different models using three lenses: (1) *stability or change* over time or space, (2) *thinking across different scales*, and (3) *cause and effect* in M-E-F relationships. Encourage them to continue using these lenses to assess whether and how a model can help explain the phenomenon under investigation.

Discuss heating the tank. Say, *It seems like we can use this model to test at least some parts of our models by heating part of the tank, as long as we remember that all models have limitations.*

Present **slide I**. Explain that the image shows how the tank is heated by using pennies stacked on a hot plate and touching the bottom of the tank. Mention that the tank does not touch the hot plate directly, so the pennies transfer heat from the hot plate to the tank. Pose the question on the slide:

- *Why do the pennies only make contact with the middle of the tank?*

Listen for students to mention that the tomography data suggested that the temperature of the mantle varies between different spots, so we want to unevenly heat the liquid in this model.

Say, *Okay, now that we have an idea of what is represented in the tank and how it can be used to test our models, let's analyze a video taken of what happens in the tank over time.*

4 · ANALYZE VIDEO FROM THE MANTLE TANK

13 min

MATERIALS: *Mantle Tank Model*, science notebook, <https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOHtsy>

Describe the video observation task. Present **slide J**. Distribute the *Mantle Tank Model* handout to each student. Say, *On this handout, we'll keep track of how we make sense of the mantle tank. You can put your Afar model in your notebook. We'll come back to it when we check our models against what we learn.* Tell students to record noticings and wonderings on their handout while we watch the video.

Watch the mantle tank video. Project the video, <https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOHtsy> (about 3 minutes long). * At the time stamps in the chart below, pause the video and use the prompts to elicit ideas.

Time stamp	What is happening in the video	Prompts to use with the class
0:07 - 0:09	A frontal view of the mantle tank setup is shown.	<i>Can someone remind us what the role of the pennies is?</i> <i>Why do you think the pennies were placed in this pattern?</i>
0:10 - 0:46	The video shows the mantle tank recorded from two angles: frontal view (right); side view (left). Each screen shows the tank and the temperature recorded, first from the front, then the side. All temperatures are equal.	<i>What do you notice about the temperature measured in the different locations?</i> <i>What changes do we see in the matter?</i>
0:50 - 1:03	The person turns the hot plate on.	<i>What do we think is going to happen to the temperature of the mantle tank?</i> <i>What do we think is going to happen to the matter as the temperature increases?</i>
1:03 - 1:33	The hot plate is on, but there are no visible changes in the mantle tank.	<i>Do we expect to see changes immediately after we turn the hot plate on?</i>

* ATTENDING TO EQUITY

Universal Design for Learning: As a second option, consider separating the video into six shorter videos, according to the series of timestamps below, to help students *perceive* the movement in the mantle tank. Students who could benefit from seeing the video up close on their devices could start and stop each video along with the class, giving them increasing access to this task.

* ATTENDING TO EQUITY

Universal Design for Learning: When asking students to describe how matter moves in the mantle, encourage them to use their hands and arms to *represent* this motion. Visual, nonlinguistic supports such as this can increase students' ability to understand concepts, especially for new learners of the classroom's dominant language.

1:40 - 2:02	The video is sped up 20 times faster, which allows observers to see changes in the matter more clearly. The plastic pellets move in a convective pattern.	<i>What scale changed?</i> <i>How is the matter moving in the mantle tank?</i>
2:10 - 2:53	The person remeasures the temperature. The highest temperature is found in the middle of the mantle tank, close to where the pennies are transferring the heat from the hot plate. The temperature is lower at the surface, and even lower at the sides, closer to the bottom.	<i>What is the temperature at different locations?</i> <i>Why is the temperature different at these locations?</i>

Collectively analyze the video. Ask students to share noticings and wonderings. If needed, rewatch parts of the video to establish consensus. Be sure that these main ideas are established: ★

- The matter moves up in the middle of the tank, along the pennies.
- The matter moves down along the sides of the tank, away from the pennies.
- The motion is cyclical.
- The highest temperature is at the bottom, in the middle, near the pennies.
- The lowest temperature is at the bottom, near the sides, away from the pennies.
- The temperature at the top of the tank, above the pennies, is lower than the temperature down near the pennies.

5 · USE M-E-F PERSPECTIVES TO EXPLAIN THE MANTLE TANK

6 min

MATERIALS: *Mantle Tank Model*, M-E-F poster made in Lessons 2-4

 **Use an M-E-F perspective to explain the movement in the tank.** Ensure that the M-E-F poster is visible in the classroom. Say, *Okay, now that we have an idea of how matter moves in the mantle tank, let's make explanatory models of what's happening in there, so we can use them to test our Afar models. We'll use the M-E-F triangle to help us make our models.*

Present **slide K**. Guide students in creating models on their handout with the slide's prompts:

- *Use the evidence we obtained from the mantle tank video to create a model to describe and explain why the matter in the tank is moving in the way we observed.*
- *Choose at least one of the following perspectives to develop in your model:*
 - *matter (particle-level interactions)*
 - *energy*
 - *forces*

Allow students 5 minutes to complete their models. It is OK if they use only one perspective in their explanation.

ADDITIONAL GUIDANCE

As students work, quickly take stock of which M-E-F perspectives they are using. If one of the three perspectives is underrepresented across the class, encourage students who finish early to consider this perspective as well.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Look for all models to **reference the observed motion of matter and the temperature readings in the mantle tank video as evidence about energy transfer and matter changes.** (SEP: 2.3)
- Models using the matter perspective should include **particle-level interactions** at various locations in the mantle tank system. (DCI: PS3.A.4)
- Models using the energy perspective should include **changes in the matter related to the energy transferred into and out of the mantle tank system.** (CCC: 5.4)
- Models using the forces perspective should mention explicitly or illustrate the forces acting on matter at various locations in the mantle tank that could explain the **convective motion of matter or energy transfer** in the model. (DCI: ESS2.A.2; CCC: 5.4)

What to do:

- If students struggle with explaining the parts of the tank that changed, encourage them to look back at the observations they recorded from the video investigation. Some students who choose the matter perspective might focus on describing the observed motion in the matter. Encourage them to use particle-level interactions in their models.
- Use the M-E-F poster to support students in using at least one of the perspectives to explain the movement of matter in the tank. Point them to the questions we should be asking ourselves about matter, energy, or forces when we try to explain a phenomenon from these perspectives.
- Consider asking more focused questions, such as the following, to help students consider how matter, energy, and/or forces can be used to explain the movement of the items in the tank and the corresponding blob movement in the mantle:
 - *What do we know about the average kinetic energy of each blob and the different sections of our tank? How is that energy transferring? How does that affect the movement of what we see in our tomography data, and the movement of liquid and beads in our tank?*
 - *What did we see the matter in the tank doing, and what changes at the particle level might explain that movement? How might the matter be similar or different in different parts of the tank, and why?*
 - *What forces do we know act on matter? How might that affect mantle parcels of different densities in our tomography data and our tank? What is pushing or pulling on this matter to make it move up and down in our tank?*
- For students who are ready to consider more than one perspective, ask them to consider how another perspective might also be explained within their model, and how that perspective might be stable or change over varying spatial and temporal scales.
- Once some students finish, encourage them to consider what forces might be acting on the matter, and how that might affect the movement.

Building toward: 6.A.2 **Develop a model to explain the relationship between energy transfer and the motion of matter** in a solid material via **thermal convection and the motion of particles.** (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)

6 · NAVIGATE AND COMPARE MANTLE TANK MODELS

10 min

MATERIALS: *Mantle Tank Model*

Compare explanatory models of the movement in the tank. Present **slide L**. Review the directions:

- *Look for a person who used the same perspective that you did to explain the motion of matter in the mantle tank. Each person will have a minute to explain their model. After each partner has shared, look for:*
 - *similarities between models*
 - *differences between models*
 - *areas of uncertainty*
 - *areas of disagreement*

After a few minutes, present **slide M**. This time, have students look for a person who used a different perspective to explain the movement. Direct them to the new prompts on this slide:

- *how both models combined help to explain the movement of matter*
- *areas of uncertainty*
- *areas of disagreement*

Have students use their handouts to record the ideas for changes or new understandings that they developed from comparing models. These will be used in the next class.

Say, *Next time, we'll use our mantle tank models to develop a consensus model, and then use that to test our Afar mantle models.* Collect the *Mantle Tank Model* handouts for review before the next class.

ADDITIONAL GUIDANCE

Use your review of the *Mantle Tank Model* handouts to anticipate how students might want to represent things during the consensus model discussion. You may want to identify specific students to ask to share their representations. See the Key Ideas callout in day 2 for guidance on what to include in the consensus model.

End of day 1

7 · REFLECT ON OUR COMMUNITY AGREEMENTS

5 min

MATERIALS: *Community Agreements poster*

Take stock of our Community Agreements. Say, *Our next step is to develop a consensus model for the mantle tank that integrates the matter, energy, and forces perspectives. That will be a tricky conversation as we're working together to come to consensus. So, this is a good time to revisit our Community Agreements.*

Present **slide N**. Display the list of agreements either digitally or physically. Use the slide's prompt to start a brief discussion: *

- *Which of our Community Agreements will help us as we work together to develop a consensus model?*

Revisit the Community Agreement shoutouts from Lesson 4. Remind students that at the end of Lesson 4, they recorded one instance when someone else's contributions had helped them figure something out. Quickly share these shoutouts with the class, and suggest that we consider using the same strategies that were identified in them for our consensus modeling today.

* ATTENDING TO EQUITY

Building classroom culture: This lesson's two focal agreements are respect and moving our thinking forward. As students create a consensus model, it is important that they think about how to treat each other with respect while advancing our understanding. This is an opportunity to emphasize that building a consensus model does not always mean agreeing with each other's ideas; sometimes challenging each other's ideas

helps us make progress in our thinking and identifies areas of consensus and uncertainty in a model.

It is important to remember that how we define respect can be culturally constructed, which is why we ask students to explicitly name what respect looks like/sounds like during the development of agreements in Lesson 1. Be aware of how the word “respect” can be used to reproduce gendered or racialized ideas (e.g., “bossy” versus “leader,” or “angry” versus “passionate”), and steer students to the more detailed Lesson 1 agreements if necessary.

8 · DEVELOP A CONSENSUS MODEL ABOUT MOVEMENT IN THE MANTLE TANK

20 min

MATERIALS: *Mantle Tank Model*, M-E-F poster, Model of Movement in the Mantle poster, chart paper markers, Community Agreements poster

Convene a Scientists Circle. Make sure the M-E-F poster is visible to everyone. Say, *Let’s try to capture what we’ve figured out about what’s happening in the mantle that can help us explain what is happening at Afar.* Return students’ *Mantle Tank Model* handouts.

Develop a consensus model for the motion of matter in the mantle tank. Display the prepared Model of Movement in the Mantle poster. Present **slide O**. Use the prompts to initiate a discussion:

- *What did we observe in the mantle tank?*
- *What do these observations tell us about matter, energy, or forces?*
- *How are things different in different parts of the tank?*

As consensus is reached about elements of the model, draw them on the poster or have students do this. Be sure to include a key so everyone knows what the representations mean. Listen for the ideas in the Key Ideas box below. To direct the discussion and model development as needed, use guiding questions for each M-E-F perspective, such as those proposed below:

Energy:

- *What evidence do we have from the video that tells us about energy?*
- *Where was energy transferred in/out of the system?*
- *Why do you think energy is being transferred in/out of the system there?*
- *How could we represent energy flow in our model?*

Matter:

- *What did we observe the matter in the tank doing?*
- *What evidence did we see that tells us the matter is changing at the particle level?*
- *What changes at the particle level explain the evidence we observed?*
- *Where in the tank did the matter have higher/lower amounts of energy/motion at the particle level?*
- *Where in the tank would the particles be closest together/farthest apart?*
- *How could we represent the energy/density of the matter in our model?*

Forces:

- *What forces act on sections of the matter as it moves around the tank?*
- *What can we infer about the gravitational force acting on sections of the matter, based on the particle-level differences we discussed?*

- *We discussed that the matter's density changed. If you make something more dense by packing more matter into the same space, what happens to the force of gravity, or the weight?*
- *Where in the tank do we see evidence of balanced or unbalanced forces?*
 - *Where does the motion of the matter change?*
- *Can differences in the force of gravity explain the rising of the matter in the middle of the tank?*
 - *What else might be pushing on the matter to cause it to start moving up?*

**ALTERNATE
ACTIVITY**

Depending on how comfortable your students are with developing consensus models, you may want to chunk this discussion into discrete perspectives. It is suggested that you start with energy, then matter, then forces. These discussions should still create a single holistic model.

KEY IDEAS

Although your students' consensus models are likely to look different from these examples, the following key ideas should be represented and explicitly discussed.

Listen for these ideas overall:

- Density changes in the matter, associated with changes in temperature, unbalance the net force on the matter in the tank in a way that causes it to cycle up and down.

Energy:

- Energy flows into the system from the pennies at the bottom of the tank, making this part of the tank have the highest temperature.
- Energy flows out of the matter to the surroundings as the matter moves around the tank.
- High-energy matter moves up, low-energy matter moves down.

Matter:

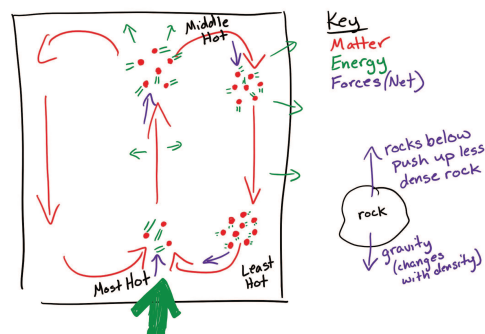
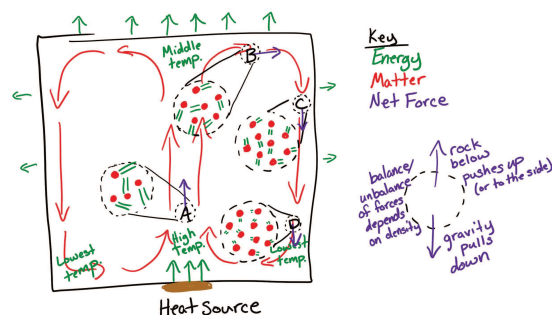
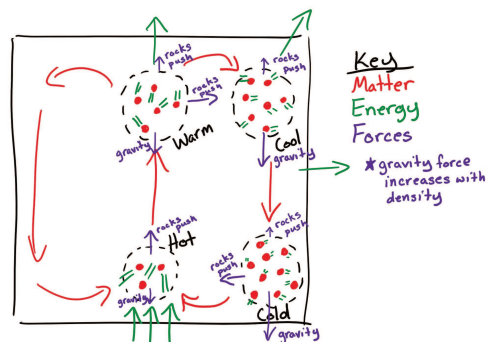
- The matter moves in a cyclical pattern up and away from the energy source and then back down around the slides of the tank.
- As the matter lowers (decreases) in temperature, the particles become closer together (move slower), changing density.
- As the matter rises (increases) in temperature, the particles become farther apart (move faster), changing density.

Forces:

- Forces that act on the matter in the tank include gravity pulling down and contact forces pushing in all directions from the matter around it.
- The denser matter is pulled down by a stronger force of gravity (because it has more matter).
- The denser matter pushes the less dense matter up, toward the top of the tank.
- The net force on a section of the matter changes as the temperature changes.
- The unbalanced net force on the matter changes the matter's motion.

Extension ideas that can be developed:

- There is a positive feedback loop driven by the movement of matter away from one location, creating less resistance in that direction for other matter to move into that space. (This helps explain the lateral motion.)



ADDITIONAL GUIDANCE

The force of the matter around an object in a fluid is often referred to as the *buoyant force*. We have deliberately chosen not to use this term. By focusing on the mechanism rather than the type of force, our goal is to help students develop an intuitive model of forces as pushes and pulls that sum to net forces; naming specific types of force comes later. But feel free to share this term with students after they have developed an intuitive understanding of why a higher-temperature parcel pushes on the matter above it.

This is also an opportunity to draw on multilingual resources in your classroom. The word *buoyancy* in Spanish is *flotabilidad*, and in French it is *flottabilité*. If students in your class speak Spanish, French, or a related language, you can point out that these words sound like “floatability” and help to describe the buoyant force as the ability of a parcel to float, determined by its density.

Once the model is established, highlight any Community Agreement that was especially well used during the discussion. For example, thank the class for their participation and collaboration to move our thinking forward. Leave the consensus model up for the remainder of the lesson.

9 · USE THE MANTLE TANK CONSENSUS MODEL TO TEST/REVISE AFAR MANTLE MODELS

10 min

MATERIALS: science notebook, *Afar Mantle Model*, *Mantle Tank Model*, <https://youtu.be/l2HLRgpJJsQ>

Observe non-uniform convection in lava lamps. Have students return to their seats and take out their *Afar Mantle Model* and *Mantle Tank Model*. Present **slide P**. Pose the prompt:

- *What are the differences between what we saw in the mantle tank and the Afar tomography data?*

Ask students to compare their two handouts. Listen for them to notice that the hottest spot in the mantle data is at the top, and there doesn't seem to be a clear cycle. Say, *One difference I'm hearing is that the tomography doesn't show the same locations for temperatures as the tank did. I have another video that shows non-uniform examples of convection.*

Project the lava lamp video, <https://youtu.be/l2HLRgpJJsQ>. Have students share out their observations in real time as the video plays.

Present **slide Q**. Ask the class to consider the questions on the slide:

- *What similarities do we see between the lava lamp video and the mantle tank video?*
- *What differences do we see?*
- *How might these differences help explain the different mantle parcels we see in our tomography data?*

Have a quick discussion using those questions. Guide students to make the following determinations:

- Both the mantle tank and the lava lamps are heated from the bottom.
- Hot stuff moves up in blobs, parcels, or sections.
- The mantle tank motion is much more continuous and flowing than in the lava lamps.
- The hot stuff at the top of the lava lamps stays at the top longer than in the mantle tank.
 - This is like what we see in the Afar tomography data.
 - This is because it takes longer for that matter to lose enough energy to sink.

ADDITIONAL GUIDANCE

If questions arise regarding the types of fluids in the lava lamps, do not dismiss them. Ask students to add these questions to the DQB. Though they will not be addressed in this unit, questions about the differences in the type of matter that exists within the mantle will be answered in the future in *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)*.

ALTERNATE ACTIVITY

If you have access to a lava lamp, consider bringing it to the classroom for direct visual observations. Be sure to advise students not to touch the lamp, as it can get extremely hot. It is suggested that the class also watch the video, as it was selected for the variety of behaviors seen across several lamps.

A non-contact thermometer can be used to make temperature observations of a lava lamp. Temperature patterns will vary based on the lamp and will not be as clear and consistent as the patterns in the mantle tank. This is because the rate of energy transfer into and out of the wax “lava” in a lamp is slower than energy transfer within the consistent fluid in the tank.



Test/revise Afar mantle models using mantle tank understanding. Present slide R. Tell students to use the newly formed consensus model to see whether their initial models explaining how and why the mantle is moving under Afar still hold. Refer to the slide's instructions:

- *Using our consensus model for the mantle tank, revise your model of the mantle movement under Afar on your handout.*
- *Make note of any lingering questions or uncertainties.*

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Look for **revised models** to include **density differences in the particle-level** modeling of the matter **based on thermal energy tomography data and evidence** from a mantle tank and lava lamps. (SEP: 2.3; DCI: ESS2.A.2, PS3.A.4)
- **Models** should include **energy being transferred into and out of the system** to heat/cool the matter of the mantle, **causing motion in the mantle**. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2)
- **Models** should reference balanced and unbalanced forces to explain the **convective motion of matter in the mantle due to density differences**. (SEP: 2.3; DCI: ESS2.A.2, PS3.A.4)

What to do:

- If students do not reference density or particle-level differences, direct them to look at the consensus model, consider the differences between mantle parcels, and consider how those differences might affect the sample's movement. If needed, direct them to look back at the optional simulation from day 1 to observe the differences in particle movement.
- If students do not show the transfer of energy through the system as shown in the convection model, direct them to look at the consensus model and consider what is occurring as one mantle parcel comes into contact with a parcel of lower kinetic energy. Tell them to think at the particle level to remember what happens as particles with higher energy come into contact with particles of lower energy. Then tell them to scale up to the size of the parcels and consider how the separate parcels might affect the movement of the entire section of mantle material.
- If students do not consider the effects of gravity on more and less dense sections of the mantle, ask them to consider what might be causing the more dense sections to be pulled down toward Earth's center. Have them consider how this might be different for different samples of different densities, and whether any pushing would occur between the parcels.

Building toward: 6.A.3 **Develop a model to explain the relationship between energy transfer and the motion of matter** in a solid material via **thermal convection and the motion of particles**. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)

10 · REVISIT THE DRIVING QUESTION BOARD

5 min

MATERIALS: 3x3 sticky notes, permanent marker

Revisit the DQB. Present **slide S**. Remind the class that at the end of the last lesson, we revisited the DQB and determined what questions we could answer, as well as what questions still need answers.

Ask the slide's first question, and have students look at the DQB to determine whether they can answer any more questions. Place a checkmark on the sticky notes with questions that have been answered, and move those to the side.

Ask the slide's second question. Distribute sticky notes and permanent markers, and tell students to add any new questions to the DQB. If questions do not emerge about where the energy/heat comes from that causes this cycle within the mantle, say: *It seems that we've figured out a lot about the movement of matter in the mantle. Did anyone draw what was causing it, or where this heat is coming from? Does anyone have ideas or questions about the energy source that could cause this movement?*

Allow students to respond. Point out that we have ideas about where the heat for this convection cycle might be coming from, and we have some questions about this as well. Say that the class should explore this topic next to determine where the energy is coming from for this cycle to occur.

11 · UPDATE THE PROGRESS TRACKER

5 min

MATERIALS: science notebook, *Progress Tracker*

Introduce the term convection. If the word has not yet been introduced, explain that the heating cycle we have been studying is called *convection*. If desired, give students a moment to add this or other terms to their Personal Glossaries.

Update the Progress Tracker. Display **slide T**. Say, *Now that we've developed our convection model, including what's happening from a matter, energy, and forces perspective, add an entry to your Progress Tracker that helps answer this lesson's question: "How is temperature related to the behavior of the matter in the mantle?"*

Give students time to update their trackers. They may write something like, "The mantle is composed of heterogeneous samples of matter that have different energy levels. The parcels with a higher average kinetic energy are pushed to the top of the mantle by the more dense parcels underneath that have a lower average kinetic energy. This cycle will continue where the more-dense parcels of matter push up the less-dense mantle parcels of matter."

Students should also mark the checkbox(es) in the tracker for any of the three lenses that we used throughout this lesson to help figure out these ideas, because each lens was utilized at least once. *

To close, remind the class that we have many unanswered questions left on our DQB, and our models don't quite reflect the source of the energy. Say that we will investigate this further next time.

* SUPPORTING STUDENTS IN DEVELOPING AND USING STABILITY AND CHANGE

Look for students to explain that the mantle's movement is predictable and also cyclical, based upon the changes that occur in the matter due to the sample's increased or decreased energy. This change happens over a long period of time.

Additional Lesson 6 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

CCSS.ELA-LITERACY.SL.9-10.1 Initiate and participate effectively in a range of collaborative discussions (one-on-one, in groups, and teacher-led) with diverse partners on grades 9-10 topics, texts, and issues, building on others' ideas and expressing their own clearly and persuasively.

Students discuss the convection in the mantle tank and Earth's mantle, coming to consensus on thermal convection. They also revisit the Driving Question Board as a class and identify any questions they can now answer. Students also add any new questions that have come up.

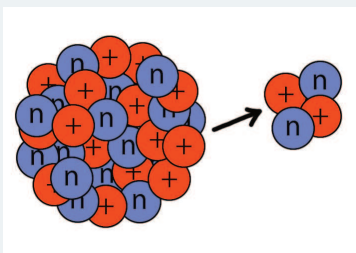
LESSON 7: Where does the energy that drives convection come from?

PREVIOUS LESSON We developed a predictive model of the movement of the mantle. We analyzed a video of a tank containing a mixture of liquid and plastic pellets simulating the matter in the mantle to figure out what happens to the matter when heat is added. We observed convection in the tank and developed a model to represent it utilizing the M-E-F triangle.

THIS LESSON

INVESTIGATION, PUTTING PIECES TOGETHER

2 days



We want to know where the heat comes from that drives mantle convection. We jigsaw a series of articles that answer this question from forces, matter, and energy perspectives. We develop a cause-effect model that integrates these three perspectives to explain how radioactive decay results in the release of enough heat to drive convection in the solid rock of Earth's mantle.

NEXT LESSON

We will analyze the radioactive element composition of rocks from Afar. We will plan and carry out an investigation using a simulation to collect data on how the amount of radioactive material in a rock crystal changes over time. We will use mathematical thinking to compare patterns in our graphs to those in an equation of exponential decay and use that equation to determine the age of rocks from Afar.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

7.A Construct a cause-effect explanation for how radioactive decay provides the heat that drives mantle convection, using ideas from our previous investigations, new evidence from a set of complementary readings, and the assumption that our past observations about matter, forces, and energy hold true across contexts. (SEP: 6.2; CCC: 2.2; DCI: ESS2.B.1, PS2.B.2, PS1.C.1, PS3.A.2)

7.B Ask questions that arise from examining models for explaining how radioactive decay at the subatomic scale can cause thermal energy transfer at the macroscopic scale to clarify and seek additional information regarding the relationships between matter, energy, and forces. (SEP: 1.2; CCC: 3.3; DCI: PS1.C.1, PS2.B.2, PS3.A.2, PS3.A.4)

WHAT STUDENTS WILL FIGURE OUT

- Nuclear energy can be modeled as being stored in the mass of the atomic nucleus itself. The conversion between mass and energy is modeled mathematically as $E=mc^2$.
- An imbalance of forces (strong and electric) in an atomic nucleus can cause protons, neutrons, and other particles to leave the atom, transferring kinetic energy into the surrounding material. This is a type of radioactive decay.
- Radioactive decay at the subatomic scale continually generates new energy, providing the primary source of the energy that drives mantle convection at the macroscopic scale.

Lesson 7 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	5 min		NAVIGATE Motivate the need to look at matter, energy, and forces interactions in the mantle.	A-B	
2	15 min		OBTAIN INFORMATION FROM A READING ABOUT RADIOACTIVE DECAY Individually read one of a series of articles about radioactive decay as part of Round 1 of a Jigsaw.	C	one of the Jigsaw handouts (<i>Radioactive Decay (Forces)</i> <i>Radioactive Decay (Matter)</i> or <i>Radioactive Decay (Energy)</i>), M-E-F poster developed in earlier lessons
3	20 min		RESPOND TO CAUSE-EFFECT PROMPTS IN ROUND 1 GROUPS Make sense of the readings by answering related cause-effect questions in Round 1 groups. Prepare for discussion in Round 2 groups in the next class.	D	one of the Jigsaw handouts (<i>Radioactive Decay (Forces)</i> <i>Radioactive Decay (Matter)</i> or <i>Radioactive Decay (Energy)</i>), M-E-F poster developed in earlier lessons
4	5 min		NAVIGATE WITH AN EXIT TICKET Complete an exit ticket about the other two corners of the M-E-F triangle.	E	loose-leaf paper
End of day 1					
5	2 min		NAVIGATE Turn and talk about the exit tickets from last time.	F	
6	15 min		DEVELOP A MECHANISTIC EXPLANATION ABOUT RADIOACTIVE DECAY Work in Round 2 groups to fill in the Cause-Effect Model handout.	G	either <i>Cause-Effect Model A</i> or <i>Cause-Effect Model B</i> , one of the Jigsaw handouts (<i>Radioactive Decay (Forces)</i> <i>Radioactive Decay (Matter)</i> or <i>Radioactive Decay (Energy)</i>)
7	15 min		COME TO CONSENSUS IN A SCIENTISTS CIRCLE Build on what we know about convection to construct a consensus cause-effect model that connects interactions at the nuclear scale to the cycling of matter in the mantle at the global scale. Update Personal Glossaries.	H-K	<i>Reference for Discussion Facilitators</i> , <i>Discussion Mapping Tool</i> , 2 clipboards (optional), Consensus Cause-Effect Model poster, chart paper marker (red), chart paper marker (green), chart paper marker (purple), chart paper marker (black), M-E-F poster
8	7 min		NAVIGATE AND REFLECT ON THE DISCUSSION MAP Discuss patterns in the discussion map, and consider what this data tells us. Identify the M-E-F connections between scales. Celebrate progress and wonder about radioactive material in Afar.	L-N	<i>Discussion Mapping Tool</i> , Community Agreements poster, Consensus Cause-Effect Model poster, Scale Chart poster, 2 3x5 sticky notes
9	6 min		COMPLETE AN ELECTRONIC EXIT TICKET Apply what we have figured out so far to a new phenomenon.	O	computer with access to https://docs.google.com/forms/d/17GF27o2OWj5tnVHBuE9KXf7dqzpotb-ZZnJ7lUncOvs/copy , L7 Electronic Exit Ticket Key
End of day 2					

Lesson 7 • Materials List

	per student	per group	per class
Lesson materials	- one of the Jigsaw handouts (<i>Radioactive Decay (Forces)</i> <i>Radioactive Decay (Matter)</i> or <i>Radioactive Decay (Energy)</i>) - loose-leaf paper - either <i>Cause-Effect Model A</i> or <i>Cause-Effect Model B</i> - science notebook - computer with access to https://docs.google.com/forms/d/17GF27o2OWj5tnVHBuE9KXf7dqzpotb-ZZnJ7lUncOvs/copy		- M-E-F poster developed in earlier lessons <i>Reference for Discussion Facilitators</i> <i>Discussion Mapping Tool</i> 2 clipboards (optional) - Consensus Cause-Effect Model poster - chart paper marker (red) - chart paper marker (green) - chart paper marker (purple) - chart paper marker (black) - M-E-F poster - Community Agreements poster - Scale Chart poster 2 3x5 sticky notes <i>L7 Electronic Exit Ticket Key</i>

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 handouts so they can be added to students' science notebooks.

Sign up for a free Gizmo - Explore Learning account.

Go to <https://s3.amazonaws.com/p.3simulation/collisions/seatbelts-airbags.html> and register for a free account. You will have free access to all the simulations for the first 30 days, then limited access to only the free simulations after the 30-day trial period. The Gizmo we use in this unit is a free Gizmo on their site. It will still be available after the 30-day trial period is over by logging into your account.

Prepare for the Round 2 Jigsaw on day 2 ahead of time by choosing a system for rearranging students quickly from their original reading groups into their new mixed groups of 3: 1 student who reads about forces, 1 who reads about energy, and 1 who reads about matter.

You need volunteers to be 2 facilitators and 2 discussion mappers for the Consensus Discussion on day 2. Consider reaching out ahead of time to students who may want to fulfill those roles. Putting the facilitator reference and the mapping tool on clipboards may make these easier to use.

At the end of day 2, students analyze the newly created discussion map and consider how to increase equitable participation. Be ready to share the completed discussion map with the class. You can do this by quickly taking a photo and adding it to a slide, projecting it with a document camera, uploading it to an LCMS such as Google Classroom, or making copies if a photocopier is available, but there is not a lot of turnaround time for this. As an alternative, you can move this conversation to Lesson 8 to allow yourself time to make photocopies that students can mark up and study more closely.

Make sure the M-E-F triangle poster developed in previous lessons is displayed where students can see it. Have the Scale Chart poster displayed near the front of the room, to be added to during this lesson.

Prepare chart paper for the poster you make in this lesson:

- Consensus Cause-Effect Model

Make a copy of <https://docs.google.com/forms/d/17GF27o2OWj5tnVHBuE9KXf7dqzpotb-ZZnJ7lUncOvs/copy>. Have computers available for each student to access your copy of the Electronic Exit Ticket on day 2. Either place the link to your copy on slide O, or provide a link for students on your school's content management platform.

Lesson 7 • Where We Are Going and NOT Going

Where We Are Going

The goal of this lesson is to fill in the blanks on our model of mantle convection by figuring out where the energy comes from to drive the process. Students complete a reading jigsaw designed to help them weave together a story that combines the matter, energy, and forces perspectives. They learned about fission in *OpenSciEd Unit C.5: How can chemistry help us evaluate fuels and transportation options to benefit the Earth and our communities? (Fuels Unit)*, and they learn about radioactive decay in this lesson.

This lesson is designed to coherently build new ideas related to the following disciplinary core ideas (DCIs):

- **PS1.C** Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process. (HS-PS1-8) (crossed-out bits are covered in *OpenSciEd High School Unit P.6: Why do stars shine and will they shine forever?*)
- **ESS2.B.1** The radioactive decay of unstable isotopes continually generates new energy within Earth's crust and mantle, providing the primary source of the heat that drives mantle convection. Plate tectonics can be viewed as the surface expression of mantle convection. (HS-ESS2-3) (crossed-out bits are covered in Lesson 10)

Students are asked to apply DCIs that they have been developing over several units, which are key to sensemaking in this lesson. These include:

- **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) (This DCI, including the crossed-out bits, is developed in *OpenSciEd High School Unit P.1: How can we design more reliable systems to meet our communities' energy needs?* This lesson focuses on fields in a new context to reinforce the ideas.)
- **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)
- 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)

Students encounter and/or co-construct ideas around several words during this lesson, and may decide to add the following words to their Personal Glossaries: *radioactive decay, neutrons*. Do not ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

Students are not asked to distinguish between different types of radioactive decay (e.g., alpha, beta, gamma). They will not learn explicitly about electromagnetic radiation until *OpenSciEd Unit P.5: How do we use radiation in our lives, and is it safe for humans? (Microwaves Unit)*. They also do not consider the potentially dangerous effects of all kinds of ionizing radiation on the human body. That will be addressed in the *Microwaves Unit* as well.

LEARNING PLAN for LESSON 7

1 · NAVIGATE

5 min

MATERIALS: None

Turn and talk about where the energy for convection might come from. Display slide A. Say, *We figured out that rock in the mantle is moving. As rock deep inside Earth heats up, it rises toward the surface. Then it cools and sinks back down again. This cycle depends on heat that's deep in the planet. What ideas did we have about where the heat might be coming from?* Remind students that we thought about this at the end of Lesson 6. Give them about 2 minutes to share their ideas with a partner.

Motivate the need to look at matter, energy, and forces interactions in the mantle. Present slide B. Use the prompt to elicit student ideas. Highlight suggestions that use science ideas to motivate the use of matter, energy, or forces, as in the examples in the table below. *

Suggested prompt	Sample student response
<i>How could each of these perspectives help us figure out where the heat might be coming from, deep inside Earth?</i>	We should look for the energy source that generates the heat, because heat is a form of energy, and energy must transfer from somewhere. We know that forces transfer energy, and heat is a form of energy, so we should look at the forces that are transferring the energy. Matter generates forces through fields, so looking at the particle changes that cause these forces will help us understand how energy is transferred as heat in the mantle.

* SUPPORTING STUDENTS IN DEVELOPING AND USING ENERGY AND MATTER

This is another instance in this unit in which ideas and prompts in the M-E-F poster are used to offer multiple means of engagement with a phenomenon. By directing their attention to the relationships between these three perspectives, students can begin to identify interactions that are crucial for further investigation.

2 · OBTAIN INFORMATION FROM A READING ABOUT RADIOACTIVE DECAY

15 min

MATERIALS: one of the Jigsaw handouts (*Radioactive Decay (Forces)* *Radioactive Decay (Matter)* or *Radioactive Decay (Energy)*), M-E-F poster developed in earlier lessons

Motivate the readings. Point to the M-E-F poster. Say, *It sounds like it might help to obtain information about matter, energy, and forces, rather than just focus on one, and see whether we can make sense of what is going on here. I have three readings to help us answer our questions. One reading takes an energy perspective, one takes a forces perspective, and one takes a matter perspective.*

* ATTENDING TO EQUITY

Differentiation opportunity/Support for emergent multilingual learners: Although all three readings are leveled between grades 8 and 9, Matter is the longest (over 1,000 words) and Forces is the shortest (under 800 words). Consider assigning students who may need additional support for literacy to the Forces group, so they have less text to read. We **do not** recommend homogenous groupings, but rather, creating mixed-ability groupings, with a higher proportion of students who need more support in the Forces group.

Organize Round 1 groups. Present slide C. Break the classroom into three reading groups: Forces, Matter, and Energy. Within each reading group, organize students into smaller groups of 3–4. Distribute *Radioactive Decay (Forces)*, *Radioactive Decay (Matter)*, and *Radioactive Decay (Energy)* to the three respective reading groups.

Give students 10 minutes to read their articles and respond to the first two questions on their handouts independently. *

3 · RESPOND TO CAUSE-EFFECT PROMPTS IN ROUND 1 GROUPS

20 min

MATERIALS: one of the Jigsaw handouts (*Radioactive Decay (Forces)*, *Radioactive Decay (Matter)*, or *Radioactive Decay (Energy)*), M-E-F poster developed in earlier lessons



Make sense of the readings in Round 1 groups. Present slide D. Have students work for 20 minutes with their small reading groups to answer the cause-effect questions on the last page of their handouts. Tell them that next time, they will each share their responses with a new group in Round 2, so they may want to take additional notes on this first conversation to prepare.

Collect students' handouts to review after class (see the Assessment Callout), but be ready to return them at the next class, as students will need them. *

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Students distill **ideas from the readings** to explain **that radioactive decay provides the heat that drives mantle convection**. (SEP: 6.2)
- Students **link cause at the particle scale to effect at the macroscopic scale** using mechanistic reasoning. (CCC: 2.2)
- Students accurately **describe radioactive decay** according to the subject of the article they read (**forces, energy, or matter**). See the accompanying *Cause-Effect Model Key* for examples at various levels of proficiency. (DCI: ESS2.B.1, PS1.C.1, PS2.B.2, PS3.A.2)

What to do: Provide feedback using the suggestions in the key. This will be useful for students in Round 2, as they join their Jigsaw groups to compare and integrate their ideas with those of their peers.

Building toward: 7.A.1 **Construct a cause-effect explanation for how radioactive decay provides the heat that drives mantle convection, using ideas from our previous investigations, new evidence from a set of complementary readings, and the assumption that our past observations about matter, forces, and energy hold true across contexts.** (SEP: 6.2; CCC: 2.2; DCI: ESS2.B.1, PS2.B.2, PS1.C.1, PS3.A.2)

* ATTENDING TO EQUITY

Supporting emergent multilingual students:

Encourage students to record their ideas using linguistic modes (e.g., written words) and nonlinguistic modes (e.g., drawings) in the space provided in the readings. This is especially important for emerging multilingual students, because making connections between written words and nonlinguistic representations helps students generate richer explanations of scientific phenomena.

4 · NAVIGATE WITH AN EXIT TICKET

5 min

MATERIALS: loose-leaf paper



Respond to the exit ticket. Present slide E. Say, *Today, each of you has been thinking deeply about only one corner of the M-E-F triangle.* Read the slide's question aloud:

- *What questions do you have about the other two corners of the M-E-F triangle that would help to explain how a process at the subatomic scale can produce enough heat to drive convection?*

Distribute a sheet of loose-leaf paper to each student. Have them respond to the prompt as an exit ticket, and then hand the paper in as they leave class.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

Accept all ideas, but across the class, look for the following:

- Students apply what they know about **matter, energy, and forces** in articulating their questions. For example, a student who reads about forces might ask, “What energy transfers when the forces are imbalanced?” A student who reads about energy might ask, “What changes can you detect in the matter when energy is released from atomic nuclei?” A student who reads about matter might ask, “What unbalanced forces cause the motion of the particles?” (DCI: PS1.C.1, PS2.B.2, PS3.A.2, PS3.A.4)
- Students **ask questions that seek to clarify an understanding** or provide additional information about **nuclear processes** to explain **macroscopic thermal energy**. Look for sentence stems like “How does ____ cause ____?” or “Why does ____ happen when ____?” (SEP: 1.2; CCC: 3.3)

What to do: Accept all student ideas. Consider using the exit tickets for strategic grouping in Round 2 of the Jigsaw, by distributing students who are asking questions that meet the above criteria across the new small groups, if possible.

Building toward: 7.B Ask questions that arise from examining models for explaining **how radioactive decay at the subatomic scale can cause thermal energy transfer at the macroscopic scale to clarify and seek additional information regarding the relationships between matter, energy, and forces.** (SEP: 1.2; CCC: 3.3; DCI: PS1.C.1, PS2.B.2, PS3.A.2, PS3.A.4)

End of day 1

5 · NAVIGATE

2 min

MATERIALS: None

Turn and talk about the exit tickets. Present **slide F**. Return students’ exit tickets, and ask them to consider the slide’s prompt:

- *How would answering these questions help us understand how radioactivity causes mantle convection?*

Have students take a moment to bounce their ideas off a partner, and add any other questions to their exit tickets before Round 2 of the Jigsaw.

6 · DEVELOP A MECHANISTIC EXPLANATION ABOUT RADIOACTIVE DECAY

15 min

MATERIALS: either *Cause-Effect Model A* or *Cause-Effect Model B*, one of the Jigsaw handouts (*Radioactive Decay (Forces)*, *Radioactive Decay (Matter)* or *Radioactive Decay (Energy)*)

Reshuffle students into Round 2 groups. Quickly arrange students into new groups of 3: one student with the Energy reading, one with the Matter reading, and one with the Forces reading.

Present **slide G**. Each group member should get up to 3 minutes to summarize the article they read in Round 1, read the three questions at the end aloud, and share their answers. Consider asking one student in each group to keep time, or use a timer at the front of the classroom.

Fill in the cause-effect handout. Tell students to work in their Round 2 groups, using the answers to all the cause-effect questions to fill in the Cause-Effect Model handout (whichever version you choose) to explain where the energy to drive convection comes from. *

* ATTENDING TO EQUITY

Supporting emergent multilingual learners: There are two versions of the same cause-effect modeling handout, which vary in the level of scaffolding they provide. *Cause-Effect Model A* is a more scaffolded version with suggestions for building the causal chain, whereas *Cause-Effect Model B* only provides sentence frames. We recommend starting with the less-scaffolded version but

having the other on hand. If a student needs extra support, offer them the more-scaffolded version in the moment as needed. However, if you have a class with many students who are multilingual, or who need additional literacy support, consider starting with the more scaffolded version for all students.

7 · COME TO CONSENSUS IN A SCIENTISTS CIRCLE

15 min

MATERIALS: *Reference for Discussion Facilitators*, *Discussion Mapping Tool*, 2 clipboards (optional), Consensus Cause-Effect Model poster, chart paper marker (red), chart paper marker (green), chart paper marker (purple), chart paper marker (black), M-E-F poster

Introduce the *Discussion Mapping Tool*. Display slide H. Say, *We're going to use a tool today to map our discussion. This will help us think about how we can all work together when we're discussing new ideas to move our thinking forward.* If you used this tool in Lesson 1, suggest to students that we might look for a shift in the focus of our discussion.

Establish student volunteers. You need 4 student volunteers for this discussion: 2 facilitators and 2 mappers. Consider reaching out ahead of time to students who may want to fulfill these roles.

ADDITIONAL GUIDANCE

The *Discussion Mapping Tool* provides a visual representation of the conversation patterns happening within the class. Use lines to track how the discussion moves between speakers. After you track the first few moves, pause to show the class what the map looks like. Ask for a volunteer to map the rest of the discussion. This can be a way to involve a student who is less comfortable speaking publicly. Each time you use the discussion tool in this unit, have a new volunteer record the map.

Though the *Discussion Mapping Tool* includes codes to mark various types of contributions, you may want to simply track discussion patterns the first few times you use the tool. As students become more comfortable with discussion mapping, you can add the contribution codes.

After framing the questions, be ready to keep track of student ideas on chart paper.



Come to consensus in a Scientists Circle. Present slide I. Convene a Scientists Circle. Gather around the Consensus Cause-Effect Model poster to construct a class consensus version of the model students have been working on. See the preparation section for more. Alternatively, you can facilitate this by projecting a digital version of the handout, or using a document camera, and filling it in together.

Have the first volunteer facilitator initiate the discussion by following the instructions in *Reference for Discussion Facilitators*:

- *To begin, ask one group to get us started by sharing their responses in the first row.*
- *When this group has finished speaking, ask the other groups to raise their hands if they have something similar. Give groups that raised their hands time to share.*
- *Ask whether any groups disagreed, or had something to add. Ask students who disagree to share their ideas.*
- *Repeat this process for each row. If there is disagreement, ask the class which ideas best explain the patterns we see at the macroscopic scale.*

As students suggest phenomena, use the *Discussion Mapping Tool* to record the first few who offer ideas. Take a moment to show the tool to the class, then ask the first volunteer mapper to take over. This allows you to focus on listening to student ideas (see the Key Ideas callout and the Assessment callout below) and recording them on the Consensus Cause-Effect Model poster. After a few minutes, pause the discussion and ask the second volunteer mapper to continue the mapping.

As students share ideas and you record these in the class consensus model, ask students to clarify the framing of the mechanisms they suggest (point to the M-E-F poster). Use black to underline key phrases and annotate them with “matter”, “energy”, or “forces” (or M, E, F).

Discuss the interconnectedness of M-E-F perspectives. Present slide J. Pose the slide’s questions:

- *Where did you integrate ideas about the interactions between matter and energy?*
- *Between matter and forces?*
- *Between energy and forces?*

Listen for ideas about unbalanced forces transferring energy (for example, when electrostatic forces and strong forces are no longer in balance, transferring energy out of the atomic nucleus). Point to the M-E-F poster to remind students that this is a principle we have previously identified.

Listen for ideas about energy transfer happening with changes to the motion of matter (for example, when heat from radioactivity transfers into the surrounding matter, causing changes to the density of the matter, which then causes it to float upward toward Earth’s surface). Point to the M-E-F poster to remind students that this is another principle we have previously identified.

Students might also point out how fields between particles in the nucleus cause forces that can be either balanced or unbalanced, or how moving matter transfers thermal energy from Earth’s core to the surface.

KEY IDEAS

Purpose of this discussion: The purpose of this discussion is to build on what we know about convection to construct a cause-effect model that connects interactions at the nuclear scale to the cycling of matter in the mantle at the global scale. The model should integrate forces, matter, and energy perspectives to explain how radioactive decay results in heat. This model motivates the need to understand how convection can be causing the surface features observed in Afar.

Listen for these ideas:

- Atomic nuclei are made of particles.
- Changing the number of protons in an atomic nucleus results in a new element.
- Unbalanced forces (electrostatic and strong) can result in a process called radioactive decay, which results in the transfer of energy and sometimes matter out of the nucleus.
- The energy transferred out of the nucleus becomes the heat that drives convection.
- Through convection, material from the mantle moves upward into the crust, and material from the crust moves down into the mantle (connect to Lesson 6).

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Listen for the **key ideas listed in the Key Ideas callout**, all of which rely on evidence from a variety of sources (our previous investigations, new evidence from the readings, and the assumption that our past observations about the relationships between matter, forces, and energy hold true across contexts). (SEP: 6.2; DCI: ESS2.B.1, PS1.C.1, PS2.B.2, PS3.A.2)
- Use the **Cause-Effect Model Key (cause-effect chain)** as an example of what a class consensus model explaining mantle convection at multiple scales might look like. (SEP: 6.2; CCC: 2.2)
- Listen for students to be able to explicitly identify **how matter, energy, and forces interact** as part of the class consensus model. (DCI: ESS2.B.1, PS1.C.1)

What to do: Press students for evidence from their small-group conversations and/or the readings. Use the sources listed in gray in the key to point students back to the places in their readings where they might find more information about gaps in their understanding.

Building toward: 7.A.2 Construct a cause-effect explanation for how radioactive decay provides the heat that drives mantle convection, using ideas from our previous investigations, new evidence from a set of complementary readings, and the assumption that our past observations about matter, forces, and energy hold true across contexts. (SEP: 6.2; CCC: 2.2; DCI: ESS2.B.1, PS2.B.2, PS1.C.1, PS3.A.2)

Add new terms to our Personal Glossaries. Present slide K. Ask students to identify 2-3 important new terms that we think we have developed definitions for and want to add to our Personal Glossaries. Make sure that *radioactivity* and/or *radioactive decay* is one of these terms. *Nucleus, isotopes, protons, and neutrons* may also be terms that students decide to define.

8 • NAVIGATE AND REFLECT ON THE DISCUSSION MAP

7 min

MATERIALS: science notebook, *Discussion Mapping Tool*, Community Agreements poster, Consensus Cause-Effect Model poster, Scale Chart poster, 2 3x5 sticky notes

Reflect on the discussion map. Display the discussion map by passing it around, putting it under a document camera, or snapping a photo and projecting it on slide L. Give students a few minutes to individually observe the map and document any patterns they notice in their notebook.

Then point to the Community Agreements and say, *After looking at this map, what are some things we should consider during our discussions to make sure that everybody plays a role in moving our thinking forward?* ✱ Listen for responses such as:

- We should ask questions and respond to each other instead of directing our responses to the teacher.
- We should invite people into the discussion who have not had chances to contribute.
- We should monitor our airtime and give other people time to talk.

Identify the M-E-F connections between scales. Present slide M. Pose the slide's first question:

- *Where do the cause-effect mechanisms we identified today belong on our Scale Chart poster?*

Move through the rows of the Consensus Cause-Effect Model poster and identify the spatial and temporal scales of each mechanism relative to what we have on the Scale Chart poster. For example, radioactive decay occurs on a very tiny spatial scale. The decay itself happens on a very short timescale, but convection occurs over millions of years. Decide as a class where it belongs along the temporal axis.

Ask students to look back at the Consensus Cause-Effect Model poster to see that we figured out that the radioactive decay causes increased particle movement in the mantle. Move over to the Scale Chart poster, add "particle movement in the mantle", and draw an arrow to it from "radioactive decay."

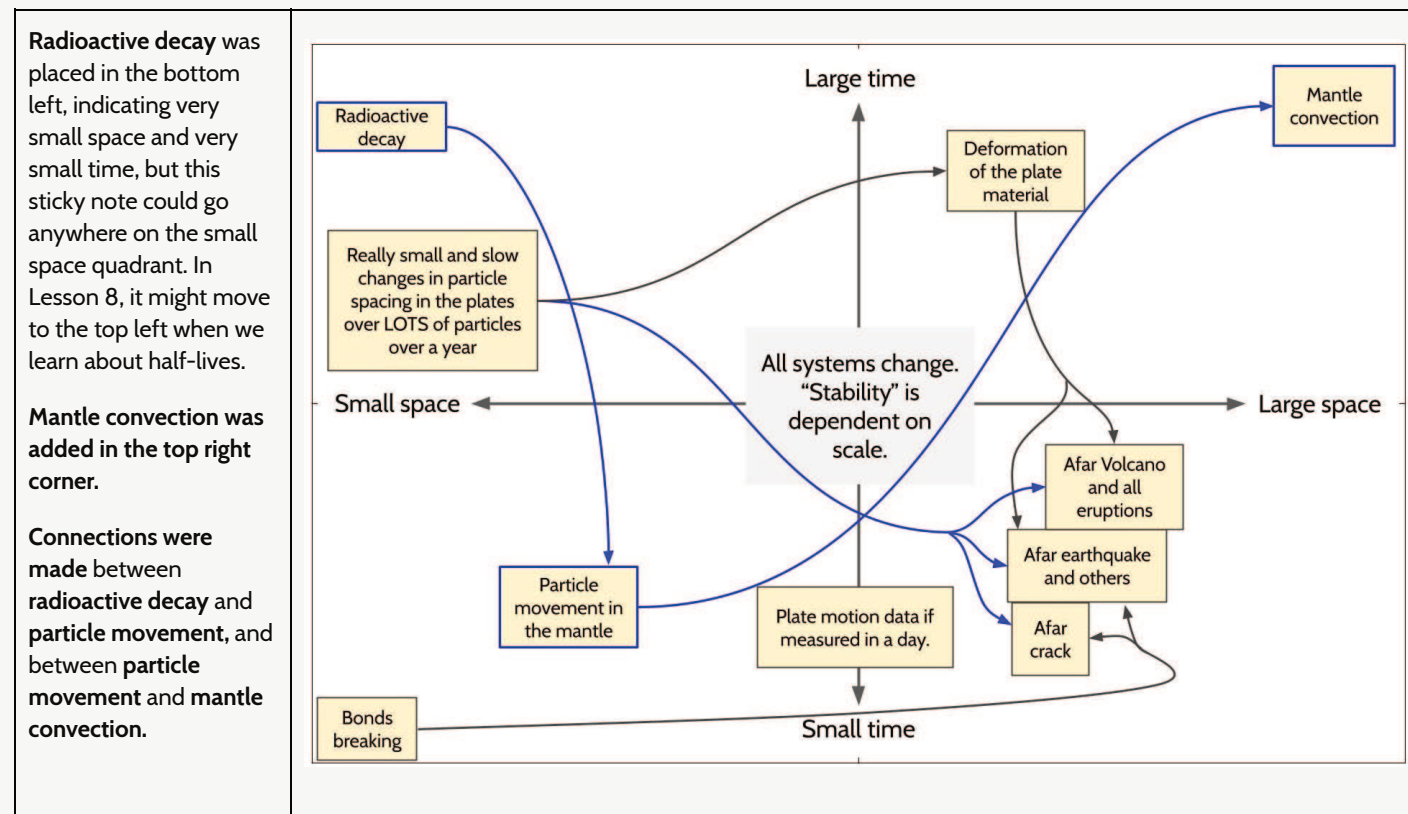
✱ ATTENDING TO EQUITY

Building classroom culture: The goal of this reflection is to notice whole-class patterns and decide how all students can move discussions forward as a community, which is a part of our Community Agreements. Avoid addressing the contributions or behaviors of specific students. If these are brought up, prompt students to return to the class-level patterns, saying, *Let's look at the whole map. What suggestions can we make that would support our whole class community?*

This is also an opportunity to remind students that the *Discussion Mapping Tool* captures only spoken contributions, and to explicitly state that nonverbal participation and listening closely are also valued. If this idea resonates with students, make sure it is reflected in the Community Agreements.

Work with the class to determine that mantle convection happens on a very large timescale and over a very large spatial scale. It should be near the top right corner of the Scale Chart poster.

Finally, ask what mechanisms cause the mantle convection. Students should say that particle movement at the micro-scale causes this macro-scale change. If they decide to add more mechanisms to the Scale Chart poster, follow their lead. An example of this is shown below.



Celebrate progress and wonder about radioactive material in Afar. Present slide N. Say, *We can explain so much now about matter, energy, and forces beneath Earth's crust! Radioactivity helps us understand what might be driving some of the processes we see. I wonder whether we'll find radioactive material in the rock in the Afar region. Quickly turn and talk with a partner. Based on our ideas, do you think we'll find evidence of radioactive material in Afar? Why or why not?*

9 · COMPLETE AN ELECTRONIC EXIT TICKET

6 min

MATERIALS: computer with access to <https://docs.google.com/forms/d/17GF27o2OWj5tnVHBuE9KXf7dqzpotb-ZZnJ7lUncOvs/copy>, *L7 Electronic Exit Ticket Key*



Assign the Electronic Exit Ticket. Before class, make a copy of <https://docs.google.com/forms/d/17GF27o2OWj5tnVHBuE9KXf7dqzpotb-ZZnJ7lUncOvs/copy>. Share the link to the copy with students (**do not** share the original link provided here, as that will create a new copy for each student, and you will not have access to their responses). Present **slide O**. Give students 5-10 minutes to complete the Electronic Exit Ticket.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Use the *L7 Electronic Exit Ticket Key* to assess student work.

What to do: This assessment is designed to make it easy to gather information about where students are still struggling to put the pieces together. It assesses one of the lesson-level performance expectations (LLPEs) from this lesson (Lesson 7), which brings together DCIs, CCCs, and SEPs from the previous three lessons.

Building toward: **7.A** Construct a cause-effect explanation for how radioactive decay provides the heat that drives mantle convection using ideas from our previous investigations, new evidence from a set of complementary readings, and the assumption that our past observations about matter, forces, and energy hold true across contexts. (SEP: 6.2; CCC: 2.2, 3.3; DCI: ESS2.B.1, PS3.A.2, PS2.B.2, PS1.C.1)

Additional Lesson 7 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

CCSS.ELA-LITERACY.11-12.RST.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.

This standard is claimed because students synthesize information from several readings to develop a coherent understanding of how radioactivity drives convection in Earth's interior. Each reading alone is not sufficient to describe the phenomenon. The class works together to create this coherent understanding.

CCSS.ELA-LITERACY.11-12.RST.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.

This standard is claimed because students determine the central ideas from the readings. They must paraphrase these important ideas to distill the cause-and-effect mechanisms required to create a consensus causal chain model.

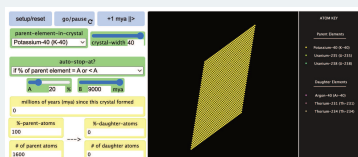
LESSON 8: Is the rock at Afar radioactive, and what can that tell us?

PREVIOUS LESSON We wanted to know where the heat comes from that drives mantle convection. We read a series of articles that answer this question from forces, matter, and energy perspectives. We developed a cause-effect model to explain the mechanism that results in energy release from radioactive decay.

THIS LESSON

INVESTIGATION

3 days



We analyze the radioactive element composition of rocks from Afar. We plan and carry out an investigation using a simulation to collect data on how the amount of radioactive material in a rock crystal changes over time. We use mathematical thinking to compare patterns in our graphs to those in an equation of exponential decay, and we use that equation to determine the age of rocks from Afar.

NEXT LESSON

We will look at the crustal ages of rocks around the world in both oceans and continents, and notice a number of patterns, including that the continental rock is significantly older, and that the farther the rock is from some plate boundaries in the ocean, the older it is. We will determine the density of basalt (oceanic crust) and granite (continental crust) and wonder about how that affects forces and energy transfer. We will add questions to the Driving Question Board about plate boundaries and types of crust.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

8.A Sketch and describe graphs for percent of parent and daughter elements versus time; use a spreadsheet to graph and compare patterns across different crystal sizes and different parent elements and compare these to patterns predicted by an exponential decay law. (SEP: 5.2; CCC: 1.4; DCI: PS1.C.2)

8.B Analyze data using a spreadsheet and an exponential decay law to find the age of various rock samples using relationships (half-lives) discovered in prior investigations; interpret the patterns across the ages of these samples and the sites where these are located to reconstruct the geologic history of Afar over the last 700 million years. (SEP: 4.1; CCC: 1.5; DCI: PS1.C.2)

WHAT STUDENTS WILL FIGURE OUT

- Radioactive decay of elements follows a characteristic exponential decay law, with a specific lifetime (timescale) for each; we can use this to determine the ages of rocks and other materials from the ratio of parent to daughter elements present.
- Some of the rock on the western and eastern edges of Afar formed hundreds of million years ago. But most of the rock in the middle of the Afar region is very young, appearing over the last few million years.

Lesson 8 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	2 min		NAVIGATE Review what we figured out was the main source of energy for mantle convection.	A	
2	5 min		CONSIDER PRESENCE OF RADIOACTIVE MATERIALS IN AFAR Discuss the possibility of finding radioactive materials in Afar, and how that can help us reconstruct the past and predict the future of this region.	B-D	
3	8 min		ANALYZE AND INTERPRET DATA Orient to the map of rock sample sites and analyze the composition of rock samples.	E-H	<i>Rock Sample Site Map</i>
4	6 min		DISCUSS RELATED PHENOMENA AND INTRODUCE RELATED TOOLS AND PROCESS Summarize the rock transformation process to make sense of patterns across the volcanic rock samples. Learn that spectrometers are used to analyze the element composition of crystals.	I-P	<i>Rock Transformation Process (optional)</i>
5	6 min		MAKE PREDICTIONS AND CONNECT TO OUR ANCHORING PHENOMENON Record predictions individually and discuss questions related to the Afar region.	Q-R	<i>Predicting Composition Trends</i>
6	8 min		PLAN AN INVESTIGATION Orient to the simulation and spreadsheet. Plan an investigation for condition 1 as a group.	S-U	group copy of radioactive decay data collection spreadsheet from https://docs.google.com/spreadsheets/d/1-7OYiN8LLC7jHzeSvRCMUc66T78H5lNx3uVqWc2e68Y/edit?usp=sharing , https://youtu.be/r6C3VnDUaq8?si=q5A3b4M3tXha5b5O , https://youtu.be/vfJkpgKkUqI (optional)
7	10 min		COLLECT DATA FOR THE FIRST CONDITION Collect and record initial data for condition 1.	V	https://openscienced-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html , group copy of data collection spreadsheet
<i>End of day 1</i>					
8	6 min		NAVIGATE Remind students where we left off last time.	W-X	https://openscienced-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html , group copy of data collection spreadsheet
9	10 min		COLLECT DATA FOR ADDITIONAL CONDITIONS Modify the spreadsheet to support data collection for additional trials and conditions. Collect additional data using the simulation.	Y-Z	https://openscienced-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html , group copy of data collection spreadsheet

Part	Duration		Summary	Slide	Materials
10	8 min		ANALYZE THE DATA Produce and analyze graphs of the data from the spreadsheet.	AA-BB	<i>Analyzing Decay Trends</i>
11	7 min		COMPARE RESULTS Compare results in jigsaw groups to determine whether crystal size affects the time at which there is a certain fraction of the parent material left.	CC	<i>Analyzing Decay Trends</i>
12	3 min		ARGUE FROM EVIDENCE Share arguments for whether crystal size affects the time at which a certain fraction of the parent material is left.	DD-EE	<i>Analyzing Decay Trends</i>
13	10 min		USE MATHEMATICAL THINKING TO ANALYZE RADIOACTIVE DECAY GRAPHS Turn and talk about patterns noticed between the time for decay to 50% and the time for decay to 25%. Use these ideas to develop a mathematical model as a class, and use the model to test predictions.	FF-GG	<i>Analyzing Decay Trends, Age of Rocks, calculator, Rock Sample Site Map, https://youtu.be/Y-GP_AedXBQ?si=kbwYEQaitgwrnxnRN, https://youtu.be/H9CPgtaorzE?si=iFOyrWZSbnGGotu1, chart paper (optional), chart paper markers (optional)</i>
14	1 min		NAVIGATE Highlight limitations of our data in calculating the age of rocks.	HH	
<i>End of day 2</i>					
15	20 min		USE MATHEMATICAL THINKING TO MAKE SENSE AND USE A MODEL OF RADIOACTIVE DECAY Recall our data's limitations to motivate exploring a mathematical model.	HH-NN	
16	10 min		DETERMINE THE AGES OF ROCKS IN AFAR Orient to the rock sample data. Determine the age of rock samples in groups.	OO-QQ	<i>Age of Rocks, Rock Sample Site Map</i>
17	8 min		ANALYZE AND INTERPRET DATA Work in partners to use the <i>Rock Sample Site Map</i> and the calculated rock ages to discuss patterns in the locations of older versus younger volcanic rocks in the Afar region.	RR	<i>Age of Rocks, Rock Sample Site Map</i>
18	4 min		UPDATE THE SCALE CHART POSTER Add ideas to the Scale Chart poster.	SS	<i>Scale Chart poster</i>
19	3 min		NAVIGATE Discuss the rocks in Afar to motivate expanding our scale to consider the age of rocks found in other parts of the world.	TT	<i>Rock Sample Site Map, Age of Rocks</i>
<i>End of day 3</i>					

Lesson 8 • Materials List

	per student	per group	per class
Lesson materials	- science notebook <i>Rock Transformation Process</i> (optional) <i>Predicting Composition Trends</i> - group copy of radioactive decay data collection spreadsheet from https://docs.google.com/spreadsheets/d/1-7OYiN8LLC7jHzeSvRCMUc66T78H5lNx3uVqWc2e68Y/edit?usp=sharing https://opencied-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html - group copy of data collection spreadsheet <i>Analyzing Decay Trends</i> <i>Age of Rocks</i> - calculator <i>Rock Sample Site Map</i>	<i>Rock Sample Site Map</i>	https://youtu.be/r6C3VnDUaq8?si=q5A3b4M3tXha5b5O https://youtu.be/vfJkpgKkUqI (optional) https://youtu.be/Y-GP_AedXBQ?si=kbwYEQaitgwrnRN https://youtu.be/H9CPgtaorE?si=iFOyrWZSbnGGotu1 - chart paper (optional) - chart paper markers (optional) - Scale Chart poster

Materials preparation (30 min 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.

Make 1 color copy of the *Rock Sample Site Map* for every 2 students in your largest class. Place these in sheet protectors. You will collect and reuse these across classes.

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

Make copies of the handouts for this lesson:

- Predicting Composition Trends* - 1 per student
- Analyzing Decay Trends* - 1 per student
- Age of Rocks* - 1 per student
- Rock Transformation Process* - 1 per student (optional, as it contains the same information presented in **slides K-M**)

Conduct the following tests of the videos for this lesson:

- Spin off a copy of the radioactive decay data collection spreadsheet, <https://docs.google.com/spreadsheets/d/1-7OYiN8LLC7jHzeSvRCMUc66T78H5lNx3uVqWc2e68Y/edit?usp=sharing>. You will share this copy with the class. Each group will then spin off a copy to share within the group so each member can contribute a row of data.
- Run the simulation, <https://opencied-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html>.
- View the simulation and spreadsheet orientation videos:
 - Using the sim, <https://youtu.be/r6C3VnDUaq8?si=q5A3b4M3tXha5b5O>
 - Collecting data using the spreadsheet, <https://youtu.be/vfJkpgKkUqI>
 - Identifying half-life patterns, https://youtu.be/Y-GP_AedXBQ?si=kbwYEQaitgwrnRN
 - Using equation to identify age of rock samples, <https://youtu.be/H9CPgtaorE?si=iFOyrWZSbnGGotu1>

Reserve enough computers for each student to use on days 1 and 2.

Lesson 8 • 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 (DCI):

- **PS1.C: 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 to HS-ESS1-5, secondary to HS-ESS1-6)

Students sketch the shape of a predicted relationship as a graph in this lesson. Most will probably draw a linear relationship. Later in the lesson, students see that their graphs show the relationships they predicted are actually nonlinear. Students who have completed the high school OpenSciEd Chemistry course have seen a nonlinear relationship in data.

This is the only time in this unit that students use a graph and an exponential decay law to determine the age of rock. They focus on the ages of rocks and do not extend this to other materials.

Students use a spreadsheet to accomplish several tasks. One task is to plan conditions to investigate and collect data, the second is to graph the data, and the third is to solve an equation. Students who have completed the high school OpenSciEd Chemistry course have had multiple experiences with these uses.

This lesson is designed to support students toward the Next Generation Science Standards (NGSS) Nature of Science Understanding titled **Scientific Investigations Use a Variety of Methods** (Appendix H). The relevant understanding element reads:

- Scientific inquiry is characterized by a common set of values that include: logical thinking, precision, open-mindedness, objectivity, skepticism, replicability of results, and honest and ethical reporting of findings.

Students assess the accuracy and replicability of their results as they investigate radioactive decay using a simulation. Working in groups and as a class, they discuss the importance of accuracy and replicability in scientific investigations.

Students encounter and/or co-develop definitions for several terms during this lesson, and may choose to add these words to their Personal Glossaries: *crystal*, *spectrometer*, *parent element*, *daughter element*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning. Then, create an opportunity to add new meanings to Personal Glossaries, if desired.

Where We Are NOT Going

Though the data analyzed in this lesson are largely based on measured samples from Afar, some simplifications have been made. One was to site locations in the *Rock Sample Site Map*. For details on this modification and why it was made, see the *Site Location Modifications* reference. Another was to the parent-to-daughter-element proportions in rock samples in the *Age of Rocks* handout. For details on this modification and why it was made, see the *Rock Composition Modifications* reference.

LEARNING PLAN for LESSON 8

1 · NAVIGATE

2 min

MATERIALS: None

Navigate. Present **slide A**. Revisit the last question in the Electronic Exit Ticket from Lesson 7:

- *Radioactivity drives mantle convection deep inside Earth. But there is also naturally occurring radioactive material on Earth's surface, and humans use radioactive materials in technology.*
 - *Where else have you heard about radioactivity occurring naturally or being used?*

Have students share out. Accept all answers. Say, *We know there is radioactive material in some places of Earth's surface, but what about Afar?*

2 · CONSIDER PRESENCE OF RADIOACTIVE MATERIALS IN AFAR

5 min

MATERIALS: None

Discuss the possibility of radioactive material in Afar. Present **slide B**. Elicit 1-2 ideas with the prompt:

- *In some regions, such as Afar, magma reaches the surface and cools, forming solid rocks. Based on our ideas, would we expect to find evidence of radioactive materials in the rocks in Afar?*

Accept all answers, but listen for students to say that we saw evidence of volcanic eruption in the Afar region, and that the lava should probably contain radioactive material. If no one suggests volcanic regions, ask them to think back to Lesson 7, and remind them that they had learned about radioactive material deep inside Earth. Direct students to consider where this material might appear on the surface, guiding them to consider that volcanic areas might be of interest.

Consider the purpose of measuring radioactive materials. Present **slide C**. Read the text at the top:

- *All rocks that contain radioactive elements undergo radioactive decay at a known rate, acting like a clock. By measuring the amount of radioactive elements in a rock sample, scientists can determine its age when it first solidified.*

Then give the class a moment to consider the slide's prompt:

- *How can comparing the amounts of radioactive materials in rocks help us reconstruct past processes that have shaped a place, and predict its future?*

Invite a few students to share their ideas with the class. Accept all answers.

Revise the Driving Question Board. Present **slide D**. Point to the DQB and elicit ideas with the prompt:

- *What questions from our DQB involve reconstructing the past or predicting the future in Afar?*

Accept all answers. Say, *I have data that can help us shed light on those questions.*

3 · ANALYZE AND INTERPRET DATA

8 min

MATERIALS: *Rock Sample Site Map*

Orient to the rock sample site map. Display **slide E**. Distribute the *Rock Sample Site Map* (in a sheet protector) to each pair of students. Have them locate the relief map in the top right corner first, then identify the red rectangle. Explain that the color map is of that red region in Afar. Help students make sense of the map with the prompt:

- *What do the colors indicate?*

Listen for them to say that the colors show similar rock formations or alluvial sediments.

Explain the difference between rock formations and alluvial sediments. Mention that similar rock formations are places where there is solid rock on the surface and the type of rock that makes it up is the same. Explain that this solid rock is volcanic in origin, whereas alluvial sediments are areas where solid rock is not visible on the surface, because it is covered by layers of sediments like dirt or sand.

Orient to the sites on the map. Tell students that the letters represent sites where scientists have collected rock samples to look for evidence of radioactive materials. Say that we will look at data for samples from all of the sites over the course of the lesson, but we are starting with a small set.

Analyze rock sample data. Display **slide F**. Explain that the data are for rock samples taken from six locations on the map. Give the class a minute to look at the data, and then discuss the related question as shown in the table below.

Some students might not recognize that K-40 is a radioactive element. Present **slide G** to highlight both K-40 and U-238 as elements on the periodic table.

Suggested prompt	Sample student response
<i>What patterns do you notice in the data across these volcanic rock samples?</i>	Each site has either K-40 or U-238, but never both. Most of the rock in the region has radioactive elements. The concentration of radioactive elements seems to be different in all the sites.

Connect with Lesson 7. Present **slide H**. Connect with students' previously developed ideas and elicit new ideas about what could account for the differences in composition, as shown in the table below.

Suggested prompt	Sample student response
<i>We know that radioactive decay is happening in the mantle under the surface, and that when the hot magma reaches the surface, it can cool to form solid rocks. So, why would there be different amounts of radioactive parent elements in different rock samples?</i>	Maybe there was more radioactive material in that part of the mantle at the time that it reached the surface. Maybe radioactive material is not uniformly distributed in the mantle. We saw that there must be hotter and cooler spots in the mantle, which implies that there are spots of material that are more and less radioactive, too.

* ATTENDING TO EQUITY

Supporting emergent multilingual students:

When developing new vocabulary, one strategy that may benefit emergent multilingual learners is to make connections to cognate words when possible. The word *alluvial* comes from the Latin words *ad* (against) and *lavere* (wash), because alluvial sediment was deposited by water washing against the land. *Lavere* has cognates in other romance languages such as French (*laver*), Spanish (*lavar*), and Portuguese (*lavar*). Encourage students who speak multiple languages to bring those valuable resources to bear in decoding academic words like *alluvial*.

The goal of this discussion is to draw connections between processes in the mantle and the presence of surface features at Afar. If students struggle to do this, you can ask the following questions:

- *If the amount of radioactive material decreases over time due to radioactive decay, how would the age of a rock that contains more radioactive material compare to the age of a rock with very little radioactive material in it?*
- *If the matter that makes up these rock samples comes from the magma in the mantle, what could the presence of rocks with varying amounts of radioactive material tell us about what has been happening in this area?*

Collect the *Rock Sample Site Map* at the end of this activity.

4 · DISCUSS RELATED PHENOMENA AND INTRODUCE RELATED TOOLS AND PROCESS

6 min

MATERIALS: science notebook, *Rock Transformation Process* (optional)

Connect to related phenomena. Present **slide I**. Say, *To figure out how much of these radioactive elements are in these volcanic rocks, scientists study the individual crystals that make up the rocks. Before we see how they do that, let's think about our own related experiences with rocks.*

Take a quick poll on the slide's question:

- *How many of you have found solid rocks with what look like tiny crystals of different colors and sizes in them?*

Most students will raise their hands. Follow up by saying, *Solid rocks with small crystals in them are typically rocks that have been either partially melted or fully melted in the past, before cooling back down. That cooling causes the crystals to form.*

ALTERNATE ACTIVITY

Differentiation opportunity: For students who are interested, you can encourage them to bring in a sample of rocks they may have collected that have such crystals in them or you can encourage students to take photos of any rocks they find around where they live or around the school that show evidence of this.

Read about formation of crystals containing radioactive elements. Present **slide J**. Say, *I have a reading that will help us understand the patterns we saw in the presence of radioactive materials across the rock samples from Afar.* Ask students to write a summary of the main ideas from **slides K, L, and M** that can help explain these patterns.

ALTERNATE ACTIVITY

Instead of having students read the text on **slides K-M**, you can distribute the *Rock Transformation Process* reading, which contains the same information.

Discuss the main ideas from the reading. Present **slide N**. Use the prompt to start a brief discussion:

- *How does the information in this reading help to explain some of the patterns we identified across the volcanic rock samples collected from Afar?*

Invite a few students to share their written summaries. Listen for the following ideas:

- Crystals are formed at different temperatures. They only contain one type of radioactive element.
- This helps explain why rock samples contain either K-40 or U-238.

Orient to the use of a spectrometer. Display **slide O**. Say, *Scientists can analyze crystals with a spectrometer to determine how much of each of these radioactive elements is in any given crystal.*

The slide shows the known relationships between three parent elements that undergo radioactive decay and the daughter elements they turn into over time. Present **slide P** to help students understand the transformations of K-40, U-235, and U-238. Before moving on, make sure they grasp the idea that matter changes through radioactive decay.

Say, Now that we understand that radioactive elements decay, let's make predictions about the trends we might see if we could measure the amount of a radioactive element in a rock crystal over time.

ALTERNATE ACTIVITY

Differentiation opportunity: If students have completed OpenSciEd chemistry courses, then they have prior experience with thinking about how spectrometers can be used to identify the elements in a sample, in their work in *OpenSciEd Unit C.3: How could we find and use the resources we need to live beyond Earth? (Space Survival Unit)*.

5 · MAKE PREDICTIONS AND CONNECT TO OUR ANCHORING PHENOMENON

6 min

MATERIALS: *Predicting Composition Trends*



Make predictions. Display **slide Q**. Distribute the *Predicting Composition Trends* handout. Give students 4 minutes to individually record predictions in their handout about what we would see if we could measure the amount of a radioactive element present in a rock crystal over time.

Draw an *x-axis* and *y-axis* on the board, and invite a volunteer to share their predictions. Then, ask students to raise their hands if they made a different prediction. Invite those who raised their hands to draw their predictions on the board as well.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- A graph that shows a trend (linear or nonlinear) with a solid line of decreasing *y-values* as *x-values* increase for the percentage of parent element found in a crystal over time, and a dotted line of increasing *y-values* as *x-values* increase for the percentage of daughter element found in a crystal. (SEP: 5.2; CCC: 1.4, DCI: PS1.C.2)

What to do:

- Collect the *Predicting Composition Trends* handout at the end of the period.
- Reach out to math colleagues to find out how they are scaffolding graphing for their high school students.
- If students are struggling, ask clarifying questions about why they are making specific decisions. This helps them articulate their reasoning, a metacognitive exercise that can be powerful in helping them figure out what to do to achieve a purpose rather than simply follow directions.
- An alternative approach to modifying instruction in support of students engaging in math and computational thinking is to ask them to describe in words the mathematical relationship they are trying to represent. This parallels similar cognitive processes while making their thinking visible. It allows you to identify areas where they might be struggling, and provide targeted support and guidance.

Building toward: 8.A.1 Sketch and describe graphs for percent of parent and daughter elements versus time; use a spreadsheet to graph and compare patterns across different crystal sizes and different parent elements and compare these to patterns predicted by an exponential decay law. (SEP: 5.2; CCC: 1.4; DCI: PS1.C.2)

Connect to the Afar region. Display **slide R**. Give students 2 minutes to turn and talk about the questions on the slide. Then discuss a variation of those as a class, as shown in the table below.

Suggested prompt	Sample student response
<i>We made predictions about the changes in the amount of parent and daughter elements in the sample. How could we use the ratio of parent and daughter elements in rock samples to measure the rate at which various processes happened at Afar in the past?</i> <i>How could we use this ratio to make predictions about the rate at which things might happen in the future?</i>	We see that they measured these elements already in the rocks at Afar, so if we can come up with some way to connect amount to rate, it could tell us how long this has been happening, and how it compares to other areas on Earth. If we know the rate that things happened in the past, we could use it to predict how often or how quickly similar things will happen in the future.

6 · PLAN AN INVESTIGATION

8 min

MATERIALS: group copy of radioactive decay data collection spreadsheet from <https://docs.google.com/spreadsheets/d/1-7OYiN8LLC7JHzeSvRCMUc66T78H5lNx3uVqWc2e68Y/edit?usp=sharing>, <https://youtu.be/r6C3VnDUaq8?si=q5A3b4M3tXha5b5O>, <https://youtu.be/vfjKpqKkUqI> (optional)

Introduce the idea that a mathematical model exists. Present slide S. Read the text aloud:

- Scientists have come up with a general mathematical model that predicts how long ago a crystal formed based on how much of each radioactive parent and daughter element is in it.

Say, *Let's see whether we can develop a similar model to figure out the rates that various processes have been occurring at Afar, by collecting some data for a simulation of radioactive decay.*

Orient to the simulation. Play the video at <https://youtu.be/r6C3VnDUaq8?si=q5A3b4M3tXha5b5O>. Then discuss the question on slide S as a class, as shown in the table below.

Suggested prompt	Sample student response
<i>What data would we need to collect from this simulation to help us develop such a mathematical model?</i>	We would need to collect data on the amount of radioactive elements in the crystals at different points in time. We would need to record amounts of both the parent and daughter elements.

Introduce the radioactive decay data collection spreadsheet. Present slide T. Tell students we have a spreadsheet for recording data from the simulation. Point out the column headings in the image on the slide. Explain that each group will spin off a copy of the spreadsheet to share so each member can contribute a row of data. Emphasize that before doing so, the group needs to make decisions about what variables to keep constant and what to change for the first condition they want to test.

ALTERNATE ACTIVITY

You can use this optional video to further orient students in using the spreadsheet to plan their first condition to collect data: <https://youtu.be/vfjKpqKkUqI>

Plan investigation condition 1. Display slide U. Reiterate that the groups now need to plan the first experiment to collect data on. Share the related link for students to spin off a copy of the spreadsheet: <https://docs.google.com/spreadsheets/d/1-7OYiN8LLC7JHzeSvRCMUc66T78H5lNx3uVqWc2e68Y/edit?usp=sharing>. Give groups 5 minutes to plan their first investigation.

As students plan, remind them that group members can start filling in the rows on their spreadsheets as they obtain the corresponding simulation results. This way of dividing the data collection ensures that the group can run multiple simulation trials at the same time.

ALTERNATE ACTIVITY

Extension opportunity: This is suggested as an optional extension opportunity for students who have demonstrated either prior fluency or a high interest in the science practice of *planning and conducting investigations*. It can function as a differentiation opportunity.

Instead of providing the ready-made spreadsheet, encourage students to develop their own spreadsheet. This approach prompts them to consider how to record, analyze, and evaluate their data.

7 • COLLECT DATA FOR THE FIRST CONDITION

10 min

MATERIALS: <https://opencied-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html>, group copy of data collection spreadsheet

Carry out the investigation for condition 1. Display slide V. Share the simulation link with the class: <https://opencied-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html>. Monitor students as they collect and record data on their first condition. As they finish, explain that we will have time in the next class to collect data on additional conditions.

End of day 1

8 • NAVIGATE

6 min

MATERIALS: <https://opencied-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html>, group copy of data collection spreadsheet

Review data and discuss trial numbers. Present slide W. Distribute a computer to each student and have them access the data they recorded last time. Say, *Last time, we were investigating how much time it takes radioactive elements within a rock sample to decay.* Instruct them to review their data for condition 1 and consider the slide's prompt:

- *How did you know whether you had completed enough trials for a condition? **

After a couple of minutes, ask students to share out. Listen for the following ideas:

- We just did it three times.
- After a few trials, the data shows results within the same range.

Collect additional data for the first condition. Present slide X. Use the slide prompt to let students decide whether to collect more data based on their current results. Give them 4 minutes maximum to collect more data if needed.

* SUPPORTING STUDENTS IN ENGAGING IN PLANNING AND CARRYING OUT INVESTIGATIONS

In Lesson 2, students had the opportunity to consider whether they had collected enough data when measuring the force combinations acting on an object. This prompt engages them in the same practice. Scan the room to decide whether students seem confident about how to answer this type of question. Knowing when they have collected enough data is key for engaging in other practices, such as developing arguments and counterarguments based on data and evidence.

If you see fit, display a sample spreadsheet that shows a limited number of trials, and conduct a few more tests using the simulation in front of the class to show that

new values are either higher or lower than the ones currently collected, which suggests the need for more trials.

9 · COLLECT DATA FOR ADDITIONAL CONDITIONS

10 min

MATERIALS: <https://opencied-static.s3.amazonaws.com/HTML+Files/Radioactive+Element+Decay.html>, group copy of data collection spreadsheet

Collect data for a second condition. Present **slide Y**. Have groups consider the slide's prompt:

- *What other conditions do you want to test? Use a different tab for each condition you test, indicating the parent element and crystal width tested.*

Give students a few minutes to decide which conditions to test with the simulation. Then, present **slide Z**. Use the prompts to orient students to the task:

- *Carry out your data collection for all your conditions and trials.*
- *You can have multiple members start collecting and recording data for different rows and tabs in your spreadsheet.*

Demonstrate how to record additional data. Show the class where to find the additional tabs to collect data for more conditions. The last part of <https://youtu.be/vfJkpqKkUqI> shows how to find these.

10 · ANALYZE THE DATA

8 min

MATERIALS: *Analyzing Decay Trends*, science notebook

Analyze and interpret data individually. Display **slide AA**. Distribute the *Analyzing Decay Trends* handout. Give students about 4 minutes to individually record their analysis of their graphs for the first two questions on the handout:

- *How do the patterns across your graphs compare?*
- *How do these patterns compare to your predictions?*



Analyze and interpret data in groups. Display **slide BB**. Have students work in groups to analyze their graphs to approximate the times (on average) when 50% and 25% of the parent element was left.

Space is provided on *Analyzing Decay Trends* to record averages for up to 6 conditions. Some groups may only complete a subset of 2-3 conditions, which is fine. This should take about 4 minutes.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: A summary of the following:

- The **patterns** in the **trends** of the data and how they compare to the predictions.
- An **estimated time determined** for at least one parent element that reached 25% **in approximately twice the time** it took to reach 50%. (SEP: 5.2; CCC: 1.4)
- How **quickly or slowly various radioactive elements change into daughter elements**. (SEP: 5.2; CCC: 1.4; DCI: PS1.C.2)

What to do: It can be helpful to first ask students to describe the shape of the graphs before asking them to interpret those patterns. If they are struggling, tell them to not make any inferences, and simply point out patterns. Ask them to consider other times they have seen patterns like these, and what those patterns meant. Then ask them to start making inferences about the data.

Building toward: 8.A.2 **Sketch and describe graphs** for percent of parent and daughter elements versus time; **use a spreadsheet** to graph and compare **patterns** across different crystal sizes and **different parent elements** and **compare these** to **patterns predicted by an exponential decay law**. (SEP: 5.2; CCC: 1.4; DCI: PS1.C.2)

11 · COMPARE RESULTS

7 min

MATERIALS: *Analyzing Decay Trends*, science notebook

Compare results. Display slide CC. Explain that you will divide the class into thirds in a moment, and within these Jigsaw groups, students should have a discussion to determine an answer to the question on the slide, circling the claim that they decide best supports the data after comparing results:

- *Does crystal size affect the time at which there is a certain fraction (e.g., $\frac{1}{2}$ or $\frac{1}{4}$) of the parent material left?*

Divide students into new Jigsaw groups. Ask for a show of hands of students who have values recorded for K-40. Assuming that more than one-fourth of the class responds, ask one-fourth of the class, comprising students whose hands were raised, to stand in one corner of the room, taking their *Analyzing Decay Trends* handout with them. Do this again, but for U-238, asking one-third of the remaining students whose hands were raised to go to a different corner of the room. Do this again, but for U-235, asking half of the remaining students whose hands were raised to go to a different corner of the room. Finally, ask the second half to join any group that they have data for. Give Jigsaw groups the remaining time to discuss the question above in their corners of the room.

12 · ARGUE FROM EVIDENCE

3 min

MATERIALS: *Analyzing Decay Trends*, science notebook

Argue from evidence. Display slide DD. Discuss the question as a class:

- *Does crystal size affect the time at which there is a certain fraction (e.g., $\frac{1}{2}$ or $\frac{1}{4}$) of the parent material left? Which of these two claims shown on the slide did the data support?*
 - *No, regardless of the crystal size, the time is similar.*
 - *Yes, the larger the crystal size, the longer the time.*

Listen for students to say that the crystal size does not matter, because the variation in times is small and the values are similar.

Motivate further analysis of the data. Present slide EE. Use the table on the slide as a reminder that last time, we looked at data for rock samples collected at various locations in Afar, showing that these had different amounts of radioactive materials. Then have students turn and talk with the prompt:

- Our analysis has helped us determine how long it takes radioactive elements to decay. How can our findings help us reconstruct the past or predict the future of Afar?

Give partners a couple of minutes before inviting them to share out. Listen for the following ideas:

- If we know how much radioactive element is left in a rock sample, we can have an idea of how old it is.
- Knowing how old rocks are can give us an idea of how long this process has been going on.

Suggest we continue analyzing our data to see whether it can help us determine the age of the rocks.

13 · USE MATHEMATICAL THINKING TO ANALYZE RADIOACTIVE DECAY GRAPHS

10 min

MATERIALS: *Analyzing Decay Trends, Age of Rocks*, science notebook, calculator, *Rock Sample Site Map*, https://youtu.be/Y-GP_AedXBQ?si=kbwYEQAitgwrnRN, <https://youtu.be/H9CPgtaorzE?si=iFOyrWZSbnGGotu1>, chart paper (optional), chart paper markers (optional)

Analyze and interpret data. Display **slide FF**. Have students report out the related values and add these to a chart on the board or on chart paper as reference. The values shown for time in mya should be within about 20% of the following (e.g., 50% of K-40 should remain at 1250 +/- 250 mya).

Parent element	% parent element	Time in mya
K-40	50%	~1250
	25%	~2500
U-235	50%	~700
	25%	~1400
U-238	50%	~4500
	25%	~9000

Direct students to turn and talk for a couple of minutes about the slide's second prompt:

- What patterns do you notice between the time for 50% and the time for 25%?

Discuss the question as a class. Listen for the following ideas:

- The time is about twice as long for 25% as it was for 50%.
- This pattern is true for each element, though the times to get to 50% are totally different.

Identify the half-lives. Say, *Scientists have found this pattern as well, and it's an important part of the mathematical model to predict how any element decays over time. Every radioactive isotope takes a certain amount of time to decay to 50% of its initial amount, no matter how much there was to start with. Scientists also noticed that the time to get from 100% to 50% is the same as it takes to get from 50% to 25%. They call this time the element's half-life.* Circle the half-life on the class half-life table for each of the elements and label it as the half-life for that element.

Demonstrate this on a graph. Say, *Let's see what half-life means on a graph.* To demonstrate this, either interactively use **slide GG** to repeatedly copy, paste, move, and shrink (by 50%) the dotted box shown on the graph, or show and narrate the related video of this process, https://youtu.be/Y-GP_AedXBQ?si=kbwYEQAitgwrnRN.

14 · NAVIGATE

1 min

MATERIALS: None

Highlight limitations of our data. Present **slide HH**. Point to the data table and say, *The Afar data show us the amount of radioactive elements in rock crystals, but the data don't tell us whether this corresponds to 50% or 25% of the remaining parent element.*

Have students turn and talk with the slide's prompt:

- *What data do we need in order to determine how much percentage of the parent element is left in each sample?*

Say, *Next time, we'll explore a mathematical model to calculate this percentage.* Collect the *Analyzing Decay Trends* handout as students leave.

End of day 2

15 · USE MATHEMATICAL THINKING TO MAKE SENSE AND USE A MODEL OF RADIOACTIVE DECAY

20 min

MATERIALS: None

Remind students of the limitations of our data. Present **slide HH** again to support this discussion. Say, *Last time, we identified patterns in the radioactive decay of elements, and we thought we could use this information to calculate the age of rocks in Afar.* Ask for ideas in response to the prompt:

- *What data do we need in order to determine how much percentage of the parent element is left in each sample?*

Listen for students to suggest that we need data about the percentages of parent and daughter elements in each sample. If they struggle to answer this question, ask these followup questions:

- *What data did we use last time to calculate the age of a rock sample?*
- *Could similar data help us calculate the age of rocks in Afar?*

Say, *Let's use a mathematical model that includes data about the parent and daughter elements.*

Introduce two equivalent equations. Display **slide II**. Orient students to the variables in the left-hand equation; point out that the brown, purple, and green are provided by the simulation, and the half-life (h) in red is what we just calculated. Remind them that we recorded the ratio or the percentage of remaining parent element compared to how much was there when the rock formed, which is shown in pink in the right-hand equation and is equivalent to the ratio in the left-hand equation.

Ask what else students notice that these equations have in common. They should say there is a $\frac{1}{2}$ in the parentheses and the same variables, age of rock (t) and half-life (h), in the exponent of this base.

Test what the equation predicts for a time of zero. Display **slide JJ**. Have students test what the equation yields for a $t=0$ for an element whose half-life is 500 mya. Give them a minute to try this on their calculators; they should say it yields 1.0. Remind them that 1.0 also means 100%, and that this should make sense because no time has passed and none of the parent atoms have decayed yet.

Test what the equation predicts for some other time values. Display **slide KK**. Have groups assign each member a row in the table to work on, determining the value for that row by calculating (with or without a calculator) what the value of P would be. This should take less than 2 minutes.

Compare predictions. Display **slide LL**. Check the reasoning that produces these values, emphasizing patterns such as:

- *0.5 is equivalent to 50% and 0.25 is equivalent to 25%, so why would the next row be 12.5%? Because that is half of the previous row.*

- Each additional 500 mya reduces the previous amount by half again.

Discuss how the variables can help calculate the age of rocks. Present slide **MM**. Say, *Let's see whether we can use this mathematical model to calculate additional variables.* Point to the components in the model as you use some of the following prompts:

- Which variables from this model do we want to calculate?
- For which variables do we have data to substitute into the equation?
- Which variables do we lack evidence for?

KEY IDEAS

Purpose of this discussion: Support students' engagement in mathematical modeling to identify the variables we want to calculate, the variables for which we have evidence, and the variables we lack evidence for.

Listen for these ideas:

- This model requires you to know (1) the amount of parent element that is there now, and (2) the amount of parent element that was in the crystal to start with (not directly measurable).
- We don't have data of the amount of the parent element when the crystal was formed.
- What is in the crystal is the daughter element and the remaining parent element.

Consider how to calculate the amount of parent element. Present slide **NN**. Read the text aloud:

- *Though we cannot directly measure the amount of parent element when it was formed, we can calculate it based on the amount of daughter element found now.*

Point to the components in the mathematical model presented on the slide as you use similar prompts from slide **MM** to support the use of mathematical thinking. Listen for the following ideas:

- The number of atoms of parent element that are there now, plus the number of atoms of daughter element that are there now, should equal the amount of parent element that was there when it was formed.
- We can use this in the original equation to determine the portion of the parent element remaining. With that, we can use the equation to determine the approximate age of that rock.

16 · DETERMINE THE AGES OF ROCKS IN AFAR

10 min

MATERIALS: *Age of Rocks, Rock Sample Site Map*

Orient to the related rock sample data. Present slide **OO**. Say, *Let's see how we can use what we figured out to determine the age of some rock samples from the Afar region that we looked at earlier.* Distribute the *Age of Rocks* handout to each student. Elicit 1-2 ideas with the prompts:

- What information do you notice has been provided for this rock sample data?
- What values have we already calculated?
- What values do we need to calculate?

Listen for students to suggest the following ideas:

- The table provides the ratios of parent element to daughter element.
- Column 3 provides the ratio needed for P in the equation at the bottom right of the page, which leaves only two variables in the equation to solve for.
- One variable is time (t) and one is half-life (h).
- We already know the half-life of these elements.
- We would need to calculate the age of rock.

Have students fill in the half-life for K-40 on the top left of the table on their handout and the half-life for U-239 on the top right, based on what the class recorded from the investigations.

Demonstrate how to use a spreadsheet and the equation to find how old a rock sample is. Play <https://youtu.be/H9CPgtaorzE?si=iFOyrWZSbnGGotu1> to show how to do this.



Determine rock ages. Display slide PP. Assign students to groups of 7. Have them assign each member a different rock sample (A-G) to determine that rock's age, using the reported value for the portion of parent element remaining (Pr) and the related graph the group made to estimate the age of each rock sample. Each student should practice creating a spreadsheet for this and entering the time, half-life, and exponential decay equation. This should take about 5 minutes.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Use the mathematical model of radioactive decay to calculate the age of their assigned group of rock samples. (SEP: 4.1; DCI: PS1.C.2)
- A is 0.12–0.33 mya, B is 0.49–4.0 mya, C is 1.9–3.2 mya, D is 4.5–8.2 mya, E is 23–25 mya, F is 29–31 mya, G is 583–659 mya.

What to do: Encourage students to use a spreadsheet for their calculations, and give them a chance to revise their responses if you notice a calculation error. The ranges listed above may shift about 25% if the simulation results provided data that led students to derive a slightly different half-life.

To ensure that the calculated ages of rocks are closer to the expected values, it is important to adhere to the following criteria:

- **Time measurement unit:** The unit of time being measured is millions of years. Make sure that when students input half-life values into their calculations, they are in millions of years. Using any other unit will produce inaccurate results.
- **Significant figures:** All values of the ratio of K-40 to K-40 now include 5 significant figures. Ask students to pay careful attention to the first 5 significant numbers when performing calculations in their spreadsheet.

Building toward: 8.B.1 Analyze data using a spreadsheet and an exponential decay law to find the age of various rock samples using relationships (half-lives) discovered in prior investigations; interpret the patterns across the ages of these samples and the sites where these are located to reconstruct the geologic history of Afar over the last 700 million years. (SEP: 4.1; CCC: 1.4; DCI: PS1.C.2)

Compare results. Display slide QQ. Give group members about 3 minutes to share and record the ages they calculated and add everyone's results to the corresponding data table shown on the slide. As they do this, distribute 3 copies of the *Rock Sample Site Map* (in sheet protectors) to each group.

17 · ANALYZE AND INTERPRET DATA

8 min

MATERIALS: *Age of Rocks*, science notebook, *Rock Sample Site Map*



Analyze and interpret data. Display slide RR. Cue students to work with a partner, using the *Rock Sample Site Map* and the rock ages calculated in their *Age of Rocks* handout, to discuss these prompts for 4 minutes:

- What patterns do you notice in the locations of older versus younger volcanic rocks?
- Use evidence to support your ideas.

Then have them report what they notice about the data in the map and table. Patterns may include:

- The oldest rock is 100s of millions of years old (~600 mya), which is much older than the rest.
- The oldest rock is located along the western and eastern edge of Afar.

- The next oldest rock is around 20–30 million years old, and formed along the west edges of Afar and a little bit on the eastern edge.
- Very little happened after that until about 5–10 million years ago, and then there was a lot of recent rock formation (a few million years and less) in between the two edges of Afar.
- The youngest rock is between older rock, like a sandwich.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Using evidence from the group data recorded on the *Age of Rocks* handout and the map in the *Rock Sample Site Map* to interpret the geologic history of Afar. (SEP: 4.1; CCC: 1.5; DCI: PS1.C.2)

What to do: Ask students to explain why they think there was no volcanic activity between 600 million and 30 million years ago, and what this tells us about what was happening to the land between the two oldest parts of Afar in the last 30 million years.

Building toward: 8.B.2 Analyze data using a spreadsheet and an exponential decay law to find the age of various rock samples using relationships (half-lives) discovered in prior investigations; interpret the patterns across the ages of these samples and the sites where these are located to reconstruct the geologic history of Afar over the last 700 million years. (SEP: 4.1; CCC: 1.5; DCI: PS1.C.2)

18 · UPDATE THE SCALE CHART POSTER

4 min

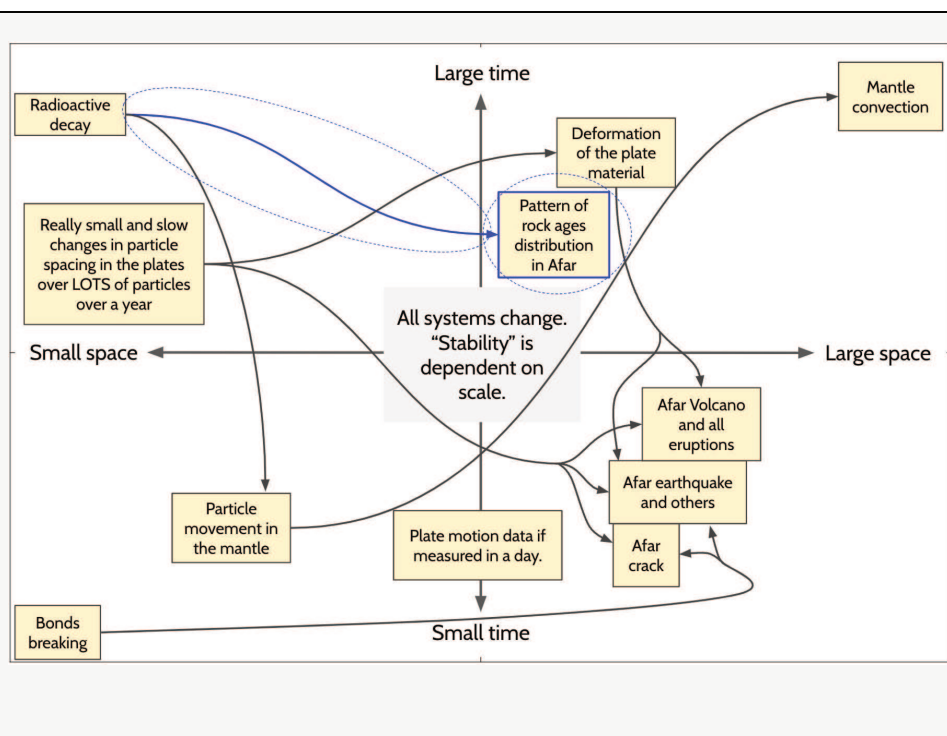
MATERIALS: Scale Chart poster

Revise the Scale Chart poster. Present slide SS. Emphasize that we should now be able to connect some of the phenomena and patterns explored in this lesson. Use the slide's prompts to elicit ideas:

- *What phenomena or patterns should we include?*
- *What new connections can we draw?*

Students might choose to move radioactive decay into large time (a half-life is very long!) or in small time (instantaneous decays). Either is fine, and if there is disagreement, you can put it in both places, labeling one “radioactive decay (half-life)” and the other “instantaneous radioactive decay”.

A connection is made between radioactive decay and half-life; a dotted line represents a different type of connection than previously shown.



19 · NAVIGATE

3 min

MATERIALS: *Rock Sample Site Map*, *Age of Rocks*, science notebook

Consider the age of rocks at the global scale. Display **slide TT**. Give students 1 minute to consider the questions on their own. Then share ideas as a class, as shown in the table below. Encourage students to refer to the *Rock Sample Site Map* and *Age of Rocks* handouts during this discussion.

Suggested prompt

How do you think the age of rocks found in other parts of the world would compare to those found at Afar?

Sample student response

(Accept all responses.)

Suggested prompt	Sample student response
<i>How could such comparisons help us better understand what is happening at Afar and what might happen there in the future?</i>	Knowing when rock was formed in different parts of the world could help us figure out how long the processes going on Afar might keep going on. If the rock in Afar is much younger than the rest of the region, that would suggest it is a relatively recent phenomenon. We could compare Afar with places that have much older rocks. That could give us clues as to what could happen to Afar in its far future.
<i>So, do you think that looking at more data will help us find patterns?</i>	The more data we have, the more patterns we can find to help us determine where Afar fits into those patterns.

Navigate into the next lesson by saying, *It sounds like more data can help us to find patterns. Let's plan to investigate your idea of looking into how the age of rocks in Afar compare to those from other places to test our predictions in the next class period.*

Additional Lesson 8 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

CCSS.MATH.CONTENT.HSA.SSE.A.1.B Interpret the structure of expressions. Interpret complicated expressions by viewing one or more of their parts as a single entity.

As students use mathematical thinking to compare patterns from the results of their investigations to those in an equation of exponential decay, they also use this equation to determine the age of rocks from Afar.

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

CCSS.ELA-LITERACY.SL.11-12.1.A Come to discussions prepared, having read and researched material under study; explicitly draw on that preparation by referring to evidence from texts and other research on the topic or issue to stimulate a thoughtful, well-reasoned exchange of ideas.

Make sure all students have access to the copy of the spreadsheet shared within each group. Give them some time to make sense of their data in their small groups before working in their new Jigsaw groups. This allows them to come prepared to have a richer discussion and participation with their peers.

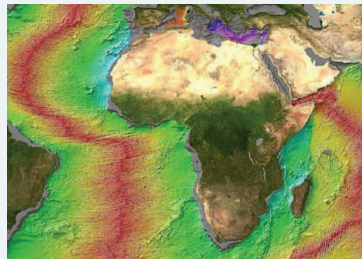
LESSON 9: How does the rock in Afar compare to the rock around the world, and what does this tell us about the history and future of the region?

PREVIOUS LESSON We analyzed the radioactive element composition of rocks from Afar. We planned and carried out an investigation using a simulation to collect data on how the amount of radioactive material in a rock crystal changes over time. We used mathematical thinking to compare patterns in our graphs to those in an equation of exponential decay, and we used that equation to determine the age of rocks from Afar.

THIS LESSON

INVESTIGATION

2 days



Adapted from: NOAA, Elliot Lim

We look at data on the crustal ages of rocks around the world in both oceans and continents, and notice several patterns, including that the farther the rock is from some plate boundaries in the ocean, the older it is. We use manipulatives to model what might be happening at these boundaries and capture our ideas in an initial consensus model. We notice many gaps in our understanding and decide to look more closely at the rocks. We determine that the density of basalt (oceanic crust) is greater than the density of granite (continental crust), and we wonder about how that affects forces and energy transfer. Finally, we add questions to the Driving Question Board about plate boundaries and types of crust.

NEXT LESSON We are wondering what is happening at plate boundaries. We will investigate how plates interact at divergent and convergent plate boundaries, and how these interactions result in different surface features.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

9.A Ask questions that arise from careful observations of patterns across multiple empirical sources to refine our model of how new oceanic crust is formed at plate boundaries. (SEP: 1.1, 1.2; CCC: 1.5; DCI: ESS1.C.1)

WHAT STUDENTS WILL FIGURE OUT

- Continental crust is, on average, significantly older and less dense than oceanic crust.
- As you move outward from some plate boundaries in the middle of the ocean that are spreading away from each other, the basalt rocks get older, suggesting that the material originated at the boundary and was pushed outward over large temporal and spatial scales.
- The rock in Afar is young basalt, suggesting that a similar process may be occurring there.

Lesson 9 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	2 min		NAVIGATE Turn and talk about the age of Afar rock.	A	
2	10 min		LOOK AT CRUSTAL AGE DATA Examine data on the age of crustal rocks with a partner.	B-D	<i>Ages of Crustal Rocks</i>
3	20 min		DISCUSS INITIAL IDEAS IN A SCIENTISTS CIRCLE Make a public record of what we noticed and wondered. Take a closer look at the mid-ocean lines, relate them to tectonic plates, and use a manipulative model to reproduce the patterns around these lines.	E-G	chart paper, chart paper markers, copy paper, large book
4	10 min		BUILD UNDERSTANDING IN A SCIENTISTS CIRCLE Construct an initial consensus model. Build ideas about matter cycling, forces, and energy transfer.	H-J	Initial Class Consensus Model: New Crust poster, chart paper markers
5	3 min		NAVIGATE Consider what to explore next to better understand how the process of new rock forming at plate boundaries will affect Afar.	K	
<i>End of day 1</i>					
6	2 min		NAVIGATE Turn and talk about what we can learn from rocks.	L	
7	20 min		PLAN AND CARRY OUT A ROCK DENSITY INVESTIGATION Make initial observations of granite and basalt rock samples. Plan and carry out an investigation of rock density.	M-O	Rock Sample Density Lab
8	10 min		DISCUSS FINDINGS AND KEEP TRACK OF OUR QUESTIONS Share our findings and discuss implications. Ask questions about plate boundaries. Add to Progress Trackers.	P-U	<i>Progress Tracker</i>
9	5 min		REVISIT THE SCALE CHART POSTER Add the creation of new crust to the Scale Chart poster.	V	Scale Chart poster, 3x5 sticky notes, chart paper markers, permanent marker
10	5 min		ADD TO THE DRIVING QUESTION BOARD Revisit the Driving Question Board to add new questions about plate boundaries and crustal types.	W	3x3 sticky notes, permanent marker
11	3 min		NAVIGATE Take a closer look at plate boundaries. Complete an exit ticket.	X	loose-leaf paper, Driving Question Board
<i>End of day 2</i>					

Lesson 9 • Materials List

	per student	per group	per class
Rock Sample Density Lab materials	<i>Measuring Rock Densities</i>	- granite rock sample - basalt rock sample - digital scale - graduated cylinder 500-ml glass beaker - plastic bin - petroleum jelly - water	
Lesson materials	- science notebook <i>Progress Tracker</i> 3x3 sticky notes - permanent marker - loose-leaf paper	<i>Ages of Crustal Rocks</i>	- chart paper - chart paper markers - copy paper - large book - Initial Class Consensus Model: New Crust poster - Scale Chart poster 3x5 sticky notes - permanent marker - Driving Question Board

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 handouts so they can be added to students' science notebooks.

Make copies of the handouts for this lesson:

- Measuring Rock Densities* - 1 per student
- Composition of Continental and Oceanic Rocks* - 1 per student (optional extension opportunity)
- Ages of Crustal Rocks* - in color, 1 per partner pair (put in sheet protectors for reuse across classes)

Prepare chart paper for the poster in this lesson:

- Initial Class Consensus Model: New Crust

Day 2: Rock Sample Density Lab

Prior to the lesson, determine what approach your materials can support for measuring volume of an irregular solid via water displacement. See the *Density Measurements Guidance* reference for options. Watch <https://youtu.be/L14LIB9RhNo?si=OKklWYhXojhWR6P> for guidance on how to measure the density of the rocks for this investigation.

- Group size:** 4-5 students.
- Setup:** For each group, prepare a granite rock sample, basalt rock sample, digital scale, graduated cylinder, 500-ml glass beaker, plastic bin, petroleum jelly, and water.
- Safety:** Students should wear indirectly vented chemical splash goggles during the investigation.
- Disposal:** All materials are reusable.
- Storage:** Dry the rock samples before using them with another group.

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 (DCI):

- **ESS1.C.1:** Continental rocks, which can be older than 4 billion years, are generally much older than the rocks of the ocean floor, which are less than 200 million years old. (HS-ESS1-5)

Students encounter and/or co-construct ideas around several terms during this lesson, and may decide to add the following words to their Personal Glossaries: *plate boundary*, *continental crust*, *oceanic crust*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

Students explore divergent plate boundaries in this lesson but do not compare these to other types of boundaries, so there is no need to attach the vocabulary of *divergence* to the phenomenon yet. In Lesson 10, they will investigate other types of boundaries and thus will need to start labeling the different kinds of interactions between plates. They will have the opportunity to add *convergent* and *divergent boundaries* to their Personal Glossaries in Lesson 10.

LEARNING PLAN for LESSON 9

1 · NAVIGATE

2 min

MATERIALS: None

Review the age of Afar rock to motivate a comparison. Say, *In the last lesson, we figured out that we can date rock using radioactivity. By this method, the youngest rock in the Afar region is less than a million years old. But we weren't sure what this meant, and were wondering how it compared to rock in other places.*

Present **slide A**. Pose the prompts on the slide as a Turn and Talk:

- *What does it tell us if the rock in the Afar region is the same age as most of the rock everywhere else?*
- *What if the rock in the Afar region is younger than everywhere else?*

You do not need to elicit student ideas right now, simply allow students to share with their partner.

2 · LOOK AT CRUSTAL AGE DATA

10 min

MATERIALS: science notebook, *Ages of Crustal Rocks*

Examine data with a partner. Instruct students to find a partner to work with. Present **slide B**. Distribute *Ages of Crustal Rocks* to student pairs. Alternatively, you can project **slides C and D** and have students come up close to the screen to look more closely. Ask students to analyze this data, keeping track of patterns they notice and questions they have in their science notebooks or on loose-leaf paper that they can add to their notebooks.

3 · DISCUSS INITIAL IDEAS IN A SCIENTISTS CIRCLE

20 min

MATERIALS: chart paper, chart paper markers, copy paper, large book

Record what students noticed and wondered. Ask students to share out. Document their noticings and wonderings on a piece of chart paper. Examples are shown in the table below.

Notice	Wonder
• Young rock comes in lines that are in the middle of the ocean, but old rock patterns are less clear. • There is a rainbow pattern that starts red (young stuff) and then kind of fades into older rock, on a continuous gradient from the middle outward. • The rainbow pattern makes a mirror image. • Mostly in the oceans, the oldest crust is less than 200,000,000 years old, but on the continents, there is crust that is billions of years old. • In the Afar region, the lines in the ocean seem to maybe continue into the lines of younger rock on the continent.	• What's going on that makes the ocean crust so different from the continents? • Why is the rock in the Afar region so new? • Why do some oceans, like the Atlantic, have a pattern radiating from the center? • What is happening to create these patterns? • How is the youngest rock on Earth formed?

* ATTENDING TO EQUITY

Universal Design for Learning: Some students may not be able to see the thin, colored strips of the oceanic crust as they are added to the paper. You can create a larger *representation* by using two desks pushed together instead of a book, and large chart paper instead of copy paper. Have students hold onto the paper with both hands and slowly pull outward. Pause every 8"-12" and create bold, contrasting stripes in a colorblind-friendly palette. You can also pre-make 8"-12" strips of different colors of chart paper to quickly tape to the chart paper as it emerges from between the desks, instead of coloring directly on the paper.

Motivate a closer look at the mid-ocean lines. Present **slide E**. Say, *We know the rock in Afar is young, and it looks like it's connected to one of these ocean lines of new rock. We should look at these places in the ocean where we see these lines of young rock. We also noticed a gradient pattern.* Have students turn and talk for a minute about the slide's prompt:

- *What might be happening to create these patterns?*

Ask them to share out. Listen for ideas about:

- different plates meeting
- breaks in the plates or crust
- magma seeping up
- volcanic venting
- new rock forming

Establish an alignment with tectonic plates. If students brought up the idea of tectonic plates, use this to motivate looking at a plate map by saying, *You mentioned the lines between plates. I have a map of tectonic plates that we can compare to our map of rock ages. Alternatively, you can say, These lines remind me of the maps from the start of this unit, which showed tectonic plate lines.*

Present **slide F**. Look at the map of tectonic plates, and pose the question on the slide:

- *What do you notice about the relationship between these lines in the ocean and the tectonic plates?*

Listen for students to point out that the boundaries (the lines between plates) match up to the lines of the youngest rock we see in the ocean. Say, *We think these lines of young ocean rock are aligned with the boundaries between the plates. So, can we call these lines plate boundaries?* If they do not agree, ask them to come up with something else to call the lines for now.

ADDITIONAL GUIDANCE

Research suggests that many students develop persistent, contextualized mental models for tectonic plates that are not aligned with current scientific understanding. They often believe that the plates are located somewhere underground, rather than being inclusive of Earth's surface. Additionally, they may visualize plates as moving chunks with large spaces in between, like rafts or subterranean bumper cars. Language that describes plates as "moving toward each other" or "moving away from each other" reinforces this inaccurate model.

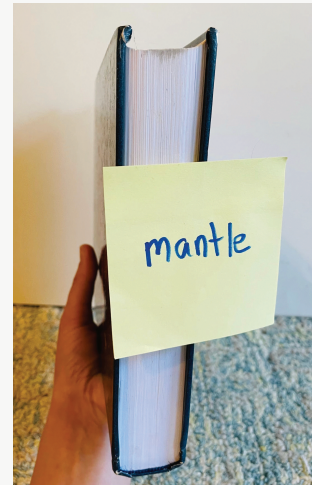
A more accurate mental model is that of a cracked eggshell. The plates are essentially continuous, like an eggshell before it breaks, but there are zones (plate boundaries) where new crust is being created or destroyed. These constructive and destructive processes define divergent and convergent boundaries, respectively. We do not define *divergence* or *convergence* in this lesson, but it is important to discuss plates and boundaries in a way that helps students build accurate mental models. For example, you can describe rocks in the ocean floor as "spreading in opposite directions" rather than "moving away from each other."

Gobert, J. D. (2005). *The effects of different learning tasks on model-building in plate tectonics: diagramming versus explaining*. Journal of Geoscience Education, 53(4), 444–455.

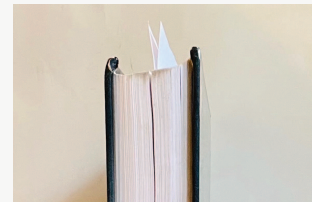
Reproduce the patterns around the mid-ocean lines. Present **slide G**. Say, *We think these red lines might represent places where magma is moving upward to form new rock. We also noticed this interesting rainbow gradient pattern on each side of the red lines. What does the gradient show us?* Guide students to reiterate that on each side, the rocks get older at increasing distance from the red line of new rock in the middle of the ocean floor.

Say, *Let's use a model to figure out what's causing that pattern in the age of the ocean crust.* Co-construct a model with the class, following the instructions below, and use it to determine the movement of tectonic plates that has created the age gradient in rocks on the ocean floor. ✱

Hold a large textbook oriented so the spine points toward the floor. Point out that this forms a wedge shape similar to the cross sections of Earth's interior that we saw in the mantle tomography. Say, We can use this book to represent a slice of Earth's mantle beneath the surface. Place a sticky note or a piece of scrap paper with tape as a "mantle" label on the book.

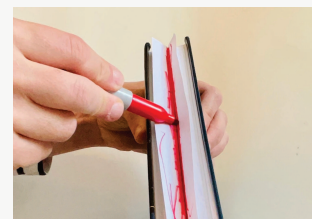


Fold a piece of copy paper (legal-size or letter-size) in half, with the fold bisecting the long side. Insert the folded paper into the book so it is sandwiched between pages in the middle, with the edge sticking out 2-3 cm beyond the book pages.

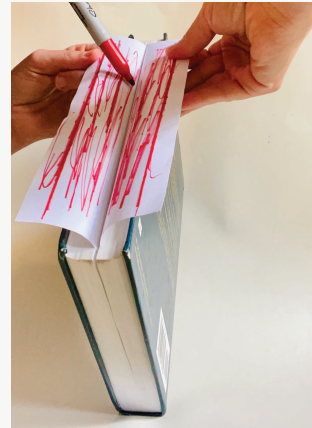


Say, Let's use this paper to represent matter flowing upward. I heard you say this matter is magma that comes through a break in the plates to form new rock. Let's use a marker to color the paper where it comes out, to show it is crystalizing into new rock. What color should we use? Use the color chosen by the majority. Students will likely suggest red, but any color is fine at this point.

Invite a student to add color in the space where the folded copy paper is emerging from the book. This works best if the chart paper marker tip is inserted vertically into the fold, so it touches both sides of the folded paper simultaneously.



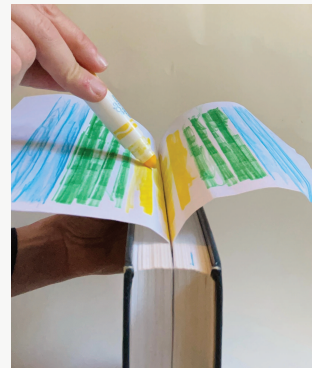
Say, We said this matter was moving upward. Let's add that movement to our model. Ask one or two students to gently pull the copy paper out of the book while you hold the book closed and the student with the marker continues to color back and forth along the crack where the paper is emerging.



After a moment, stop to display what the paper looks like so far. You can take it out of the book and unfold it, or leave it in. Ask students what they notice. Highlight responses that get at the symmetrical nature of the marker pattern on the paper. Ask why the marker ink ended up on both sides of the paper. Discuss how the marker colored both sides simultaneously because they initially came out of the book in the same place, before separating.

Point to the image on slide G and say, Let's look back at this pattern. What other colors do we need to represent the range of ages we see in oceanic crust rocks? Students should note rocks coded in yellow, green, and blue. Other colors in the rainbow are also acceptable. Put a different volunteer in charge of each marker color.

Reset the model with a new piece of copy paper. Ask how we can use the markers so our final product ends up looking like this section of the map, with a red line in the middle and the rainbow gradient progressing outward toward both edges. Allow multiple attempts if necessary, using a new piece of copy paper each time.



ADDITIONAL GUIDANCE

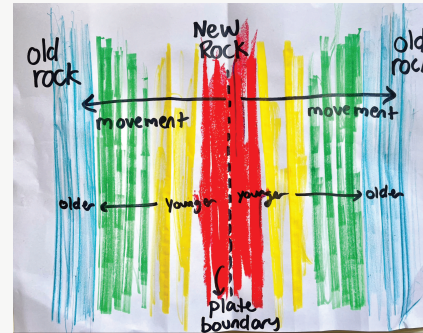
Students may initially struggle to get the order of colors to match the map. If so, look at the paper together, and ask why the colors are in the “wrong” order.

To accurately re-create the pattern in the ocean crust, red should be the last marker used as the paper is pulled all the way out of the book. Students should start with a color near the end of the rainbow (e.g., blue) and proceed to color the paper in backward-rainbow order as it is pulled out.

It is easiest for the class to see what is happening if the students pulling on the paper spread the edge of the sheet out to the side, rather than straight upward. This is also a more accurate representation of what happens to the matter on Earth’s surface; it spreads out to the sides, rather than continuing to build upward.

This model also presents an opportunity to reinforce the idea that plates are adjacent at a boundary, and there is not an increasing space between them. Note that the distance between the sides of the copy paper at the point where it emerges from the book is not changing.

Label the finished model to correspond to Earth components. Remove the paper from the book and open it fully in a similar orientation to the visible section of the ocean floor age map. Say, *Scientists make models to help figure things out. Let’s annotate our model to show what it tells us about Earth.* Use sticky notes or write directly on the paper with a black marker.



Suggested prompts	Sample student responses	What to label
<i>Which part of the paper got colored most recently?</i>	The middle. The red part.	<i>“New rock” in the red section at the center of the paper.</i>
<i>What would this represent?</i>	It represents the youngest, newest rock.	
<i>Which part of the paper got colored first?</i>	The outside edges. The (first color).	<i>“Old rock” on both edges of the paper. Make sure the label is written on the same color on both sides.</i>
<i>What would this represent?</i>	It represents the older rock that was formed earlier.	

Suggested prompts	Sample student responses	What to label
<i>How did the paper have to move to create this pattern?</i> <i>What does this tell us is happening to the rocks on the ocean floor? Think about processes as well as movement.</i>	Outward. In opposite directions. Upward. New rock is forming in the crack. Old rock is being carried/pushed away to each side. The rocks that used to be in the middle are getting split up.	<i>Draw two arrows going in opposite directions. Both arrows should start in the central red section. One arrowhead should point left and the other should point right. Label the arrows "movement".</i> <i>Add any labels or descriptions that are useful.</i>

4 · BUILD UNDERSTANDING IN A SCIENTISTS CIRCLE

10 min

MATERIALS: Initial Class Consensus Model: New Crust poster, chart paper markers

Start an initial consensus model. Present **slide H**. Bring the class's attention to the Initial Class Consensus Model: New Crust poster. Ask what scale we should model at. Listen for students to suggest a chunk of oceanic plate, or even the whole Atlantic Ocean, which should also work. Go with the class's suggestion (within reason). Set up the model as a cross section with the surface and interior visible.

Build ideas about matter cycling. Present **slide I**. Discuss the prompts as shown in the table below.

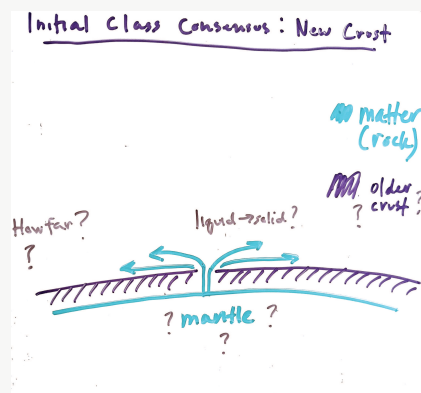
Suggested prompts	Sample student responses	What to draw
<i>What did the model tell us about what was happening to the matter in the system?</i> <i>Where was the matter coming from, exactly?</i> <i>What evidence do we have for this from previous lessons?</i>	The matter was coming out of Earth. The mantle. The crust. (You can remind students who say "the crust" that the radioactive elements in the crust are the same as those in the mantle material, so it could be the mantle.) (Allow students to cite any relevant data or evidence from previous lessons.)	<i>Ask students how to represent this, and sketch matter emerging from Earth's interior.</i> <i>Label beneath Earth's surface. Use question marks to indicate disagreement or uncertainty.</i>

Suggested prompts	Sample student responses	What to draw
What state was the matter in?	Liquid. Solid.	If students aren't sure, write "liquid? solid?" to indicate uncertainty.
What evidence do we have for this from previous lessons?	(Allow students to cite any relevant data or evidence from previous lessons.)	
What would we see if we could "rewind" this model backward? Would the whole crust get sucked back into this line?	Probably not, because there are a lot of cracks. The crust would get sucked back in, but if something didn't get pushed out at some point, Earth would get bigger. No, because if we ran time forward and all the crust came out, then Earth's interior would be empty eventually.	Indicate uncertainty with short phrases and question marks.

Wherever there was controversy or confusion on the model, add question marks and phrases indicating *why*. You might also have a question mark to indicate that we are not sure where the matter is coming from, or whether continental crust would have emerged in the same way if we could rewind time back far enough.

Say, *It sounds like we have some ideas, but also a lot of questions. We think the lines may be aligned with tectonic plate boundaries. New crust is forming at the boundary between these plates. So, that could be a place where material is coming up from the mantle. This is maybe a place where there's a break in the crust, or in the plate (crust plus magma), or both.*

Build ideas about forces and energy transfer. Present slide J. Pose the question for discussion, as shown below.



Suggested prompt	Sample student response
What are the unbalanced forces in the system that could be responsible for the motion of the matter?	Mantle convection. (We got this from Lessons 6 and 7.) Buoyant force. Gravity.

Add the forces that students suggest to the model, again indicating controversy or uncertainty with question marks and phrases.

Suggested prompt	Sample student response
<i>These pushing forces must transfer energy somewhere. Where is the energy going?</i>	Maybe it goes into the motion of the plates?

Again, add question marks to the model to indicate that we aren't sure how the energy transfers.

5 · NAVIGATE

3 min

MATERIALS: science notebook

Think about where to go next. Present **slide K**. Pose the questions on the slide as a Stop and Jot:

- *How might the young rock we see in the oceans, and in the Afar region, be different from older continental rock?*
- *How could that help us make progress on our questions about the Afar region?*

End of day 1

6 · NAVIGATE

2 min

MATERIALS: None

Turn and talk about what we can learn from rocks. Say, *We had a lot of ideas last time about how the differences in continental and oceanic rock might affect the dynamics of the Afar region.* Encourage students to look back at their Stop and Jot to refresh their memories.

Present **slide L**. Have students turn and talk about the prompt on the slide:

- *What can we learn from samples of oceanic and continental crust?*
- *What could this tell us about the Afar region?*

If needed, remind the class that both types of rock have been found in and around the Afar region. Elicit student ideas after a minute.

7 · PLAN AND CARRY OUT A ROCK DENSITY INVESTIGATION

20 min

MATERIALS: Rock Sample Density Lab

Make initial observations of rock samples. Present **slide M**. Say, *Let's look at these two types of crust (actual rock samples).* Explain that granite is generally found on continents and in continental crust. The younger basalt is generally found in oceanic crust. The new rock in Afar is basalt, like the new rock forming in the ocean, but there is a lot of granite in the surrounding regions. Because of this, these sample rocks are representative of the types of rocks found in the crust in Afar.

Organize the class into groups of 4-5. Direct each group to pass their samples around, holding the rocks in their hands. Point out which one is granite (continental) and basalt (oceanic). Have students share their observations. If they mention color, ask what could give rocks different colors. Listen for them to recall that crystals in rock like this are made of different elements. Highlight any inferences that the different colors must mean the rocks have different composition, but it is not necessary to push students to reach this conclusion if they don't bring it up.

Remind the class that we are interested in the forces at play in Afar. Ask the slide's second question:

- *What could we test or observe that could help us understand how each might interact with other parts of the crust or rigid mantle?*

Listen for students to suggest density. Say, *We could measure the density of these rocks.*

ADDITIONAL GUIDANCE

Students might also suggest rigidity, temperature, or composition. If they suggest temperature, this would be easy to measure in the classroom. Tell students rigidity and composition require equipment that we don't have, but encourage them to look it up later and report back.

Highlight density as something that affects both convection and seismic velocities, so it is definitely worth investigating.

Watch <https://youtu.be/L14LIB9RhNo?si=OKkILWYhXojhWR6P> for additional guidance on how to measure the density of the rocks for this investigation.

ALTERNATE ACTIVITY

Extension opportunity: The standards do not require students to investigate the composition of various types of rock and how that affects their density. For those who are eager to learn more, consider offering the optional extension reading, *Composition of Continental and Oceanic Rocks*. You can also have them research the composition of other types of rocks in Earth's crust, and come to class prepared to share this information with their peers.

Plan an investigation of rock density. Present **slide N**. Point out that the rock in the photo isn't easily measured by a ruler or other device meant to measure straight or flat sides.

Say, *How can we measure the density of these rocks? Remember that density is mass per volume. So, to calculate density, we need to determine the mass and volume of these rocks. We can get the mass with a scale. But how do we get the volume of an irregular shape?*

Listen for students to suggest that we can put the rock in water and measure the volume of water displaced. But if they don't come up with this idea quickly, don't play guess-what's-in-my-head. Say, *One way to get the volume of an irregular object is to measure the volume of water that it displaces.*

Share the available tools for measuring volume this way (see *Density Measurements Guidance* for guidance). Ask students to describe how we could use the tools to accurately measure the volume of water displaced by a rock. As a class, develop a plan for using these tools to calculate the water displacement.

Conduct the investigation. Present **slide O**. Distribute the *Measuring Rock Densities* handout to each student. Distribute lab materials to each group, or have students share and retrieve materials as necessary.

Instruct groups to carry out the investigation, measuring the mass of each rock sample with the digital scale. Remind them to record mass measurements to at least tenths of grams, and volume to the nearest milliliter. It may be helpful to have them recall that 1 mL of volume is the same as 1 cubic centimeter; therefore, each displaced milliliter of water is equivalent to a measurement of 1 cm³ of solid rock. As students work, circulate to ensure that they are recording the *displaced* water volume.

ADDITIONAL GUIDANCE

Students use the density formula, density = mass/volume, for each rock sample. If their measurements and calculations are accurate, they should find a density for granite in the range of 2.6–2.7 g/cm³ and a density for basalt in the range of 2.9–3.0 g/cm³. The more important conclusion they should reach is that granite is less dense than basalt, and thus, oceanic crust is denser than continental crust.

8 · DISCUSS FINDINGS AND KEEP TRACK OF OUR QUESTIONS

10 min

MATERIALS: science notebook, *Progress Tracker*

Share findings and discuss implications. Gather the class in a Scientists Circle. Present **slide P**. Use the prompts for a quick debrief:

- Which rock was more dense?
- How did you figure that out?

Listen for students to agree that the basalt was more dense, because it had a higher g/cm^3 according to their measurements.

Ask questions about plate boundaries. Present **slide Q**. Pose the two questions:

- Why would dense, new rock be forming where these two plates are in contact?
- Could this be happening at every plate boundary (where two plates are in contact)?

Students may respond that new rock must be coming from the mantle. They may also identify that in some locations where new crust is forming, the older crust has to go somewhere, so it might be getting moved toward other boundaries. If these ideas do not come up, use further prompts on **slides R-T** to elicit them, specifically the creation of new rock from the mantle.

Present **slide R**. Ask students to turn and talk for about 2 minutes about the prompt:

- How might the different densities of these rocks affect what is happening at those boundaries?

Have students share out. Accept all ideas, and ask questions to help students clarify their thinking, such as:

- I heard you say ____; is that what you meant?
- Could someone rephrase that idea?
- What other processes work in the way you just described?

Present **slide S**. Ask, *What do we know about the crust in Afar?* Students should recall that the new crust in the Afar region is basalt. They may make the connection that this is the same type of rock as in the crust in the ocean, not the crust usually found on continents. If they do not, consider bringing up **slide B** to remind them that the rock in the Afar region is relatively new, then direct them back to our investigation and the rock types to consider what type of rock is present in the Afar region.

Ask the slide's second question:

- What might that mean about what's happening in the Afar region, based on our model?

Students should have ideas about how processes similar to what is happening in the lines along the ocean floor might be happening in Afar. If they are stuck, point them to our new consensus model.

Present **slide T**. Have students stop and jot about the question:

- If the crust in the Afar region is basalt, does that mean a new ocean is forming there?

After a few moments, ask students to share their ideas. They may say that the Afar region's basalt suggests that new oceanic plate material is emerging there. They may also say that a new ocean could be forming in this location. Propose that we revisit the Scale Chart poster to add this new process, but first, students should take some time to update their Progress Trackers.

Add to Progress Trackers. Project **slide U**. Give students a couple of minutes to add to their trackers. Make sure they can see the poster of the class consensus model developed earlier.

Students may add ideas related to creation at the ridges, over geologic timescales, of new crust containing basalt, which is more dense than the granite commonly found on continental crust. They may cite change over time as a crosscutting concept that helped them, because they considered small changes over large time periods in creation of new crust at plate boundaries that are spreading apart, as with the Afar region

or the Mid-Atlantic Ridge. They may also cite thinking across different scales, because they zoomed out to the world view after analyzing the more local view of a particular boundary where two plates were spreading apart.

At this point, students may also choose to add the following words to their Personal Glossaries: *plate boundary*, *continental crust*, and *oceanic crust*.

9 · REVISIT THE SCALE CHART POSTER

5 min

MATERIALS: Scale Chart poster, 3x5 sticky notes, chart paper markers, permanent marker

Add the new phenomenon to the Scale Chart poster. While students are still in the Scientists Circle, shift their attention to the Scale Chart poster. Present **slide V**. Point out that we have just paused to reflect on our learning, and in that process, reminded ourselves that we had explored a new phenomenon occurring over both time and space. Say, *We're trying to explain what happened in Afar at multiple scales, and our Scale Chart is helping us make those connections. What new phenomenon did we explore in this lesson that we can add to the chart?*

Students should explain that we have learned about the creation of new crust at ridges. They may describe this as seafloor spreading or use other terms that make sense to them at the moment. In the example chart below, this sticky note is labeled “new plate material creation”.

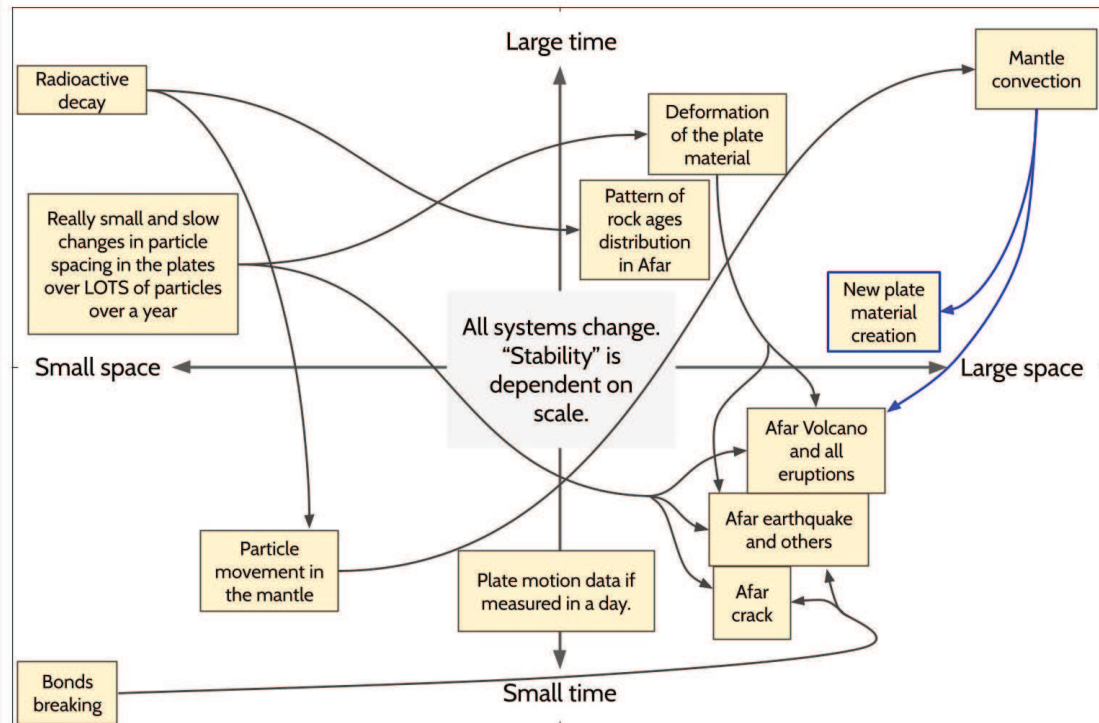
Ask where this phenomenon would be located on the Scale Chart poster. Students should determine that this change happens very slowly and over a large spatial scale. They should suggest placing it in the upper right of the chart, above mantle convection (the positive, positive quadrant).

However, if students argue that this change can happen slowly but is observable at smaller timescales in millimeter distances, negotiate a new place for the sticky note. Place the sticky where it makes sense from the class's temporal and spatial perspective.

Connect new crust creation to other processes. Step back and ask students whether this phenomenon is caused by or connected to any other processes on the chart. They should identify that it is driven by mantle convection, which is driven by the smaller-scale process of parcels moving because of particle movement. Draw arrows between these processes to show how they are related, if these arrows do not exist yet. See the example image here, with new items outlined in blue.

New plate material creation was added under mantle convection on the large time, large space quadrant. Because students may be thinking about the scale of this change over a single year or centuries, the placement of this sticky note can be wherever students argue is best on the time axis.

Connections were made between mantle convection and new plate material as well as the Afar volcano.



10 · ADD TO THE DRIVING QUESTION BOARD

5 min

MATERIALS: 3x3 sticky notes, permanent marker



Add new questions to the DQB. Present slide W. Say, *We've thought about how new crust is created at places where plates are spreading apart, but what does that make you wonder about now? What new questions do you have about plate boundaries, crust, and forces in the Afar region?*

Distribute sticky notes and markers to students and direct them to add their new questions about plate boundaries and continental versus oceanic crust to the DQB.

ASSESSMENT OPPORTUNITY

What to look for/listen for:

- Assess whether students are asking questions intended to refine our model by looking for alignment with the question marks on the Initial Class Consensus Model: New Crust poster. (SEP: 1.1, 1.2)
- Assess student understanding of the DCI by looking for questions about plate boundaries, oceanic versus continental crust, and the ages of rocks in the Afar region and elsewhere that require empirical evidence to answer. (CCC: 1.5; DCI: ESS1.C.1)

What to do: Encourage students to draw on their observations of patterns across multiple empirical sources by pressing them to link their questions to a source of data from the lesson; for example, ask, *What empirical evidence from today's lesson led you to wonder that?* (SEP: 1.1; CCC: 1.5)

Building toward: 9.A Ask questions to refine our model of how new oceanic crust is formed at plate boundaries that arise from careful observations of patterns across multiple empirical sources. (SEP: 1.1, 1.2; CCC: 1.5; DCI: ESS1.C.1)

11 · NAVIGATE

3 min

MATERIALS: loose-leaf paper, Driving Question Board

Motivate a closer look at plate boundaries. Present slide X. Elevate any new DQB questions about the two types of crust we have seen in the Afar region and the impacts of the creation of new crust.

Remind students, *We learned about a type of plate boundary that's in the middle of oceans, where new oceanic crust is forming and two plates of oceanic crust are spreading out in opposite directions. We also figured out that the density of the crust on the continents is less than the density of the crust in the ocean. So, what happens in the places where those two types of crust meet, like at these boundaries?* Point to a convergent boundary on the map where subduction is occurring, such as the western edge of South America, and elicit student responses. Accept all ideas, and point to places on the DQB where we still have questions and controversy.

Say, *We still have a lot of questions about what happens at the places where plates meet, and in particular, about what happens when these two types of crust meet up. Next time, let's look at these boundaries between plates and find out more about what is happening to the material there.*

Administer an exit ticket. Have students respond on loose-leaf paper to the slide's prompt as an exit ticket:

- *What do you think might be happening at the places where these two types of crust meet up? Why do you think that?*

Collect the exit ticket as students exit the classroom, and read through these as a formative assessment before the next lesson.

Additional Lesson 9 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

CCSS.ELA-LITERACY.RST.9-10.1 Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

Students who would like to learn more about crustal composition have the opportunity to read about the chemical composition of granite and basalt. If students engage in this opportunity, they are also given the opportunity to research the topic and share what they have learned with the class.

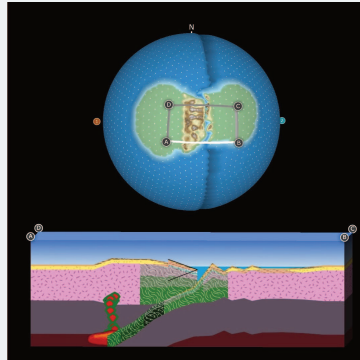
LESSON 10: What is happening at plate boundaries?

PREVIOUS LESSON *We looked at data on the crustal ages of rocks around the world and noticed several patterns. We modeled what might be going on at plate boundaries, where we observed interesting patterns, and we determined the densities of basalt versus granite. We added questions to the Driving Question Board about plate boundaries and types of crust.*

THIS LESSON

INVESTIGATION

2 days



Images generated using Tectonic Explorer (<https://tectonic-explorer.concord.org/>), developed at the Concord Consortium.

We wonder what is happening at plate boundaries. We look at plate motion based on GPS data and notice that not all plates move at the same speed. We identify three types of plate boundaries--divergent, convergent, and transform--according to the plate motion at those boundaries. We use a simulation to investigate plate interaction at convergent and divergent boundaries, and we analyze data to compare surface features on Earth and in the simulation. We read about the flow of matter between the mantle and the crust, and we use these ideas to develop a consensus model that explains how plate interactions result in the surface features we identified at the simulated boundaries. We use multiple sources of evidence to predict what Afar and Africa will look like in the future. We wonder which forces acting on plates can help us explain the patterns we identified in their motion.

NEXT LESSON *We will wonder how forces act on plates to cause their motion, and we will create initial models to represent our ideas. We will consider the properties of plates that might influence how forces act on them. We will plan and carry out an investigation to understand the properties that affect friction forces, and we will connect these to plate motion.*

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

10.A Use a computer model that simulates the movement of tectonic plates to produce data to serve as the basis for evidence that can support an explanation of how plate interactions at plate boundaries shape the planet's surface features. (SEP: 2.6; CCC: 4.3; DCI: ESS2.B.3)

10.B Construct an explanation about the patterns in radiometric data using a consensus model of plate interactions at convergent and divergent boundaries. (SEP: 6.2; CCC: 1.5; DCI: ESS2.B.1, ESS2.B.3)

10.C Construct and revise an explanation about the future of Afar and Africa based on valid and reliable evidence obtained from a variety of sources and the assumption that plate tectonics is the unifying theory that explains the past and current movements of the rocks at Earth's surface. (SEP: 6.2; CCC: 4.4; DCI: ESS2.B.2, ESS2.B.3)

WHAT STUDENTS WILL FIGURE OUT

- Convection in the mantle causes hot, solid rock to move from regions of higher pressure into regions of lower pressure, lowering the rock's melting temperature.
- At convergent boundaries, the high density of the oceanic crust causes it to slide beneath lower-density crust into the mantle.
- As the oceanic crust slides down at a convergent boundary, its water content is released, causing overlying rocks to melt at lower temperatures.
- The movement of plates and their interactions at plate boundaries shape the planet's surface features, such as mountains, islands, earthquakes, and volcanoes.

Lesson 10 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	2 min		NAVIGATE Discuss what was figured out about plate boundaries and share ideas about the expected changes on Earth's crust.	A	
2	7 min		INTERPRET PLATE MOTION AT THE GLOBAL SCALE Share noticings and wonderings about a map of Earth's tectonic plates to motivate investigating plate boundaries. Identify the types of plate boundaries.	B-C	<i>Rate and Direction of Plate Movement</i> , chart paper, chart paper markers, whiteboard marker
3	13 min		EXPLORE SIMULATION OF PLATE BOUNDARIES Learn about the simulation's functionalities through a class demonstration. Use the simulation in small groups to investigate plate boundaries.	D-F	device with access to https://tectonic-explorer.concord.org/
4	17 min		INVESTIGATE PLATE BOUNDARIES Work in groups to choose a convergent plate boundary and a divergent plate boundary from the <i>Rate and Direction of Plate Movement</i> reference and investigate these in the simulation.	G	<i>Investigating Plate Interactions</i> , https://tectonic-explorer.concord.org/ , <i>Rate and Direction of Plate Movement</i>
5	6 min		NAVIGATE AND READ ABOUT MAGMA Complete a reading about magma. Orient to where we are going next.	H-I	<i>Magma's Origins</i>
End of day 1					
6	2 min		NAVIGATE Recall the purpose of investigating plate boundaries.	J	<i>Magma's Origins</i>
7	5 min		DRAFT AN EXPLANATION ABOUT AFAR'S FUTURE Make a prediction about what will happen to Afar and East Africa in the future, and construct an explanation using evidence about plate interactions (from the computer model) and magma formation (from the reading).	K	<i>Predicting the Future of Africa and Afar</i> , <i>Investigating Plate Interactions</i> , <i>Magma's Origins</i>
8	3 min		PREPARE FOR THE SCIENTISTS CIRCLE Organize thoughts on plate boundaries before the class discussion.	L	
9	15 min		DEVELOP A CONSENSUS MODEL OF PLATE BOUNDARY INTERACTIONS Have a Consensus Discussion in a Scientists Circle to build a consensus model about plate boundary interactions that can be used to make predictions about Africa and Afar.	M	<i>Investigating Plate Interactions</i> , <i>Predicting the Future of Africa and Afar</i> , <i>Plate Interactions Consensus Model</i> poster, chart paper markers, https://tectonic-explorer.concord.org/
10	5 min		USE THE CONSENSUS MODEL TO EXPLAIN RADIOMETRIC DATA Use the Plate Interactions Consensus Model to explain patterns found in the radiometric data explored in Lesson 9.	N	<i>Plate Interactions Consensus Model</i> poster, https://tectonic-explorer.concord.org/

Part	Duration		Summary	Slide	Materials
11	15 min		REVISE EXPLANATIONS ABOUT THE FUTURE OF AFAR Revise our explanations of what will happen to Africa and Afar, using multiple sources of evidence to support our ideas.	O	<i>Investigating Plate Interactions, Predicting the Future of Africa and Afar, Progress Tracker, Rate and Direction of Plate Movement, Plate Interactions Consensus Model poster</i>

End of day 2

Lesson 10 • Materials List

	per student	per group	per class
Lesson materials	- science notebook <i>Rate and Direction of Plate Movement</i> <i>Investigating Plate Interactions</i> https://tectonic-explorer.concord.org/ <i>Magma's Origins</i> <i>Predicting the Future of Africa and Afar</i> <i>Progress Tracker</i>	device with access to https://tectonic-explorer.concord.org/	- chart paper - chart paper markers - whiteboard marker - Plate Interactions Consensus Model poster https://tectonic-explorer.concord.org/

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 handouts so they can be added to students' notebooks.

For day 1, make 1 copy per student of:

- Magma's Origins*
- Investigating Plate Interactions*
- Rate and Direction of Plate Movement* - Follow the directions on this reference to cut out the map for students ahead of time, and have them reuse this map on day 2.

For day 2, make 1 copy per student of:

- Predicting the Future of Africa and Afar*

For day 2, also make several copies of the following document. These data sets that we have used in the past are sources of evidence that students may want to use to support their predictions about Africa and Afar:

- Measuring Rock Densities*

For day 2, prepare a sheet of chart paper in landscape orientation with the title "Plate Interactions Consensus Model".

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 ideas (DCIs):

- **ESS2.B.1: Plate Tectonics and Large-Scale System Interactions.** 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. (ESS2.B Grade 8 GBE) (secondary to HS-ESS1-5)
- **ESS2.B.3: Plate Tectonics and Large-Scale System Interactions.** Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust. (ESS2.B Grade 8 GBE) (HS-ESS2-1)

This lesson focuses on exploring how the movement and interactions of tectonic plates are responsible for (1) the flow of matter between the plates and the mantle and (2) the planet's surface features, such as ridges, mountains, trenches, and volcanoes. Students are asked to use plate tectonics to explain the age of rocks explored in Lesson 9 and to make predictions about the future of Afar. As a result, it is important that during the first investigation with the simulation, students describe the plates' vertical and horizontal movement, the movement of matter, and the surface features that result from plate interactions. Having a clear idea about plate movement allows them to pay attention not only to the dynamic frictional forces generated through convection, but also to the role of gravitational forces in driving the plates' motion during Lesson 11.

Students encounter and/or co-construct ideas around several terms during this lesson, and may decide to add the following words to their Personal Glossaries: *convergent boundary* and *divergent boundary*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

Although students will be able to connect the role of density to a central component affecting the movement of the plates, this lesson does not focus on the role of the forces explaining the patterns in the plate movement that students observe during their investigations.

Students also observe trends about the depth and magnitude of earthquakes and the boundaries where these originate. This connection is not explored here, but it represents a rich extension opportunity to intentionally use some of this unit's central ideas with the elements of the M-E-F triangle.

LEARNING PLAN for LESSON 10

1 · NAVIGATE

2 min

MATERIALS: None

Review where we are coming from. Present slide A. Say, *Last time, we saw that the Afar region had a lot of younger basalt rock, like you would find in oceanic crust. We also left with questions about what happens at the boundaries where plates meet. In particular, we wanted to know what is happening where oceanic and continental crusts meet up.* Pose the slide's question:

- *Why did we want to investigate what happens at plate boundaries where these two types of crust meet?*

Accept all responses. Listen for students to say that because basalt was found in Afar, we need to learn more about places where basalt and granite crust meet. Say, *Well, let's look at the places where plates meet up!*

2 · INTERPRET PLATE MOTION AT THE GLOBAL SCALE

7 min

MATERIALS: science notebook, *Rate and Direction of Plate Movement*, chart paper, chart paper markers, whiteboard marker

Present a map of rates of plate motion. Present slide B. Distribute the precut *Rate and Direction of Plate Movement* reference to each student. Give them a minute to look at the map, then ask, *What do the arrows on the map represent?* They should say that the arrows represent the rate of movement (velocity) and direction of the plates. Remind them that the lines represent plate boundaries, or places where two plates meet. (The colors represent information that we do not need for now.)

Give students about 3 minutes to capture noticings and wonderings about the map on a T-chart in their notebooks, as indicated on the slide. Then elicit noticings and wonderings, and spend 5 minutes making a public record of these ideas on a T-chart at the front of the room.

Expected noticings:

- Not all plates are moving at the same rate or direction.
- At some boundaries, plate material is moving apart (arrows pointing outward).
- At some boundaries, plate material is colliding (arrows pointing inward).
- The Caribbean plate and the North American plate are moving past each other (or any example of specific plate interactions).
- Plates are next to each other, so the motion of one might affect the motion of the surrounding plates.
- Some plates have arrows pointing in multiple directions.

Expected wonderings:

- What is happening between the Nazca plate and the South American plate?
- Why does the Pacific plate move much faster than other plates?
- What happens when two plates move toward each other?
- Why are so many of the blue arrows moving apart in the ocean?

Say, *It seems like plates are moving in different directions at the boundaries. What are the possible ways that two adjacent plates are moving at the boundary between them?* Listen for these three ideas:

- Plates are moving toward each other, colliding.
- Plates are moving away from each other, spreading.
- Plates are sliding past each other, without getting closer together or farther apart.

Introduce the types of plate boundaries. Say, *Scientists have named these types of boundaries according to how the plates are moving.*

* ATTENDING TO EQUITY

Supporting emergent multilinguals: The names *convergent* and *divergent* clearly describe relative motion at a boundary. Students may or may not be familiar with these terms in general. It is worth taking a few moments to establish a common understanding of what “converge” and “diverge” mean independently of tectonic plates. You can use hand gestures to represent these motions, and make connections to more familiar words. For example, “diverge” is like “divide” and illustrates something being broken apart into smaller pieces.

Transform plate boundaries are so named because they connect to other plate boundaries. The word “transform” does not refer to a direction of motion, but to the transformation (change) of relative plate motion or the site of plate motion. Students do not need to know this etymology, but it may help them understand the overall convention of naming boundaries based on patterns of movement.

Divergent and convergent plate boundaries are the focus of this lesson. They relate to the motion and properties of mantle

Project **slide C**. Introduce the terms *convergent plate boundary*, *divergent plate boundary*, and *transform plate boundary*. Write these on a whiteboard. Have students identify some of these on the map, and quickly add short definitions to be used for the rest of the lesson. Consider using familiar words, as in the *Attending to Equity* callout to the right, to create a student-friendly definition in the moment. *

material more directly than transform boundaries do.

3 · EXPLORE SIMULATION OF PLATE BOUNDARIES

13 min

MATERIALS: device with access to <https://tectonic-explorer.concord.org/>

Motivate the need to investigate plate boundaries. Present **slide D**. Say, *Now that we have words to describe these types of boundaries, let's think about what happens there.* Pose the slide's first question:

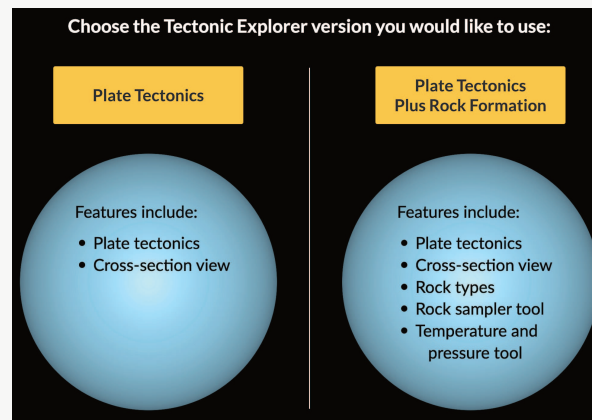
- *What changes do you expect would happen on Earth's surface near plate boundaries over time?*

Accept all responses. Continue by saying, *We should investigate these possible changes! However, it's difficult to test predictions about phenomena that take place over millions of years. What tools have we used in the past to investigate phenomena that are very slow?* Listen for students to suggest a simulation or computer model. Say, *I have just the right simulation to investigate our predictions!*

Demonstrate the simulation with a plate boundary example. Present **slide E**. Say, *We'll use the simulation together to explore the variables we can investigate to answer some of our questions.* Organize the class into small groups of 2-3 students, and distribute computers or devices to the groups so they can explore the simulation simultaneously.

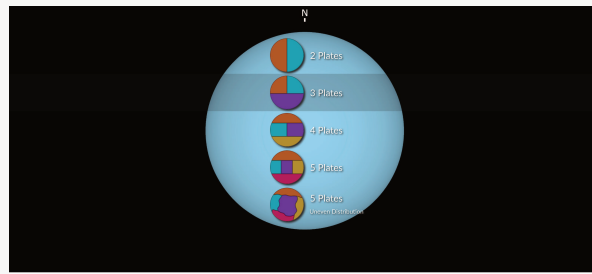
Project <https://tectonic-explorer.concord.org/> and make sure all students can easily see the screen. Share the link so they can open the simulation on their devices. See the demonstration prompts in the table below.

Begin by selecting "Plate Tectonics Plus Rock Formation".



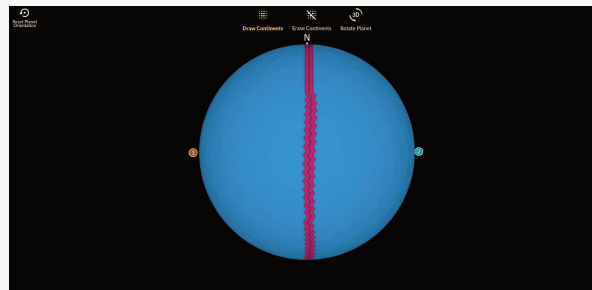
Images generated using Tectonic Explorer (<https://tectonic-explorer.concord.org/>), developed at the Concord Consortium.

Then select the “2 Plates” option.



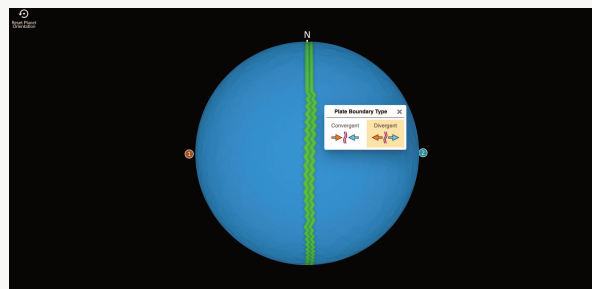
Images generated using Tectonic Explorer (<https://tectonic-explorer.concord.org/>), developed at the Concord Consortium.

Tell students not to draw a continent. Remind them that there is a solid, rocky crust beneath the ocean waters they see on the globe. Using the oceanic plates for this demonstration simplifies the analysis and allows them to focus on the global changes they observe. Click “Next”.



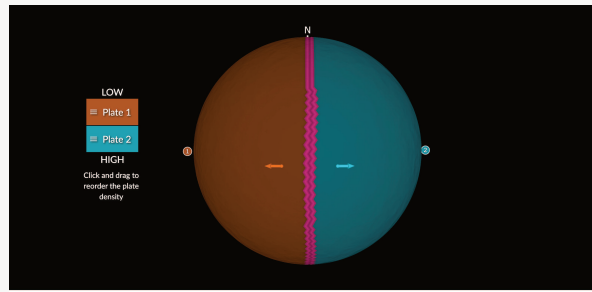
Images generated using Tectonic Explorer (<https://tectonic-explorer.concord.org/>), developed at the Concord Consortium.

Ask students to select the divergent boundary. Tell them that although there are some places with different patterns of movement (transform plate boundaries), our focus is on divergent and convergent boundaries.



Images generated using Tectonic Explorer (<https://tectonic-explorer.concord.org/>), developed at the Concord Consortium.

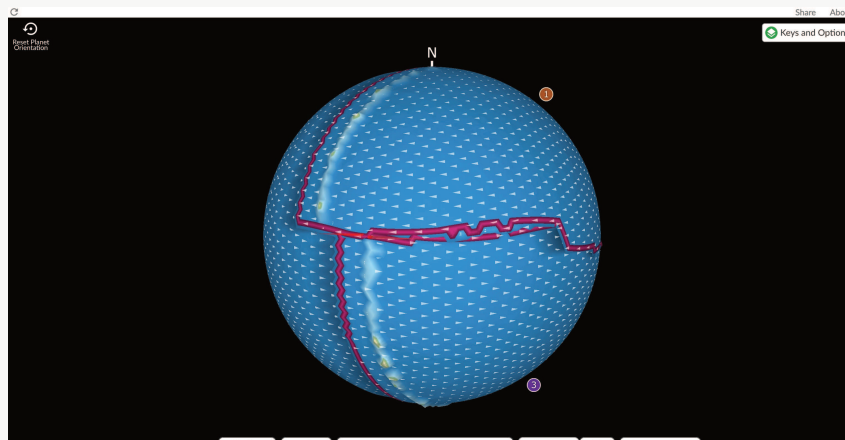
Tell students not to change the density of the plates for this demonstration. Just make sure they are aware that Plate 1 is less dense than Plate 2.



Images generated using Tectonic Explorer (<https://tectonic-explorer.concord.org/>), developed at the Concord Consortium.

When you click “Finish”, the simulation starts running automatically. Pause it, and ask students to do the same. Tell them to use the lowest “Model Speed” to allow more time to make sense of the rapid and multiple changes. To change the speed, click on the “Options” tab in the top right corner and move the bar to the desired speed.

Unclick the “Metamorphism” and “Show Sediments” options, and click on the “Force Arrows” and “Plate Boundaries” options. This allows students to observe changes at the global scale while thinking about the forces causing them. Show them how to rotate the planet by clicking on the dark area around it and dragging the cursor to the desired orientation.



Images generated using Tectonic Explorer (<https://tectonic-explorer.concord.org/>), developed at the Concord Consortium.

Let the model run for a few seconds, enough for students to get puzzled about what is happening at the boundary. Pause it and ask what they see. It is productive if they feel confused by these elements:

- The white arrows moving in opposite directions. Clarify that these represent velocity arrows.
- The ambiguous surface features shown at the boundary in the simulation.

Identify patterns at the global scale. Present **slide F**. Say, *Now, use the simulation with these settings, and notice any interesting changes at the global scale. Let it run for a longer time. You can always click the “Restart” button to move the plates back to their initial positions.*

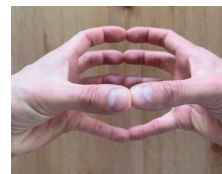
After 3 minutes, invite groups to share what they noticed. Listen for the following observations:

- Sometimes one of the plates breaks into two smaller plates.
- It's hard to see what is happening on the surface of the planet.
- Although plates are moving away from each other, they are moving toward each other on the opposite side of the planet.

ALTERNATE ACTIVITY

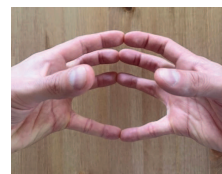
Because this is a 3D representation with multiple interactions happening all at once, some students may struggle to connect the changes happening on different parts of the planet. If you notice expressions of confusion, you can help them use their hands to make sense of the plates' motion and the forces acting on them.

Say, I hear you saying that the plates are moving away from each other at this boundary, but what is happening on the other side? Have students put their hands together as if grabbing a sphere. Each hand represents a plate, and the thumbs represent the plates at the divergent boundary. The size of the planet is represented by the spherical space between the hands.



Ask students to represent the oceanic plates moving away from each other. They should move their thumbs apart.

Follow up by asking, *Where do you feel a force when your thumbs move apart?* Students should say they felt more pressure on the tips of their fingers. Say, *Interesting--when plates are moving, the forces change and something happens on the opposite boundary. But wait a second, what would happen to the size of the planet if the plates (the thumbs) keep moving apart?* They should say that Earth would get larger.

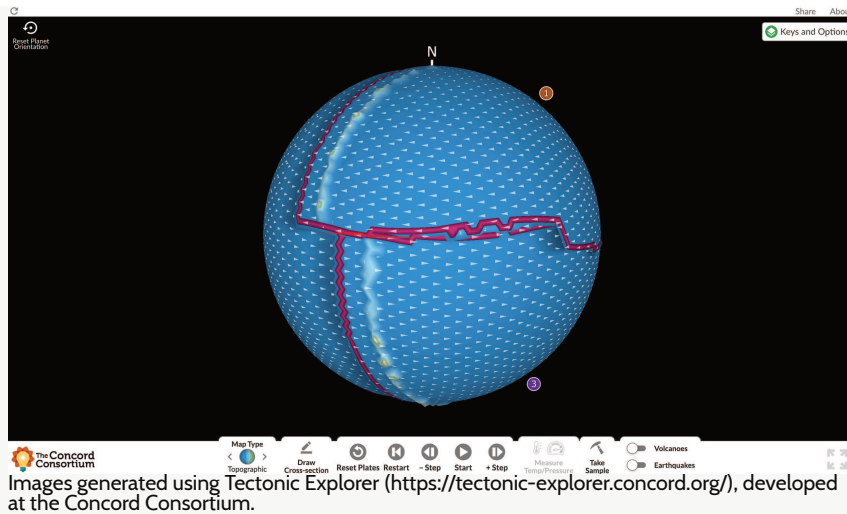


Then ask, *Is Earth growing in size in the simulation or in real life?* They should say no. Continue, *What would we need to do with the rest of our fingers to avoid increasing the size of the planet?* Listen for them to suggest overlapping or crossing their fingers.

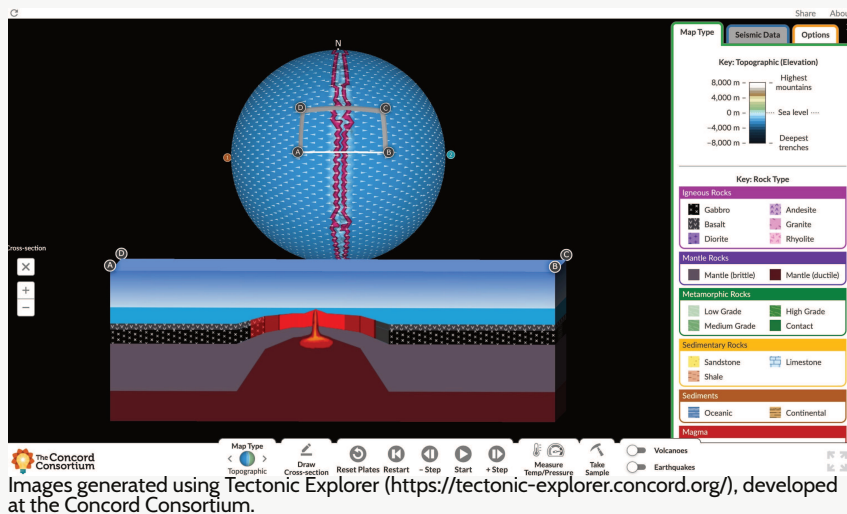
Say, Those are great suggestions. Where on the planet in the simulation do we want to see what is actually happening? Students should suggest looking at the opposite side. Rotate the camera and press the "Start" button again. Let it run for a few seconds to demonstrate that it is hard to see changes at the surface level.



Discuss the formation of a new plate. If students did not notice that a plate can break into two different plates, run the simulation again until this happens. Pause the simulation and discuss what could have triggered this event. Point out that the velocity vectors are pointing at different directions on each of the resulting plates, and discuss how this movement in opposite directions (as shown by the velocity vectors) can result in the formation of two plates.



Motivate the need to look at cross sections. Ask, *If we cannot see clear changes on the surface, where else could we look to explore how these plates are interacting with each other?* Listen for students to suggest using a cross section in that region. Show them how to generate one by clicking on the “Draw Cross-Section” button at the bottom. Use the “Map Type” tab in the top right to show the keys to these representations.



Then say, *Let's restart the simulation to see what's happening here from the beginning.* Click on “Restart”. Warn students that they should only click the “Reset Plates” button to test a new plate boundary, as they will need to define all the variables again.

Discuss what is represented in the simulation:

- The brittle and ductile sections of the mantle. To help students understand the meaning of these, recall that in Lesson 3 we described how materials with a higher elastic limit than others can sustain larger deformation when forces act on them. Here, the ductile mantle has a higher elastic limit than the brittle mantle, so it can sustain higher forces before breaking.
- The basalt rock from the oceanic crust.

Finally, show that the simulation also lets us visualize volcanoes and earthquakes. Say, *When we first read about Afar, we saw that people felt a strong earthquake, and then the giant crack formed close to a volcano. This simulation allows us to visualize volcanoes and earthquakes, so maybe we can find more evidence about how those could be related to the land stretching and breaking.* Activate the visualizations of volcanoes and earthquakes by clicking on the switches at the bottom right.

Click on the “Seismic Data” tab and ask how the depth and magnitude of the earthquake are represented. Students should notice that the depth is represented by the color, and the magnitude is represented by the diameter of the circles.

4 · INVESTIGATE PLATE BOUNDARIES

17 min

MATERIALS: *Investigating Plate Interactions*, <https://tectonic-explorer.concord.org/>, *Rate and Direction of Plate Movement*



Distribute materials and give instructions for the investigation. Present slide G. Say, *Now that we have a better idea about how to use this simulation, let's investigate how plates interact at different boundary types.* Distribute the *Investigating Plate Interactions* handout to each student. Explain that although this is group work, everyone needs to record their findings for an individual task later on. Give the class the rest of the period to complete the handout.

As students conduct their investigations, circulate through the classroom and ask what is happening with the plates (matter) in the system, and how the plates interact with other matter in the system. * If they do not finish the investigations, give them additional time at the beginning of the next class. Collect the handouts before students leave (they will need these for the next class). *

* SUPPORTING STUDENTS IN DEVELOPING AND USING SYSTEMS AND SYSTEM MODELS

In this unit, students consider many parts of the Earth system, both interior and exterior. This computer model allows them to describe the matter flow between Earth's interior and exterior. By changing the simulation's speed, students can model the flow of matter and energy within the Earth system at different timescales. You can support them in recognizing their use of this crosscutting concept by using systems language in your verbal prompts. For example:

- *What components (parts) of the system are interacting at this boundary?*
- *What interactions between system parts are occurring at this boundary?*
- *Do these interactions involve transfer of matter or energy? Can you describe how that works?*
- *Over what timescales do these transfers of matter or energy take place?*

* SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Using the *Investigating Plate Interactions Key*, look for students to:

- Rows 2 and 3: *Use a model to generate data to serve as the basis for evidence that can support an explanation.* In row 3 specifically, look for a description of the plates' vertical and horizontal motion. This evidence will be central for the investigation in Lesson 11. (SEP: 2.6)
- Row 4: *Use ideas about density to explain how plate interactions at plate boundaries shape the planet's surface features.* (DCI: ESS2.B.3)
- Row 5: Use the simulation to describe the *interactions between these components of the system's matter: moving plates, mantle material, magma, and surface features.* (CCC: 4.3)

What to do: Walk through the classroom as groups complete their investigations, asking them to briefly describe to you the changes they see at plate boundaries.

Listen for the following observations of convergent boundaries:

- The denser plate is moving underneath the other one.
- The sinking plate is melting, creating magma.
- The magma flows upward when the subducting zone reaches a certain depth.
- The magma forms continental crust over the less-dense plate.
- Mountains form where the continental crustal matter is being crumpled.
- Volcanoes form where the magma is erupting.

Listen for the following observations of divergent boundaries:

- Magma is coming from the mantle into the point of divergence.
- Magma is turning into oceanic crust.
- The oceanic crust is spreading out to each side.
- The boundary moves over time.
- Magma reaches the crust at a higher point of elevation, and over time, it moves downward.
- Volcanoes form where the magma is erupting.

Building toward: 10.A *Use a computer model that simulates the movement of tectonic plates to produce data to serve as the basis for evidence that can support an explanation of how plate interactions at plate boundaries shape the planet's surface features.* (SEP: 2.6; CCC: 4.3; DCI: ESS2.B.3)

While SEP 2.6 is being assessed, students are also using the model to investigate the relationships between components of the system by observing the relationships between plate density, plate movement, magmatism, and formation of surface features. This can also be used as an assessment moment for 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." Listen for students to make connections between components, such as:

- The horizontal inward movement of plates at a convergent boundary and the subduction (downward movement) of the denser plate, which is being forced below the less-dense plate.
- The subduction of the denser plate and the formation of magma from the melting rock.
- The rising magma at convergent boundaries and the formation of surface features from continental crust.

About 6 minutes before the class ends, move on to the next activity.

5 · NAVIGATE AND READ ABOUT MAGMA

6 min

MATERIALS: *Magma's Origins*

Motivate the reading. Present slide H. Motivate a closer look at magma, as shown in the table below.

Suggested prompt	Sample student response
<i>We have been investigating convergent and divergent plate boundaries. Before we discuss the differences we found, let's quickly share what they actually have in common.</i>	Plates are moving. There are volcanoes and earthquakes. There is magma moving in both plate boundaries.

Suggested prompt	Sample student response
<i>Interesting. Was there magma everywhere?</i>	No, only in some locations, at the place of divergence, and deep where the denser plate was moving inside the mantle at convergent boundaries.
<i>What do we know about magma?</i>	Magma is really hot. It is molten rock.
<i>Was the motion of magma in the mantle characteristic of the motion of matter in the mantle when we investigated convection?</i>	No, matter circulates in the mantle.

Then say, *It seems magma is different from the rest of the matter in the mantle, but it's present at both types of plate boundaries. I have a reading that will help us understand how magma is formed, and why it moves through the mantle in the patterns that we found.*

Read about magma. Present **slide I**. Distribute the *Magma's Origins* reading to each student, and explain that we will use ideas from this reading to build a model in our next class. Give them time to read the passage. Prompt them to use their preferred method of notetaking and marking key information in the reading to help them figure out what is happening in Afar.

ALTERNATE ACTIVITY	If students prefer to read independently outside of class, <i>Magma's Origins</i> could be assigned as home learning.
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End of day 1

6 · NAVIGATE

2 min

MATERIALS: science notebook, *Magma's Origins*

Orient to where we left off. Present **slide J**. Say, *Last time, we read about the formation of magma. Why did we want to learn more about that?* Accept all responses, highlighting ideas about how magma's properties and movement are different from other mantle and crust material.

Continue by saying, *We used a simulation to investigate what was happening at plate boundaries. Why was that investigation important for helping us figure out what's going on in Afar?* Accept all responses.

7 · DRAFT AN EXPLANATION ABOUT AFAR'S FUTURE

5 min

MATERIALS: science notebook, *Predicting the Future of Africa and Afar*, *Investigating Plate Interactions*, *Magma's Origins*

Draft an explanation for what will happen in Afar. Say, *You all had some ideas about what might happen to Afar in the future. We wondered whether it was going to become an ocean, or maybe heal up, or break into two plates. Now that we've taken a closer look at magma formation and plate interactions, what do you think will happen to Afar in the future?*

Present **slide K**. Return the *Investigating Plate Interactions* handout and distribute the handout *Predicting the Future of Africa and Afar* to each student. Give them 5 minutes to complete the front side (Questions 1 and 2). Encourage them to refer to *Investigating Plate Interactions* for evidence of plate interactions from the simulation, and to the *Magma's Origins* reading for evidence about magma formation.

Motivate development of a consensus model. Say, *It can be hard to make a prediction about what's going to happen in Africa when there are so many pieces of the system interacting and multiple sources of evidence. Let's sort through our evidence and create a model with all our ideas about the way plates interact. That can help us improve our predictions about the future of Africa and Afar.*

8 · PREPARE FOR THE SCIENTISTS CIRCLE

3 min

MATERIALS: None

Prepare for the Scientists Circle. Present **slide L**. Say, *Developing a consensus model requires contribution from all of us. The more ideas we have on the table, the more we can make sense of this system together, and the more useful our model is. Let's go back to your groups and discuss the main ideas that can help us explain the points on the slide: **

- the movement of the plates at convergent and divergent boundaries
- the relationship between the movement of the plates and the observed changes in the crust at each boundary
- the movement of matter we observed between the mantle and the plates at each boundary

Prior to the Scientists Circle, circulate while groups discuss to listen for key ideas about plate movement and surface features at each major boundary type.

* ATTENDING TO EQUITY

Recruit a student who participates less frequently in whole-class conversations to share an idea from their group conversation. You can quietly let that student know about your intent in advance so they can think through their response ahead of time or let you know if they don't feel comfortable sharing. For example, you might say, *When we move to the Scientists Circle, I'd like you to share your group's idea about how the magma is forming at a convergent boundary. Would you be willing to go public with this really productive idea?*

9 · DEVELOP A CONSENSUS MODEL OF PLATE BOUNDARY INTERACTIONS

15 min

MATERIALS: science notebook, *Investigating Plate Interactions*, *Predicting the Future of Africa and Afar*, Plate Interactions Consensus Model poster, chart paper markers, <https://tectonic-explorer.concord.org/>

Lead a Consensus Discussion about plate boundary interactions. Present **slide M**. Convene a Scientists Circle, asking students to bring their handouts with them and to sit next to the members of their group in the circle. Have <https://tectonic-explorer.concord.org/> ready in case it is needed during this discussion.

Display the chart paper titled "Plate Interactions Consensus Model" to develop the model with the class. See the finalized version of this model below for an idea of how to use the space on the poster.

Discuss divergent boundaries of oceanic plates. Begin the discussion with a divergent boundary, as shown in the table below.

ADDITIONAL GUIDANCE

Project <https://tectonic-explorer.concord.org/> and use it to demonstrate particular points where the class disagrees or an idea seems unclear. Having a student who feels confident about using the simulation for these demonstrations will help you focus on leading the Consensus Discussion while building the model. Make sure to invite this student to take part in the discussion.

KEY IDEAS

Purpose of this discussion: To press the class toward a common model of plate tectonics. This will serve not only as the basis for making predictions about Africa and Afar, but also for considering the forces that might be acting on the plates that can help us explain the differences in their velocity. As a result, it is important for the model to include the following key ideas:

- the main elements of the system (type of crust, mantle, surface features, magma)
- the direction of movement of these elements
- the interactions between the plates and the mantle
- the surface features present at each plate boundary (ridges at divergent boundaries and trenches at convergent boundaries, in addition to volcanoes and mountains)

Additional prompts that can help you build this consensus model include:

- *How are these explanations similar? How are they different?*
- *Both groups seem to be using the same term but in a different way. Could someone explain the difference?*
- *How can we modify what we have, to account for the evidence that we agree is important to consider?*
- *What modifications would you make to clarify confusion or address the discontent that this group feels?*
- *Is more evidence or clarification needed before we can come to an agreement? What is that?*

Suggested prompt

Let's look at each other's divergent boundary models. What elements did we all include?

Plates have either continental crust or oceanic crust. What type of crust do we see in divergent boundaries?

Sample student response

The two plates.

Magma between both plates.

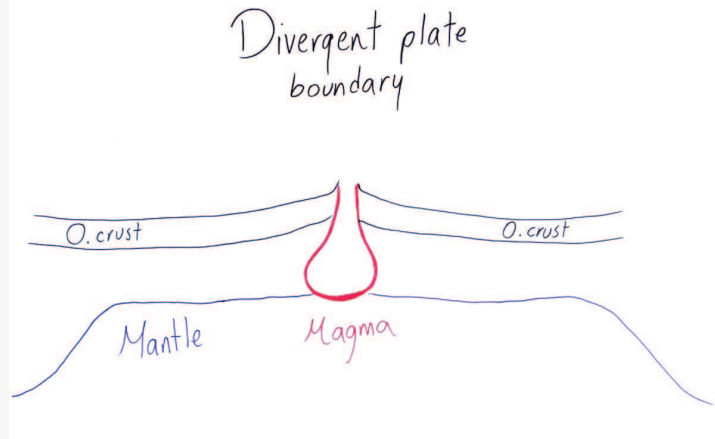
The mantle.

Volcanoes.

Earthquakes.

Oceanic crust.

Draw these elements on the poster, leaving out the volcanoes and earthquakes for now. Continue, including new elements and interactions that emerge during the discussion.



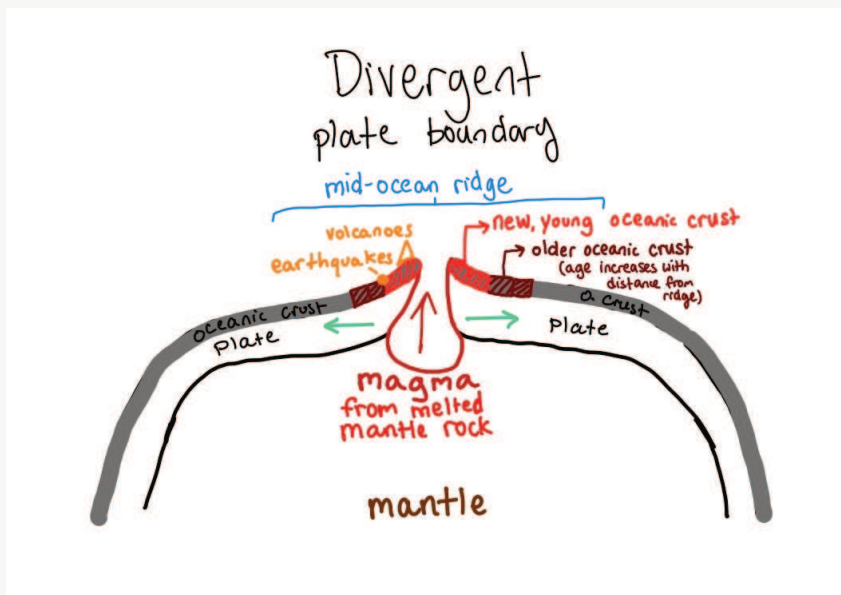
Add arrows for the motion of various components as they are discussed, as shown in the table below.

Suggested prompt	Sample student response
<i>Let's now focus on the motion at this divergent plate boundary. How is the plate material moving at this boundary?</i>	The plates are moving in opposite directions. Plate material is moving away from the boundary. The plate material is spreading out/apart.
<i>What about magma?</i>	Magma is moving upward from the mantle.
<i>Is the movement of the plates and the movement of magma related, or do they move independently of each other?</i>	They are not independent of each other. As magma moves upward, it pushes the plates.
<i>What evidence do we have to support this idea?</i>	The red material, magma, accumulates on top and slowly pushes the rest of the darker material away.
<i>So, what happens with the magma that reaches the crust over time?</i>	It becomes oceanic crust (igneous rock/basalt). It forms volcanoes.

Use the prompts in the following table to draw and label the mid-ocean ridge at the location of the newest ocean crust, with earthquake and volcanic activity.

Suggested prompt	Sample student response
What do you notice about the shape, or feature, of the crust at this location?	It is pushed upward. The location where the new rock is forming is at a higher elevation. It's like a line of small mountains under water.
Yes, this ocean floor feature is called a ridge. In the simulation, we saw different colors in the oceanic crust on each side of the ridge. What do the colors represent?	The red color is the newest crust. The darker the color, the older the rock.
Great. The rock of the oceanic crust is formed from magma that comes from the mantle. Why does magma move upward?	Magma is less dense. When the rock melts, it moves upward.
But magma seems to be formed only in a particular region of the mantle. Why does it form there?	The rock is super-hot and moves upward. As it moves, there is less pressure from the overlying rock, so it melts. When it is melted, it continues moving upward.
Some of you mentioned earthquakes. The simulation gave us information about the depth and magnitude of earthquakes. Did you notice any patterns in their depth or magnitude at this plate boundary?	They were mostly shallow, close to the surface. A lot of them were low magnitude.

By now, the model should look like this:



Discuss both types of convergent boundaries. Follow the above discussion thread for modeling convergent boundaries, as shown below.

Suggested prompt	Sample student response
<i>Let's now look at each other's convergent boundary models. What elements did we all include?</i>	Two oceanic plates. Two continental plates. One continental and one oceanic plate. Mountains. Volcanoes. Earthquakes.

If students describe only oceanic plates, continue to the section below the next set of prompts and responses.

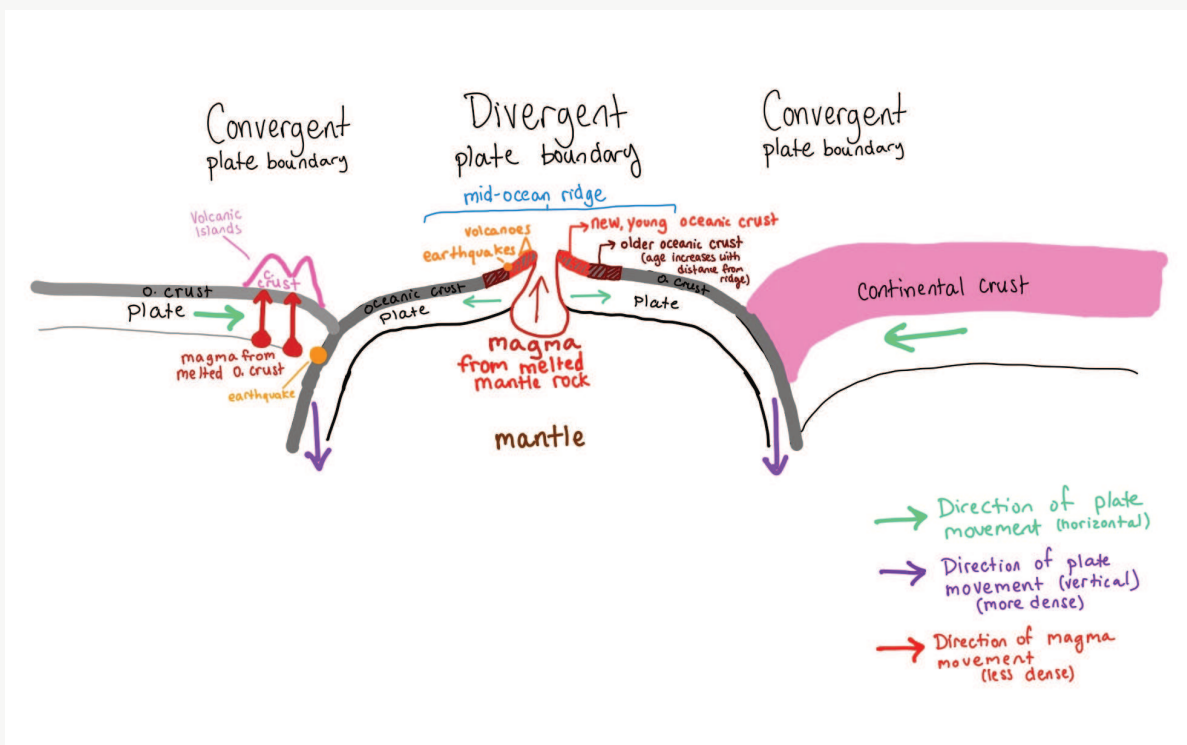
If students do bring up continental plates, say, *Because you mentioned two types of plates, I'm going to include a different type on each side of the model. How should we draw the continental crust to distinguish it from the oceanic crust?* Accept all responses, and press toward a common representation. For example, students should note that continental crust is thicker. Using a different color may also be helpful. (The example model uses pink to represent the minerals typical of continental igneous rocks.)

Draw the plates without including surface features yet (mountains, volcanoes, or earthquakes). Continue with the discussion as shown below, adding new elements that the class suggests.

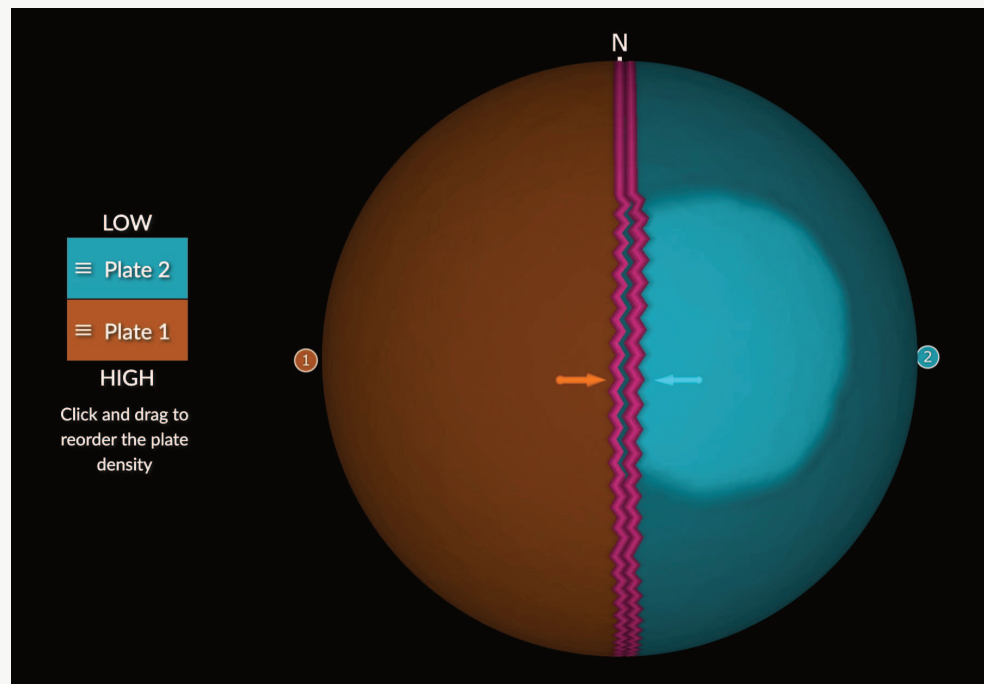
Suggested prompt	Sample student response
<i>Let's focus on the motion at this plate boundary where two oceanic plates are converging. How are the plates moving here?</i>	The plates are moving toward each other. One plate slides down under the mantle. One plate moves downward.
<i>What determines which plate slides down under the mantle?</i>	The denser plate. The plate with high density goes beneath the plate with low density.
<i>What kinds of features, components, or events are common at a boundary where two oceanic plates are colliding?</i>	Volcanoes. A magma pocket or magma forming. Islands. Earthquakes.

Suggested prompt	Sample student response
Let's begin with the magma. Where does it come from and where does it go?	It comes from the oceanic plate that is sliding down into the mantle. It goes upward toward the surface.
At the divergent boundary, we saw that magma was pushing the plates away from each other. What does the magma do at this convergent boundary?	It forms volcanoes. It accumulates on top of the oceanic crust and creates continental crust. It forms islands.
Some of you mentioned earthquakes. Did you notice any patterns in their depth or magnitude at this plate boundary?	A lot of them happened deeper in the mantle. There were earthquakes of all types of magnitudes.

At this point, the model should look like this:



If students describe only oceanic plates, draw that side of the model first. Then prompt them, *Remember, we were curious about what happens when continents and ocean floor meet at a plate boundary. How can we use the simulator to include that in our model?* Project and run <https://tectonic-explorer.concord.org/> for the class to observe the collision of a continental plate and an oceanic plate. Be sure that the plate with the continent is less dense, as seen in the settings in the image below:



Images generated using Tectonic Explorer (<https://tectonic-explorer.concord.org/>), developed at the Concord Consortium.

Continue the discussion as shown below, moving to the model's other convergent boundary. Add motion arrows to the plates and magma on the site of oceanic-continental convergence.

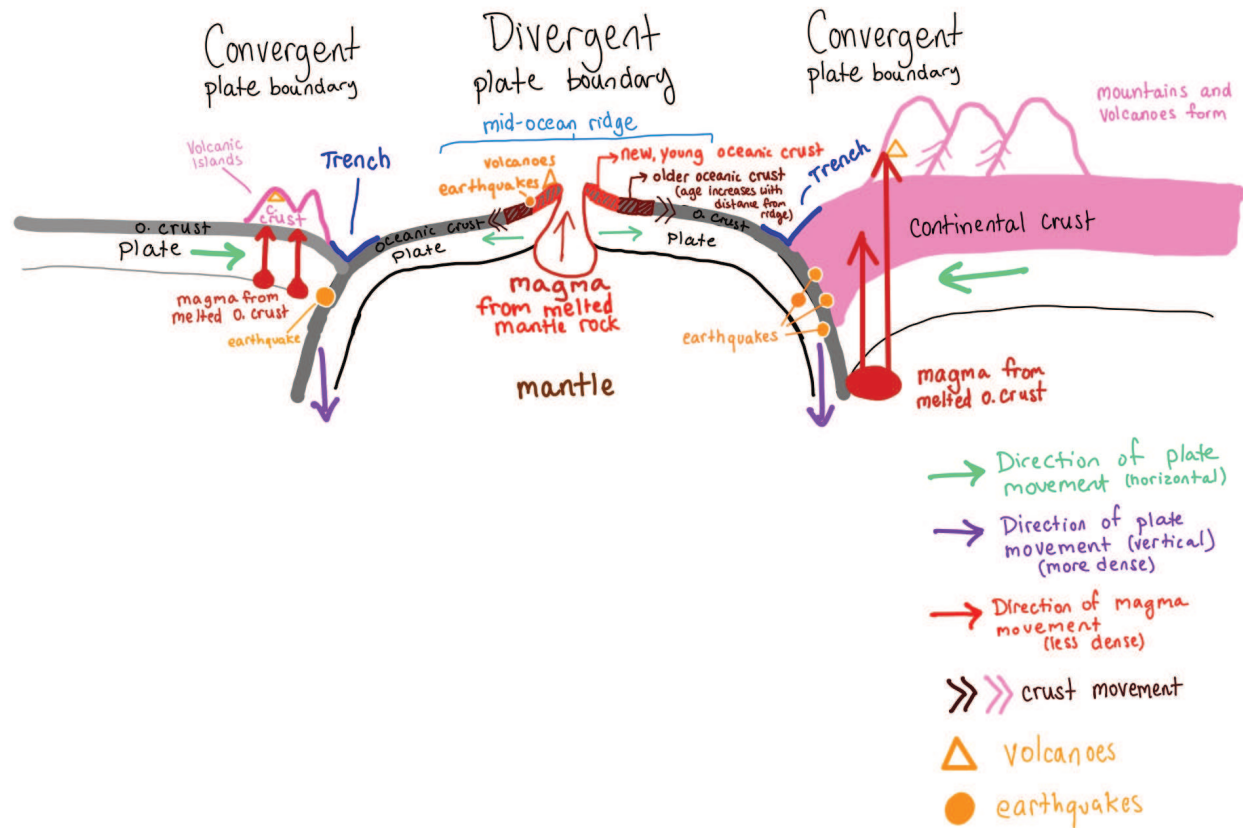
Suggested prompt	Sample student response
<i>Let's now focus on the boundary where the continental and oceanic plates are converging. What elements did we include in our models?</i>	Mountains. Volcanoes. Earthquakes.

Suggested prompt	Sample student response
<i>The other convergent boundary we modeled did not have mountains. What makes mountains form when oceanic and continental plates converge?</i>	Because both plates are moving toward each other, the continental crust crumples and rises while the oceanic crust slides down into the mantle.
<i>Why does the crust get pushed upward on the continent side?</i>	Continental crust is thicker and less dense, so it can't sink down into the mantle. It has to be pushed higher as it collides.
<i>What evidence do we have about the differences between oceanic and continental crust?</i>	When we measured the density of the rock samples, the granite had a lower average density than the basalt.
<i>What about the magma? Where does it come from and where does it go?</i>	It's the same as the other convergent boundary. It comes from the oceanic plate that is sliding down into the mantle, then it goes upward toward the surface.

Use the prompts below to label the earthquakes and trenches at convergent boundaries.

Suggested prompt	Sample student response
<i>What happens when the magma reaches the surface?</i>	It forms volcanoes and it accumulates on the crust.
<i>And the earthquakes? Did you notice any patterns in their depth or magnitude at this plate boundary?</i>	A lot of them happened deeper in the mantle. There were earthquakes of all types of magnitudes.
<i>You noticed that earthquakes happen deeper at this type of boundary. What do you notice about the depth of the crust itself? We can look at the key on the elevation map for help.</i>	The elevation gets very low on one side of a convergent boundary.
<i>Yes, a place like this where the ocean gets very deep is called a trench. (Label trenches on both convergent boundaries.) Why do you think the elevation gets so low here?</i>	The place where the plates converge is being dragged downward. The sinking plate is bending the other plate where they are colliding.

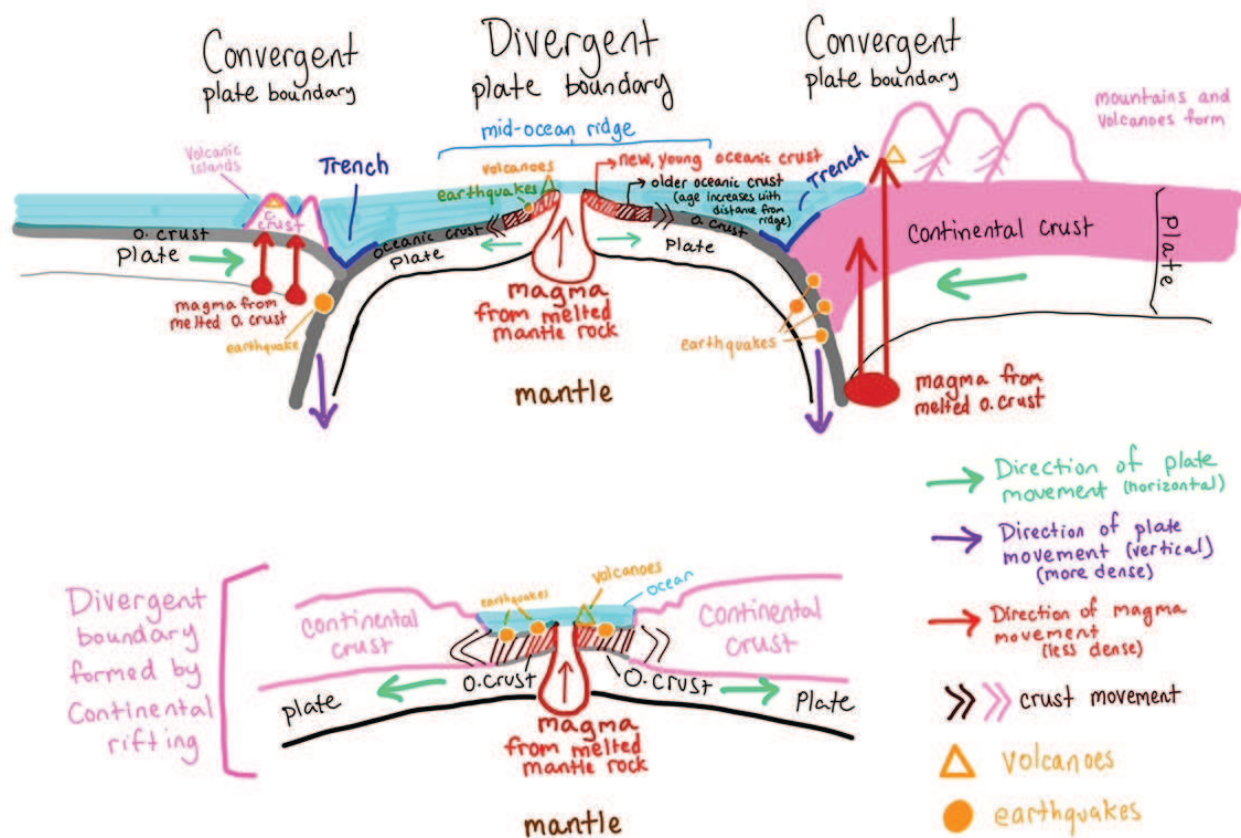
At the end of this discussion, your consensus model should look something like the image below. Notice that it does not include explicitly named force vectors. The focus has been on the motion of the elements included in the model, and the arrows represent movement, not forces.



Discuss a divergent boundary of two continental plates. Make sure to demonstrate this boundary by projecting <https://tectonic-explorer.com/cord.org/>. This time, when setting up the simulation, draw a continent on the center of the planet before defining the boundary. Guide this discussion as shown below.

Suggested prompt	Sample student response
<i>We can also use this simulation to investigate boundaries where two continental plates are moving away from each other. Why is this simulation particularly relevant for us?</i>	Because we think this is what is happening at Afar.
<i>When two oceanic plates moved away from each other, we saw new oceanic crust forming at the boundary. What happens when two continental plates move away from each other?</i>	Oceanic crust is also formed in the space between the plates.
<i>What happens to the continental crust as that happens?</i>	It is stretched and separated. Eventually, it breaks apart.
<i>Did we observe any surface features at this boundary that were caused by the motion of the plates?</i>	Yes, we saw the land stretching and forming a stair-like structure. We also saw earthquakes and volcanoes around the plate boundary.
<i>At this boundary, we have not included interactions with other boundaries on the right and the left. If the other plates on the right and the left are either diverging or converging, would that change the surface features we would see?</i>	It matters. If the plate to the right is converging with another plate on that side, we would see mountains. If the other plate is diverging, then maybe we would not see mountains.

This is how the final consensus model might look:



10 · USE THE CONSENSUS MODEL TO EXPLAIN RADIOMETRIC DATA

5 min

MATERIALS: Plate Interactions Consensus Model poster, <https://tectonic-explorer.concord.org/>



Use the consensus model to explain radiometric data. Present slide N. Say, *Scientists develop models to try to explain patterns they identify in their data. Maybe we can use our model to explain patterns we identified earlier in the ages of oceanic and continental crusts. Can someone remind us what those patterns were?*

Listen for students to say we found that continental crust is much older than oceanic crust, and that with increasing distance from divergent boundaries, the oceanic crust gets older, with the youngest crust along the zone of divergence. You may choose to display the Tectonic Explorer using the “crust age” map type on the bottom menu to support the discussion of oceanic crust age patterns. Write these patterns on the board.

At this point, ask students to turn towards the members of their groups. Continue by saying, *Take a few minutes with your group to use the class consensus model to explain how the flow of matter through this system could create these patterns.* After a few minutes, invite students to share their explanations.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Explicitly use the consensus model of plate interactions to explain the patterns in radiometric data. (SEP: 6.2; CCC: 1.5; DCI: ESS2.B.1, ESS2.B.3)
- Include the flow of magma through the system as a mechanism that influences the movement of rocks and that explains the patterns in the ages of crustal rocks. (CCC: 1.5; DCI: ESS2.B.1, ESS2.B.3)
- Include divergent and convergent plate boundary interactions to explain the differences in composition of the crust. (SEP: 6.2; DCI: ESS2.B.1, ESS2.B.3)

What to do: Invite students to come to the front of the classroom and use the consensus model to illustrate their ideas, which might look like the following:

- At divergent boundaries, magma, which comes from melted mantle, moves upward. The magma reaches the surface and becomes part of the oceanic crust. This is why oceanic crust is youngest right at the divergent boundary. The matter is flowing between Earth's interior system and Earth's surface.
- Over time, newer oceanic crust pushes older oceanic crust. This is why the age of oceanic crust increases as you move away from the divergent boundary. The matter flows in the direction from where it is created toward where it is destroyed. This flow of matter is also the movement of tectonic plates.
- Continental crust forms when magma from re-melted oceanic crust solidifies. This continental crust does not sink easily. As a result, it does not get destroyed at convergent plate boundaries. This is why continental crust persists over very long periods of time. Its matter is not transformed back into magma.

Building toward: 10.B Construct an explanation about the patterns in radiometric data using a consensus model of plate interactions at convergent and divergent boundaries. (SEP: 6.2; CCC: 1.5; DCI: ESS2.B.1, ESS2.B.3)

11 · REVISE EXPLANATIONS ABOUT THE FUTURE OF AFAR

15 min

MATERIALS: science notebook, *Investigating Plate Interactions*, *Predicting the Future of Africa and Afar*, *Progress Tracker*, *Rate and Direction of Plate Movement*, Plate Interactions Consensus Model poster



Revise explanations about the future of Afar. Have students return to their seats. Present **slide O**. Say, *Scientists also use models to make predictions about future patterns. Let's use models to explain what will happen to Afar in the future. You can change or add to the predictions and explanations you developed at the start of class. Be sure to consider the new evidence that we used to develop our consensus model.*

Give students the rest of the period to complete this task. They should revise their responses to Questions 1 and 2 on the handout *Predicting the Future of Africa and Afar*, and respond to all parts of Question 3 on the back. Collect the handout as students leave.

ASSESSMENT OPPORTUNITY

When to check for understanding: When students complete the handout *Predicting the Future of Africa and Afar*. Use the *Predicting the Future of Africa and Afar Key* to get an idea of the types of predictions and supports that students might bring to the task of making a prediction about the future of Afar and Africa.

What to look for/listen for in the moment:

- Question 1: The **prediction** about the future of Afar and Africa should be focused on changes to surface features. Students should not explain anything at this point. Drawings might be a good way for them to represent important surface features. (CCC: 4.4)
- Question 2: Students should **use multiple sources of evidence and the consensus model to construct an explanation of how the plate interactions under Africa will cause the predicted surface changes.** (SEP: 6.2; CCC: 4.4; DCI: ESS2.B.2, ESS2.B.3)

What to do: Encourage students to use various sources of evidence for their explanation. Students might want to use the following handouts to support their predictions about Africa and Afar:

- *Measuring Rock Densities*
- *Rate and Direction of Plate Movement*

Tell students that you have copies of data sets we have used in the past. Let them take a copy to their seat and return it when they are done with it.

These are some of the additional sources of evidence students might include:

- findings collected in the *Investigating Plate Interactions* handout
- *Progress Tracker*

Building toward: 10.C Construct an explanation about the **future** of Afar based on valid and reliable evidence obtained from a variety of sources and the assumption that **plate tectonics is the unifying theory that explains the past and current movements of the rocks at Earth's surface.** (SEP: 6.2; CCC: 4.4; DCI: ESS2.B.2, ESS2.B.3)

Additional Lesson 10 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

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 synthesize information from multiple sources, including the reading about magma and the computer simulation of plate interactions, into a coherent understanding of plate tectonics as a unifying theory that explains multiple phenomena in the Earth system. This includes how interactions involving the transfer of energy and matter at plate boundaries lead to the development of distinctive surface and ocean-floor features, characteristic patterns in the ages of rock, and distinctive patterns in earthquake depth.

LESSON 11: How might forces between the mantle and plates affect plate motion?

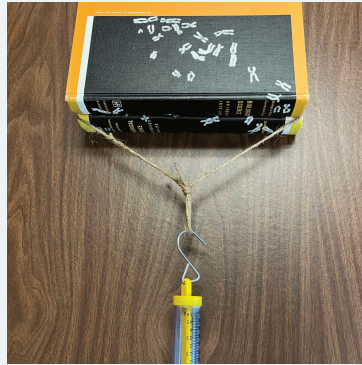
PREVIOUS LESSON

We used a simulation to investigate plate interaction at divergent and convergent plate boundaries. We analyzed data to compare surface features on Earth and in the simulation. We developed a consensus model that explains how plate interactions result in the surface features we identified, and we used it to predict what Afar and Africa will look like in the future. We wondered which forces acting on plates can help us explain the patterns we identified in their motion.

THIS LESSON

INVESTIGATION

2 days



We model how we think forces might be acting on plates. We consider the properties of plates that might influence how forces act on them. We plan and carry out an investigation of variables that we think can affect friction forces between an object and the surface it slides over. We connect conclusions from our investigation to plate properties and motion. We wonder how other forces could act on plates.

NEXT LESSON

We will model forces on plates and investigate how gravity can be represented as components when objects are on an incline. We will use this to update our Plate Interactions Consensus Model poster from Lesson 10.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

11.A Develop and revise models that predict the relationship between mass, surface area, or texture and the force of friction acting on Earth's plates due to mantle convection, which is a process that is too large and too slow to observe directly. (SEP: 2.3; CCC: 3.2; DCI: ESS2.A.2)

WHAT STUDENTS WILL FIGURE OUT

- The force of friction between an object and the surface below it depends on the mass of the object and the material of the surfaces rubbing together, but not on the surface area between the object and the surface.

Lesson 11 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	5 min		NAVIGATE Review the differences in the motion of the plates. Consider the forces acting on them that could explain these differences.	A-B	Plate Interactions Consensus Model poster, Forces and Variables poster, chart paper markers
2	20 min		DEVELOPING INITIAL MODELS Develop a model in groups of forces acting on plates that could explain their motion. Propose ideas about plate variables that might affect these forces. Revise models individually and compare them in a gallery walk.	C-F	chart paper, chart paper markers, Plate Interactions Consensus Model poster, M-E-F poster, Forces and Variables poster
3	5 min		CONSIDER THE ROLE OF FRICTION Discuss commonalities among models. Use a book in a thought experiment for considering factors affecting the force of friction.	G-H	book
4	10 min		ESTABLISH HOW TO MEASURE FRICTION Learn from a class demonstration how to measure the force of friction using a spring scale.	I-N	M-E-F poster, fast tumble buggy (2 batteries), slow tumble buggy (1 battery), 3 spring scales (1N), piece of pink insulation foam with string loops, cardboard box, sticky tack, books or blocks, push-pull spring scale (5N), 1 yard of string
5	5 min		DEVELOP INITIAL INVESTIGATION IDEAS AND NAVIGATE Brainstorm plate properties to explore in the <i>Friction Investigation</i> , and consider all relevant variables. Develop a hypothesis in groups about the relationship between the independent and dependent variables.	O-Q	
End of day 1					
6	1 min		NAVIGATE Work in groups to revisit hypotheses for the variables to be investigated.	R	chart paper, chart paper markers
7	8 min		PLAN THE FRICTION INVESTIGATION Design the group <i>Friction Investigation</i> . Discuss the investigation plans in a round robin.	S	chart paper, chart paper markers, Friction Investigation
8	10 min		CARRY OUT THE FRICTION INVESTIGATION Conduct the <i>Friction Investigation</i> , collect data, and write conclusions.	T	Friction Investigation
9	12 min		MAKE SENSE OF THE FRICTION INVESTIGATION Discuss and make sense of findings from the <i>Friction Investigation</i> in a Scientists Circle.	U	sheet of investigation findings/conclusions, group investigation plan, chart paper, chart paper markers
10	12 min		CONNECT FINDINGS TO PLATE MOTION Draw connections between the findings from the <i>Friction Investigation</i> and plate motion. Revise initial predictive models.	V-X	initial predictive model from day 1, <i>Rate and Direction of Plate Movement</i> from Lesson 10, Plate Interactions Consensus Model poster, M-E-F poster

Part	Duration		Summary	Slide	Materials
11	2 min		NAVIGATE AND COMPLETE AN EXIT TICKET Consider other forces that could help to explain the differences in the motion of plates.	Y	Forces and Variables poster

End of day 2

Lesson 11 • Materials List

	per student	per group	per class
Friction Investigation materials	loose-leaf paper	- chart paper - chart paper markers - push-pull spring scales (5N) 1 yard of string - books or blocks	
Lesson materials	- book - science notebook - sheet of investigation findings/conclusions - initial predictive model from day 1	- chart paper - chart paper markers - group investigation plan <i>Rate and Direction of Plate Movement</i> from Lesson 10	- Plate Interactions Consensus Model poster - Forces and Variables poster - chart paper markers - M-E-F poster - fast tumble buggy (2 batteries) - slow tumble buggy (1 battery) 3 spring scales (1N) - piece of pink insulation foam with string loops - cardboard box - sticky tack - books or blocks - push-pull spring scale (5N) 1 yard of string - chart paper

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.

Prepare a piece of chart paper for a poster titled “Forces and Variables”.

Have the Plate Interactions Consensus Model poster from Lesson 10 and the M-E-F poster developed in previous lessons readily visible in the classroom.

For day 1, prepare the setup for the balanced forces at a constant velocity demonstration. See the *Demonstration Setup Instructions* and *Zeroing Spring Scales Horizontally* references for setup instructions.

For day 2, the *Friction Investigation* utilizes found objects from your classroom, books or blocks, string, rulers, digital scales, and spring scales (5N).

Day 2: Friction Investigation

- Group size:** 3–4 students.
- Setup:** For each group, prepare a ruler, a digital scale (3 kg max weight), 1 yard of string, and a spring scale (5N). Gather several found objects (such as books or blocks) from your classroom for students to use in this investigation. Some criteria for choosing these items:
 - The objects for the demonstration should be similar to those available for the students’ investigation.
 - Choose objects of similar materials that can be placed next to each other and pulled together or that have the same material on different-sized sides so they can be tipped to change the surface area without changing the mass.

- You also need different surfaces to pull the objects across. Alternatively, you can use objects that have different textures on different sides with the same surface area.
- **Notes for during the lab:** Tell students that they should all write down a copy of the data their group collects in case time runs short and they need to share their results the next day.
- **Safety:** Students should wear indirectly vented chemical splash goggles during the investigation.
- **Disposal:** Discard the string after use.
- **Storage:** Digital scales must be stored level, without weight on them. Storing them on their sides or with things on top of them may cause them to stop working or be less accurate.

See the following links for an idea of how this investigation can be conducted:

- Friction Investigation Demonstration (part 1): <https://youtu.be/9w-ORd14Ucs?si=miufUs3GPylVlViO>
- Friction Investigation Demonstration (part 2): <https://youtu.be/idYX7kkRqbs?si=q4l9SKus4gvEkrU3>.

Lesson 11 • 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 (DCI):

- **ESS2.A.2: Earth Materials and Systems.** 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)

For this DCI, students investigate friction to discuss how mantle motion could affect plate motion, and investigate how gravity acts on objects on an incline to discuss slab pull. Students have previously discussed the movement of denser materials toward Earth's interior in Lesson 6, and in Lesson 12, they will explore how gravity acts on plates at different boundaries to explain why some plates move more than others because of gravitational forces.

In this lesson, students establish that forces are balanced on objects moving at a constant velocity, and that this can be used to measure the force of friction on an object. This concept and technique will be built on when learning about vehicle braking times in *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*.

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:

- Scientists often use hypotheses to develop and test theories and explanations.

Students encounter and/or co-construct ideas around several terms during this lesson, and they may decide to add the following word to their Personal Glossaries: *friction*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

We do not discuss acceleration or how acceleration is related to forces. This idea will be covered in the *Vehicle Collisions Unit*.

For the DCI above, we do not specifically talk about convection moving mantle material, as that was covered in Lesson 6 of this unit.

In the demonstration on day 1 for measuring friction (with balanced forces at a constant velocity), we lightly use--but do not try to establish--Newton's third law. Students have worked with related ideas if they have experienced *OpenSciEd Unit 8.1: Why do things sometimes get damaged when they hit each other? (Collisions Unit)*. Ideas for collisions will be reestablished in the *Vehicle Collisions Unit*.

This investigation does not introduce the relationship between mass and force of gravity, which is not covered until *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)*. It does not introduce the concept of normal force, nor of force components on angled surfaces; this will be covered in Lesson 12. The understanding in this lesson is therefore limited to friction between flat surfaces and the physical property of mass of sliding objects--that is, sliding friction. Other types of friction (such as static friction) and the differences between these types are beyond the scope of this lesson.

LEARNING PLAN for LESSON 11

1 · NAVIGATE

5 min

MATERIALS: Plate Interactions Consensus Model poster, Forces and Variables poster, chart paper markers

Consider what we know about plate motion. Present **slide A**. Make sure the Plate Interactions Consensus Model poster from Lesson 10 is readily visible to everyone. Use it to elicit responses to the slide's first prompt:

- *What were the main differences we observed in the motion of the plates?*

Students might say their direction and their speed.

Consider what forces might act on plates. Say, *Last time, we were thinking about forces that could be acting on the plates that could help to explain those differences.* Elicit responses to the second prompt:

- *What forces do we think are acting on plates that could explain the motion we observed?*

Students might suggest:

- gravity
- friction
- convection

On the Forces and Variables poster, create a T-chart with the heading "Forces Acting on Plates" on the left side. Record ideas about forces on this side of the chart; leave the right side empty for now.

Consider what objects might interact with plates. Present **slide B**. Say, *Good ideas. We learned previously that forces are interactions between two things. For the forces we've listed, what is interacting with the plates to push or pull on them?* Students might suggest:

- gravity
- the mantle
- Earth
- other plates

2 · DEVELOPING INITIAL MODELS

20 min

MATERIALS: chart paper, chart paper markers, Plate Interactions Consensus Model poster, M-E-F poster, Forces and Variables poster

Develop an initial model of forces acting on plates. Say, *So, we think multiple forces are acting on a plate at once. Let's work in groups to develop a model to illustrate those forces and what would happen to a plate's motion when multiple forces act on it at the same time.* Organize students in groups of 3.

Present **slide C**. Have groups draw initial models on chart paper, as described on the slide. Give them a few minutes to complete this model.

Conduct a round robin about the initial models. Describe the protocol of the round robin: each group has 1 minute to share their model, using the ideas from the Plate Interactions Consensus Model poster, and other groups are invited to ask clarifying questions or propose alternative explanations.

* SUPPORTING STUDENTS IN DEVELOPING AND USING SCALE, PROPORTION, AND QUANTITY

As students model plate behavior, they are modeling systems and components whose interactions occur at too large of a spatial and temporal scale to observe directly.

ADDITIONAL GUIDANCE

Some students might be thinking about plate boundaries, and some might be thinking about the whole plate. The more ideas on the table, the easier it is to motivate investigating the role of friction, and of inclines to drive plate motion.

KEY IDEAS

Purpose of the discussion: To share ideas about the forces acting on plates. Push for elaboration of evidence and reasoning, and encourage other groups to critique and provide alternative explanations. The end goal of this discussion is to motivate the need to identify how characteristics of plates affect these forces.

Listen for these ideas:

- The mantle causes plates to move through convection.
- Denser plates slide down into the mantle, so gravity must be involved.
- Magma coming out of divergent boundaries pushes plates away from each other.
- Forces act on the plates.

Possible areas of disagreement or controversy:

- how magma can push the plates when it moves upward
- the role of gravity as a plate slides down into the mantle

Consider variables affecting the forces acting on plates. Say, *We have some great ideas about how forces act on the plates. We're trying to understand how and why the plates move in certain ways. Point to the M-E-F poster and ask, What can we say about the relationship between forces and motion right now?* Listen for students to suggest that forces are related to how something moves.

Do not expect students to associate unbalanced forces with a change in motion yet; but if they make this connection, validate it, and say, *If the motion of these plates is changing in different ways, then the forces acting on them must be different.* If they do not make this connection, say, *We know forces are related to changes in the motion of objects. So, if the plates move differently, there might also be a difference in how the forces we identified are acting on them.*

Present **slide D**. Use the first prompt to elicit student ideas, as shown in the table below. On the right side of the Forces and Variables poster, write the heading "Plate Variables" and record the ideas that emerge during this discussion.

Suggested prompt

What physical properties of the plates could cause differences in the forces acting on them?

Sample student response

Their density.

Their thickness.

Their mass/size.

The type/shape of rock (texture).

The other plates surrounding that plate.

Their speed.

ADDITIONAL GUIDANCE

Though speed is not a physical property of a plate, students may still bring this up, as it has affected plate movement in prior lessons. The next investigation includes a demonstration showing that speed does not affect the force of kinetic friction.

Say, *We seem to be saying that these properties are variables that can affect the forces acting on the plates. One way to understand how a variable affects a system's behavior is to change it.* Pose the slide's second question:

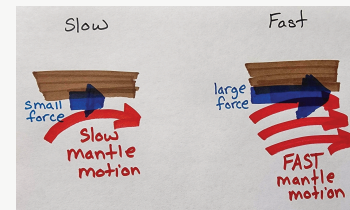
- *What are some ways that we can change a variable to investigate its effect?*

Listen for students to suggest increasing it, decreasing it, or removing it. Ask whether we can test these ideas directly. They should say that we cannot, because we have no control over the variables, the plates are too large, and the motion of the plates is too slow to observe directly.



Use a model to predict changes in the forces on plates when other variables change. Present slide E. Say, *Based on our discussion, and your ideas about plate properties, I want you to revise your model on another piece of paper, to predict what would happen to the forces acting on the plates if one of the plate properties were changed.*

Distribute a new piece of chart paper to each group, and have students draw their models as a group. Prompt them to show two versions: one in which the property changed is large, and one in which the property is smaller. An example that shows incorrect physics but covers the key ideas needed at this point is shown to the right. Collect these models for review; you will return them for revision on day 2.



ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Models should include:

- Interactions between the plates and other systems, such as the mantle (via friction) or Earth (via gravity). (SEP: 2.3; DCI: ESS2.A.2)
- Mantle movement affecting the plates through system interactions. (SEP: 2.3; DCI: ESS2.A.2)
- Earth-sized systems of plates and the mantle interacting and representing change that occurs over large timescales. (CCC: 3.2; DCI: ESS2.A.2)

What to do:

- If students do not include interactions with the mantle, ask them what systems are interacting to cause changes in the plates' movement.
- Remind students of the list of physical properties we brainstormed, and have them consider how those properties would affect plate movement.
- Ask students to review the model developed in Lesson 10 and consider which of its components might apply to their current predictive models. Direct them to recognize that the systems of the mantle, plates, and their interactions are important to include and explain in these models.
- If students choose to model how gravity affects plate motion, these models are not addressed in this lesson, but they will be in Lesson 12, and are a valid choice at this point.

Building toward: 11.A.1 Develop and revise models that predict the relationship between mass, surface area, or texture and the force of friction acting on Earth's plates due to mantle convection, which is a process that is too large and too slow to observe directly. (SEP: 2.3; CCC: 3.2; DCI: ESS2.A.2)

Compare and discuss revised models. Present slide F. Have groups participate in a gallery walk to compare their models with those of their peers, looking for similarities and differences. After a few minutes, ask them to return to their seats.

3 · CONSIDER THE ROLE OF FRICTION

5 min

MATERIALS: book

Motivate the need to investigate the role of friction. Present **slide G**. Use the prompts to elicit noticings about students' initial predictive models, as shown in the table below.

Suggested prompt	Sample student response
<i>What do our models have in common?</i>	We are using arrows to represent forces. The size of the arrow represents the magnitude of the force. Some of us have included convection.
<i>What are the differences between our models?</i>	The driving forces are different (the mantle dragging versus gravity pulling). Some plates are flat and some are at angles.

Say, *It seems like we still have a lot of questions about forces on the plates. Two themes that I'm hearing are rubbing forces between the mantle and crust, and where the plates seem to be sliding down inclines pulled by Earth's gravity. Maybe we need to investigate these forces more to build our understanding.*

Conduct a thought experiment. Present **slide H**. Say, *Let's think for a minute about the interaction between the mantle and the plates. Use your hand and a book to model how we think these two layers are interacting.* Demonstrate putting a book on top of your hand and sliding it across your hand. If students have books available, encourage them to do the same.

Continue by saying, *With your hand as the mantle, what do you feel as the book plate slides across it?* Listen for students to say resistance. Then ask, *What could you change that would make the sliding easier or harder?* Listen for them to suggest decreasing or increasing the friction between the book and their hand. Say, *Interesting. It seems we are saying that friction is a force that can affect how an object moves when it's sliding in relation to another object.*

If students do not use the word *friction* explicitly, ask, *What is a word that we use for sliding or rubbing forces?* Guide them to determine that a word that might be used is friction.

4 · ESTABLISH HOW TO MEASURE FRICTION

10 min

MATERIALS: M-E-F poster, fast tumble buggy (2 batteries), slow tumble buggy (1 battery), 3 spring scales (1N), piece of pink insulation foam with string loops, cardboard box, sticky tack, books or blocks, push-pull spring scale (5N), 1 yard of string

Problemalyze quantifying/measuring friction. Say, *To understand how friction might affect plate motion, we need to investigate what variables affect how friction interacts with moving plates. To do this, it would be useful to have a way to quantify or measure friction. How have we measured forces in the past?* Listen for students to suggest spring scales.

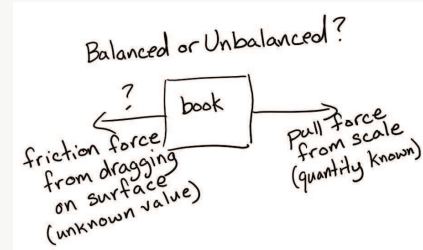
Present **slide I**. Have students turn and talk about the prompt:

- How could we use a spring scale to measure the force of friction acting on an object?

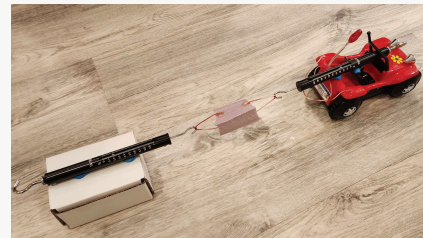
Listen for them to suggest dragging objects with spring scales. Present **slide J**. Pose the question:

- How could we model the forces on a book being dragged by a spring scale?

Start a free-body diagram on the board, depicting a book being dragged by a spring scale as shown on the slide. Ask what forces should be included and how they should be represented. Refer to the M-E-F poster's questions about system stability, and ask whether the forces should be balanced or unbalanced and why. Highlight that we do not yet have evidence either way. Note that because friction is a horizontal force, considering vertical forces is optional. At this point, your free-body diagram should look something like the image to the right.



Introduce the constant velocity forces demonstration. Place the slow tumble buggy, foam, and box setup (see *Demonstration Setup Instructions*) where students can see it. Say, *This car setup can help us gather evidence about whether forces are balanced or unbalanced for objects moving at a constant velocity.* Explain that the car is specially designed to always pull at a constant speed.



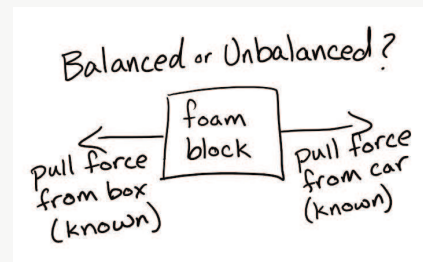
Present **slide K**. Have students turn and talk about the forces acting on the foam. After a minute, ask a few students to share out. Highlight that both horizontal forces on the foam are directly measurable, unlike the friction on the book or box. Use student input to draw a free-body diagram for the foam. It should look something like the example to the right.

Measure forces on an object moving at a constant velocity. Have students gather around the demo on a stretch of open floor. Ask for a couple of volunteers to read the newtons force measurement off the scales on the car and box while these are moving. Turn on the car, let it run, and have the volunteers take force readings.

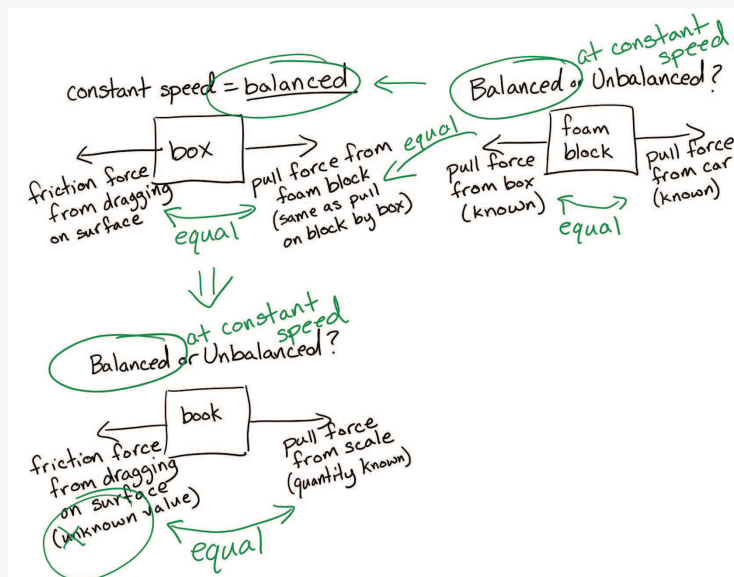
Present **slide L**. Point out the photo example of equal force readings, and pose the slide's questions:

- What do our data tell us about the friction between the box and the ground?
- What about the book and the surface?

Guide students through thinking about the forces being balanced on the foam and how the pull on the foam by the box is equal to the pull forward on the box by the foam.



Draw the free-body diagram for the box and show that because it is also moving at a constant speed, the force of friction must be balanced with the pull forward shown on the scale. Connect this to the free-body diagram of the book with friction acting on it (see image below). As all the forces are balanced, we know they are equal. Therefore, if we pull the book with a scale at a constant speed, we can infer the friction force on the book.



ADDITIONAL GUIDANCE

Note that we are not trying to establish Newton's third law with this demo. Students who have experienced the *Collisions Unit* have learned Newton's third law, and it will be reestablished for collisions in the *Vehicle Collisions Unit*. It is best not to spend time proving or establishing it in this lesson.

ALTERNATE ACTIVITY

If you have time, create your own photo for **slide L** so the force measurements match your specific mass/floor combination. Use a single photo with zoomed crops of each scale to show they are displaying the same measurement.

Consider and test the role of speed. If students haven't already raised questions about speed, ask, *Is the book pulled at the same speed as the car? Does that matter?* Present **slide M**. Let students discuss for a moment; then offer to test this with another car that moves at a faster constant speed. Repeat the demonstration with the faster car to show that not only are the forces still balanced, but the measurements are the same as for the slower car.

ALTERNATE ACTIVITY

If students bring up questions about speed before this moment, the faster car demo can be conducted at the same time as the slower car demo.

Establish a friction measurement protocol. Present slide N. Say, *From our mini-investigation and free-body diagrams, we now know that if we drag a book with a spring scale at a constant speed, the scale tells us the force of the friction between the book and the surface it's being dragged over. This could help us think about how friction might affect the motion of plates on Earth.*

5 · DEVELOP INITIAL INVESTIGATION IDEAS AND NAVIGATE

5 min

MATERIALS: science notebook

Consider friction on different objects. Project slide O. If students have not considered the role of surface area or type of material as variables affecting the friction on plates, say, *Before we consider how friction might affect plate motion, let's consider what we know about friction from our everyday experiences.* Use the slide to elicit ideas, as shown in the table below. Otherwise, skip this discussion.

Suggested prompt	Sample student response
<i>What characteristics of an object might increase or decrease the force of friction acting on it?</i>	Its size. Its material. The material of the surface. Its mass. Its shape.
<i>Do we think these characteristics could also affect the force of friction acting on the plates? Why or why not?</i>	Yes--maybe the more surface area there is, the more friction is acting on a plate. We learned that plates are made of different types of rocks, so maybe some rocks generate more friction when interacting with the mantle.

Brainstorm ideas for investigating friction. Present slide P. Say, *Now that we have a tool for measuring friction forces, let's brainstorm which of the plate properties we've identified might affect friction forces specifically.* Ask students to turn to their groups and discuss their ideas. Give groups a minute before inviting them to share. Listen for them to identify mass, surface area, and material/texture.

Tell the groups to choose one of these three variables to investigate. Write each group's choice on the board, and make sure that every variable is being investigated by at least one group.

ADDITIONAL GUIDANCE	If students are discussing density as opposed to mass, you can point out that density includes two variables: volume and mass. Then you can explain that separating volume (related to surface area) and mass when investigating friction allows us to build a more nuanced understanding. Alternatively, you can let students first try to investigate density, and then have a problematizing discussion about how switching between two objects with different densities is actually changing two variables (or, in the case of two objects of the same size/shape with different densities, that it is really only changing the mass).
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* SUPPORTING STUDENTS IN THREE-DIMENSIONAL LEARNING

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:

- Scientists often use hypotheses to develop and test theories and explanations.

This is an opportunity to make explicit that a hypothesis should have an explanatory component and not just be an overly simplified if/then statement.

ADDITIONAL GUIDANCE

If you are having trouble visualizing the lab, watch these videos: <https://youtu.be/9w-ORd14Ucs?si=miufUs3GP yJvIvIQ> and <https://youtu.be/idYX7kkRqbs?si=q4I9SKus4gvEkrU3>

Develop hypotheses in groups. * Present slide Q. Say, *With your group, think for a moment about your dependent and independent variables. When designing an investigation, a hypothesis is often used to make predictions about the relationship between variables. It can be tested by finding evidence that either supports or refutes it. In this case, the hypothesis would be about how these variables affect the friction force between surfaces. Let's format our thinking as a hypothesis before we jump into the investigation.*

Have students work in groups to create a hypothesis for the variable they plan to investigate and record it in their notebooks, using the sentence stem on the slide:

- If _____, then when we _____, we will observe _____ because _____.

The goal of the sentence stem is to support students in thinking not only about how changing one variable will affect the other, but also about the cause or explanation of that relationship. An example hypothesis using the sentence stem is: "If mass positively affects the force of friction, then when we increase the mass, we will observe the friction force increasing because the object is heavier."

ADDITIONAL GUIDANCE

If students struggle to distinguish between the independent and dependent variables, remind them that the independent variable is the one they will actually modify/change directly, and the dependent variable is the one they will measure because they think it will be affected by the independent variable. Also, discuss what variables they will control, and why it is important to control these.

End of day 1

6 · NAVIGATE

1 min

MATERIALS: science notebook, chart paper, chart paper markers

Revisit hypotheses. Present slide R. Have groups revisit their hypotheses for the variables they want to investigate, and record it on their group's chart paper with their initial models from last time.

7 · PLAN THE FRICTION INVESTIGATION

8 min

MATERIALS: Friction Investigation, chart paper, chart paper markers

Design the *Friction Investigation*. Present slide S. Distribute chart paper and markers to the groups. Display the materials available for students to use in the investigation. Say, *Now, spend 5 minutes in your groups, thinking about how you can use these materials to obtain the data you need. Sketch your design for your investigation and data table to share with the class.* As groups work on their designs, walk around the room. Pay close attention to those investigating surface area, as it is likely that some will suggest using more books and dragging them together; make a mental note of the groups who make these suggestions.

ADDITIONAL GUIDANCE

As it has been a while since students last worked in groups to design and conduct an investigation, this may be a good time to revisit the class's Community Agreements.

As you circulate, check that students are organizing their data in the tables they designed. Ask clarifying questions to help them identify and fix flaws in their methods, for example:

- *What tool could you use to collect your data that could also help others understand your results?*
- *What variable are you measuring when you do that?*
- *Are you sure that changing this variable does not cause a change in any of the other variables?*
- *How will you quantify that variable? How are you ensuring that your data is accurate?*

Share investigation plans in a round robin. After 5 minutes of planning, invite the groups investigating the role of mass to share out. It is very likely that the investigation plans for mass are more simple and only change mass without changing surface area or material. After the first group shares, ask the class, *Which other groups investigating mass designed a similar investigation? Which other groups investigating mass designed a different investigation?*

Next, invite the groups investigating surface area to share out. If their investigation plan also changes the mass, say, *Remember that to know what's causing the change in friction, we need to be careful to only change one variable at a time. Do any of your ideas also change another variable?* Listen for students to say things like adding another block next to the first would also add mass.

Then ask how they might change the surface area without changing the mass, or point to a strategy a group already shared. For example, starting with two books next to each other and then stacking those books would change the area in contact with the surface while keeping the mass the same. An example prompt and response for the two books strategy is below.

Suggested prompts	Sample student responses	Follow-up questions
<i>How could we alter our book/block-spring scale system to change one of these variables?</i>	Add more books next to each other to increase the surface area.	<i>How could we do that without changing the mass? Or, how could we then change back to a smaller surface area without changing the mass?</i>

Continue this discussion using a similar protocol until all investigation designs for mass, surface area, and material/texture have been shared and only change one variable. Then ask groups to update their investigation plan on their chart paper if they did not already do so during the discussion.

8 · CARRY OUT THE FRICTION INVESTIGATION

10 min

MATERIALS: Friction Investigation

Investigate variables affecting friction. Present slide T. Say, *Let's carry out our investigations. As you work, record your data as a group on your investigation plan and your findings/conclusions individually on loose-leaf paper.* Tell students that you will collect their investigation plans and data tables after the investigation. Distribute the lab materials and loose-leaf paper and give groups 10 minutes to complete their investigation. *

Use the last prompt on the slide to guide students to craft a conclusion statement:

- *Complete this sentence on a new piece of paper to frame your conclusion for the investigation: When we _____, we observed _____. This evidence supports the conclusion that _____.*

An example of a student conclusion statement is: "When we increased the mass of the books being dragged, we observed higher friction forces. This evidence supports the conclusion that mass is positively related to friction force."

* ATTENDING TO EQUITY

Students with physical disabilities may have a hard time pulling the books at a constant velocity. Consider supplying them with the low-speed car and the box from the demo. If they are investigating mass, give them things to place inside the box. If they are investigating surface area, suggest that they rotate the box to a smaller side.

This method of measuring friction with the car will be used again in the *Vehicle Collisions Unit*.

9 · MAKE SENSE OF THE FRICTION INVESTIGATION

12 min

MATERIALS: sheet of investigation findings/conclusions, group investigation plan, chart paper, chart paper markers

Discuss findings from the investigation. Give students 3 minutes to organize their ideas, then have them bring their investigation results to a Scientists Circle for discussion.

Present **slide U**. Use the prompts to invite groups focusing on a particular variable (e.g., surface area) to share their findings and conclusions. Invite other groups to ask clarifying questions or offer wonderings about the role of friction. Record the main findings and conclusions as a public artifact (e.g., on the class whiteboard).

KEY IDEAS

As students discuss their findings, listen for the following conclusions:

- When we increased the mass of the object, we observed an increase in the force of friction resisting the object sliding over a surface. This evidence supports the conclusion that the more mass an object has, the higher the force of friction acting on it.
- When we changed the surface area between the object and the surface it was sliding over, while keeping its mass constant, we did not see any change in the force of friction between the two. This evidence supports the conclusion that the surface area does not impact the force of friction acting on an object.
- When we changed the material at the interface of the object and the surface it was sliding over, we observed a change in the force of friction. We found that rougher-textured surfaces have higher resistive friction forces and smoother surfaces have lower resistive friction forces. This evidence supports the conclusion that there is a positive relationship between the texture of a material and the force of friction acting on it.

ADDITIONAL GUIDANCE

This investigation does not introduce the relationship between mass and the force of gravity (which is not covered until *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)*), the concept of normal force, nor force components on angled surfaces (covered in Lesson 12). The understanding in this lesson is therefore limited to flat surfaces and the physical property of mass of sliding objects.

10 · CONNECT FINDINGS TO PLATE MOTION

12 min

MATERIALS: initial predictive model from day 1, *Rate and Direction of Plate Movement* from Lesson 10, Plate Interactions Consensus Model poster, M-E-F poster

Connect friction and plate motion. Have students return to their seats. Present **slide V**. Say, *Now that we have a better idea of how different variables affect the force of friction experienced between two objects, let's go back to how we think this force might affect plate motion.* Pose the question on the slide:

- *Would a high force of friction acting on a plate make it speed up or slow down?*

Accept all responses. If students do not suggest that friction can both help and resist motion, have them place one hand on top of the other to represent the mantle and a plate. Direct them to simulate the plate moving slower than the mantle (in the same direction), and demonstrate the movement with your own hands. Have them notice what they feel on the palm of their hand on top, and the top of their hand on the bottom. Listen for them to say the friction would be pulling the plate with the mantle. Then, direct them to simulate the plate moving faster than the mantle (in the same direction). Listen for them to say the friction with the mantle would resist motion.

Present **slide W**. Redistribute *Rate and Direction of Plate Movement* from Lesson 10 to the groups and continue this discussion using the slide's prompts, as shown in the table below. Use the Plate Interactions Consensus Model poster to help students discuss the regions where plates are experiencing friction.

Suggested prompt	Sample student response
<i>Where do we think plates are experiencing friction?</i>	In the subduction zone along the surface that is in contact with the mantle. In the convergent boundary, where the oceanic plate rubs against the continental plate as it starts to slide down into the mantle. In transform boundaries. (Optional.) In the lower part of the plate, where it interacts with the mantle through the motion of matter due to convection.
<i>How could we use our results from our Friction Investigation to help explain the plate motion that we have observed?</i>	The map suggests that plates that have convergent boundaries move faster. So something is different there. Larger plates should be experiencing larger forces of friction because they have more mass.

Point to the M-E-F poster and help students see how forces might be related to motion. For example, you can perform a simple demonstration of dragging a stack of books to show how different forces (pulling force and friction force) affect the motion. Suggest that we keep this relationship in mind, and forecast that a later unit will explore the relationship between forces and motion in more detail.

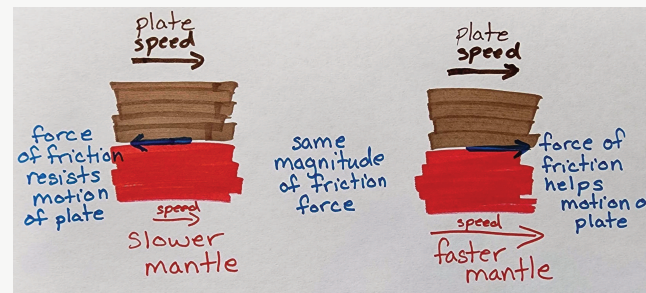
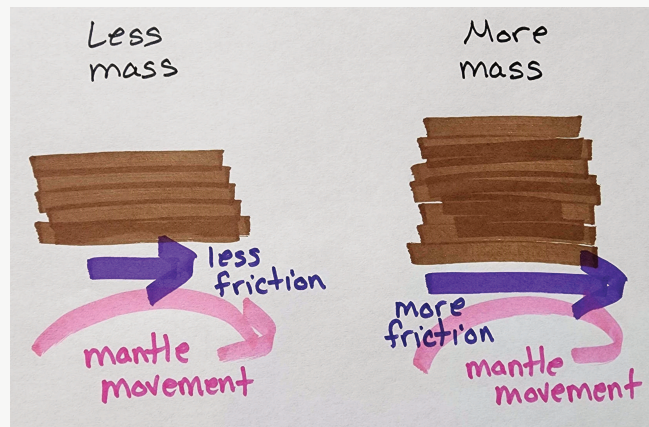
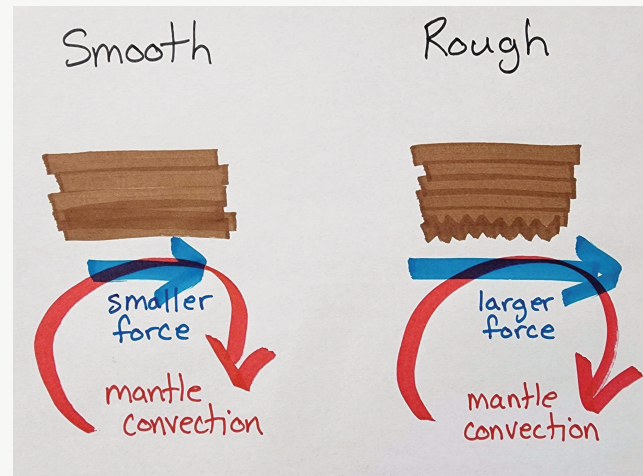
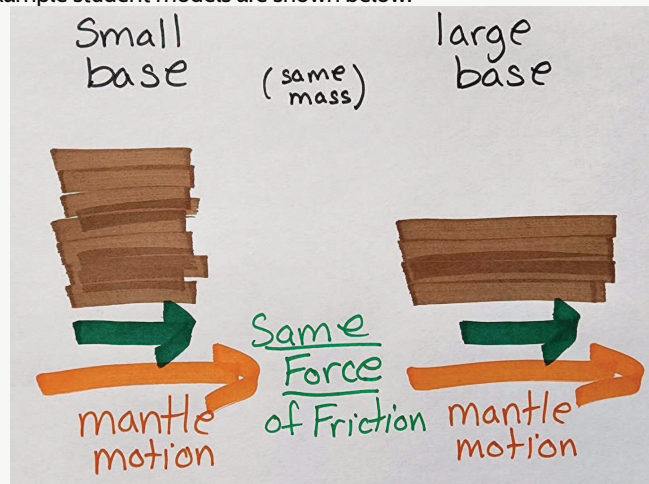
ADDITIONAL GUIDANCE	If students struggle to come up with ideas to answer this prompt, return to the Plate Interactions Consensus Model poster and highlight other directions that the plates are moving, like plates sliding down into the mantle or the oceanic crust moving upward at a divergent boundary. Students should suggest that some plates move upward. Follow up by asking, <i>Which force have we explored before that can cause up-and-down movement?</i> They should suggest gravity.
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Revise predictive models into explanatory models. Present **slide X**. Return students' predictive models from day 1. Guide the class in the next task with the slide's prompt:

- *Use your initial predictive models and your findings from the Friction Investigation to model the relationship between friction and mass, surface area, or texture.*

Example student models are shown below.



ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Models should include:

- Interactions between the plates and other systems, including the mantle (via friction) or other plates, influencing the motion of the plates. (SEP: 2.3; DCI: ESS2.A.2)
- Mantle movement affecting the plates through friction force interactions between systems. (SEP: 2.3; DCI: ESS2.A.2)
- Earth-sized systems of plates and the mantle interacting and representing change that occurs over large timescales. (CCC: 3.2; DCI: ESS2.A.2)
- The relationship between mass (more mass, more friction), surface area (no relationship), or texture (rougher texture, more friction) and the force of friction between the plates and the moving mantle. (SEP: 2.3; DCI: ESS2.A.2)

What to do: If students struggle to connect the *Friction Investigation* findings to plate motion, use simple models such as books, paper, or your hands to emulate some of the conditions occurring within the mantle.

Building toward: 11.A.2 Develop and revise models that predict the relationship between mass, surface area, or texture and the force of friction acting on Earth's plates due to mantle convection, which is a process that is too large and too slow to observe directly. (SEP: 2.3; CCC: 3.2; DCI: ESS2.A.2)

Add to Personal Glossary. Give students an opportunity to add terms to their Personal Glossaries. They may choose to add *friction*, with a meaning like “a dragging/sliding force between two surfaces.”

11 · NAVIGATE AND COMPLETE AN EXIT TICKET

2 min

MATERIALS: science notebook, Forces and Variables poster

Complete an exit ticket about additional forces acting on plates. Make sure the Forces and Variables poster is readily visible so all students can see the forces and plate variables that will be the focus of the next investigation. Keep this poster to use again in Lesson 12. Say, *OK, I think we made some progress, but it seems we still have some questions about how forces are acting on plates.*

Present **slide Y**. Tell students to take a moment to record their ideas related to the prompt as an exit ticket in their notebooks:

- Which other force(s) should we investigate that could help us explain why some plates change motion differently than others?

Say that in our next class period, we will revisit this prompt and consider our ideas as a class.

Additional Lesson 11 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

These are the CCMS-related ideas that are used to support sensemaking in this lesson:

Number and Quantity:

- **CCSS.MATH.CONTENT.HS.N-VM.1** Represent and model with vector quantities: Recognize vector quantities as having both magnitude and direction.
- **CCSS.MATH.CONTENT.HS.N-VM.3** Represent and model with vector quantities: Solve problems involving velocity and other quantities that can be represented by vectors.

Students review that forces are vector quantities and have both magnitude and direction. They also observe that force vectors balance to a net force of zero on an object moving at a constant velocity, and they use this concept to measure the force of friction on a sliding object.

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA

A Common Core Speaking and Listening standard is targeted in this lesson:

- **CCSS.ELA-LITERACY.SL.11-12.4** Present information, findings, and supporting evidence, conveying a clear and distinct perspective, such that listeners can follow the line of reasoning, alternative or opposing perspectives are addressed, and the organization, development, substance, and style are appropriate to purpose, audience, and a range of formal and informal tasks.

Students present their lab findings to the class, citing their collected evidence from lab observations.

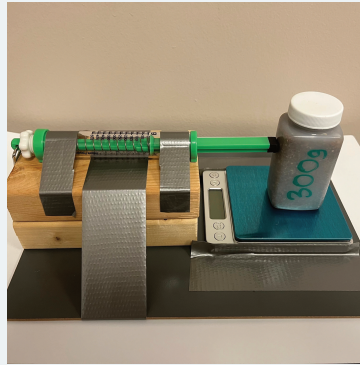
LESSON 12: How do forces act on objects, such as the plates, when they are on inclines?

PREVIOUS LESSON We created initial models of how we thought forces acted on plates. We considered the properties of plates that might influence how forces act on them. We investigated the properties that we thought could affect the friction forces between an object and the surface it slides over. We connected our conclusions to plate properties and motion. We wondered how other forces could be acting on plates.

THIS LESSON

INVESTIGATION, PUTTING PIECES TOGETHER

2 days



We model forces acting on plates and wonder how gravity can pull plates to cause changes in motion. We investigate forces on an object placed on an incline and model how the force of gravity can be split into two vector components to make sense of how gravity pulls down inclines. We connect this to plate motion and update our Plate Interactions Consensus Model poster from Lesson 10 and our Progress Trackers.

NEXT LESSON We will revisit our Scale Chart poster to add processes and update connections. We will revisit our Driving Question Board. We will engage in a transfer task to explain why the Midcontinent Rift did not tear apart.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

12.A Use mathematical models to illustrate the force interactions (including gravity) between a plate and other systems to explain stability and change of plate motion that is too large and too slow to observe directly. (SEP: 2.3, 5.2; CCC: 3.2; DCI: ESS2.A.2)

WHAT STUDENTS WILL FIGURE OUT

- The force of gravity can be broken into components that pull parallel and perpendicular to an incline, and as the incline gets steeper, the component of gravity parallel to the incline increases.
- The force of gravity on an object is directly proportional to the mass of the object.
- The force of gravity contributes to changes in plate motion through processes called slab pull and ridge push.

Lesson 12 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	2 min		NAVIGATE Reorient to the forces we identified as acting on plates, and identify gravity as the force to investigate next.	A	Plate Interactions Consensus Model poster, Forces and Variables poster
2	15 min		MODEL GRAVITY Review what we know about the force of gravity. Construct free-body diagrams of plates on various inclines, orient to a simplified system for investigation, and develop consensus for the free-body diagram of the simplified case.	B-G	plastic bottle, funnel, water or sand, small whiteboard, books or blocks, painter's tape, Model of Movement in the Mantle poster from Lesson 6 (optional), chart paper, chart paper markers
3	10 min		DEVELOP A MATHEMATICAL MODEL FOR GRAVITY Develop an equation for the force of gravity acting on an object of a given mass in grams.	H-I	push-pull spring scale (5N)
4	8 min		PLAN AN INVESTIGATION ABOUT GRAVITY Orient to the investigation setup, and use it to discuss the forces and variables that can affect an object on an inclined plane.	J-K	plastic bottle, funnel, water or sand, digital scale (3 kg max weight), push-pull spring scale (5N), protractor, small whiteboard, books or blocks, painter's tape
5	8 min		CARRY OUT AN INVESTIGATION ABOUT GRAVITY Measure forces on an object parallel and perpendicular to the incline it is on for multiple angles, observing what happens to the forces as the angle changes.	L	Measuring Forces on Inclines Investigation
6	2 min		NAVIGATE Record initial noticings about the data for the forces acting on an object on an incline.	M	
End of day 1					
7	2 min		NAVIGATE Revisit initial noticings about the data for the forces acting on an object on an incline.	N	
8	13 min		REPRESENT FORCE DATA WITH COMPONENTS Review force vector components from Lesson 2. Draw free-body diagrams for the lab data and calculate the force of gravity using the indirectly measured components.	O-R	<i>Measuring Forces on Inclines Investigation</i>
9	12 min		MAKE SENSE OF DATA AND CONNECT TO PLATE MOTION Make sense of how the forces change with the angle, and connect this to mass. Consider what would happen if the forces become unbalanced. Connect lab findings to plate motion on the handout.	S-W	<i>Measuring Forces on Inclines Investigation</i>
10	7 min		DEFINE FORCE PHENOMENA AT PLATE BOUNDARIES Discuss forces within the context of divergent and convergent plate boundaries. Add to Personal Glossaries.	X-Z	

Part	Duration		Summary	Slide	Materials
11	11 min		ADD TO THE PLATE INTERACTIONS CONSENSUS MODEL Update the Plate Interactions Consensus Model poster with friction and gravity ideas. Update Progress Trackers.	AA-CC	Progress Tracker, Plate Interactions Consensus Model poster, chart paper markers

End of day 2

Lesson 12 • Materials List

	per student	per group	per class
Measuring Forces on Inclines Investigation materials	• <i>Measuring Forces on Inclines Investigation</i>	• plastic bottle • funnel • water or sand • digital scale (3 kg max weight) • push-pull spring scale (5N) • protractor • small whiteboard • books or blocks • painter's tape	
Lesson materials	• science notebook • <i>Measuring Forces on Inclines Investigation</i> • Progress Tracker	• push-pull spring scale (5N)	• Plate Interactions Consensus Model poster • Forces and Variables poster • plastic bottle • funnel • water or sand • small whiteboard • books or blocks • painter's tape • Model of Movement in the Mantle poster from Lesson 6 (optional) • chart paper • chart paper markers • digital scale (3 kg max weight) • push-pull spring scale (5N) • protractor

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.

Make 1 copy of the *Measuring Forces on Inclines Investigation* handout for each student.

Make sure that all students can easily see the Plate Interactions Consensus Model poster from Lesson 10 and the Forces and Variables poster from Lesson 11.

Day 1: *Measuring Forces on Inclines Investigation*

- Group size: 3-4 students.
- Setup:

- Fill the plastic bottles with water or sand using a funnel so each bottle has a different mass between 300 and 500 grams. The different masses between groups set up a richer discussion about mass at the end. Prepare 1 bottle for each group plus 1 for demonstration.
- Prepare a scale platform for each group with a small whiteboard or other small board, digital scale (3 kg max weight), and push-pull spring scale (5N). Using painter's tape, carefully tape the digital scale to the whiteboard on the edges so the scale plate is still free to move. Tape blocks, boxes, or books to the whiteboard next to the digital scale to create a platform for the spring scale to be level with about the middle of the bottle while it is on the digital scale. Tape the spring scale to the blocks with the plunger hanging over the digital scale. Test the setup as described in the *Measuring Forces on Inclines Investigation* handout to make sure the scales are free to work properly. See the example in the lesson image and the image within this lesson.
- Provide each group with a protractor.
- **Notes for during the lab:** Look for students to follow the steps described in the handout when they collect their data. If they do not remove the bottle from the scale and tare it before the next reading, the reliability of their data will be compromised.
- **Storage:** Digital scales must be stored level and without weight on top of them. Storing them on their sides or with things on top of them may cause them to stop working or be less accurate.

Lesson 12 • Where We Are Going and NOT Going

Where We Are Going

In this lesson, we target the following disciplinary core idea (DCI):

- **ESS2.A.2: Earth Materials and 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)

For this DCI, we investigate how gravity acts on objects on an incline to discuss what causes slab pull and ridge push at plate boundaries and how this can affect plate motion. This builds on the mechanisms for plate motion developed in Lesson 6 (convection) and Lesson 11 (friction with the mantle). Although the DCI describes plate motion as primarily caused by convection, in recent years scientists have come to accept that gravity through slab pull is the main driver of plate motion on Earth.

The SEP and CCC coverage of this lesson builds on extensive development across the unit:

- In Lesson 1, students begin their engagement with 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”) with the development of an initial predictive model based on observations of the anchor phenomena. In Lesson 6, they use data from a mantle tank video to develop a model for thermal convection within Earth's mantle. This model is then used in combination with tomography data in Lesson 7 to explain surface features. In Lesson 10, students pull together all the pieces so far into an overarching explanatory model that combines concepts from across the unit. In Lesson 11, they create predictive models about how friction is involved in plate motion and then revise these models based on data from their investigation.
- In this lesson, students add the final piece of the force of gravity and update their model from Lesson 10 with friction and gravity. This updated model will then be used for the assessment in Lesson 13. The use of this SEP element in this unit differs from its development in *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*, in which models were primarily energy transfer models. In this unit, students use and develop a variety of models, including free-body diagrams, particle-level representations of matter, and illustrated explanatory system models.
- Students engage throughout this unit with CCC 3.2: “Some systems can only be studied indirectly as they are too small, too large, too fast, or too slow to observe directly.” Development of the Scale Chart poster helps them to track processes at both large and small spatial and temporal scales. In this lesson, students use an investigation of small objects on inclines to make sense of much larger, slower processes of changes in plate motion due to the force of gravity.

Students encounter and/or co-construct ideas around several terms during this lesson, and may decide to add the following words to their Personal Glossaries: *slab pull* and *ridge push*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

For the DCI above, we do not specifically talk about deep probes and seismic waves, reconstructions of historical changes in Earth's surface and magnetic field, chemical processes, nor convection moving mantle material. These topics were discussed in previous lessons and built into the Plate Interactions Consensus Model developed in Lesson 10, to which the physical processes of gravitational forces are added in this lesson.

LEARNING PLAN for LESSON 12

1 · NAVIGATE

2 min

MATERIALS: Plate Interactions Consensus Model poster, Forces and Variables poster

Revisit the Lesson 11 exit ticket. Make sure everyone can easily see the Plate Interactions Consensus Model poster and the Forces and Variables poster. Present **slide A**. Say, *Last time, we investigated the role of friction on an object's motion, and we found that some plate variables affect the force of friction acting on a plate. But we think other forces are involved. Let's consider what we should investigate next.*

Give the class a moment to review their exit tickets from the end of Lesson 11. Ask a few students to share out. Listen for suggestions that we should investigate the force of gravity. If gravity is not mentioned, point to the Plate Interactions Consensus Model poster to focus students' attention to the motion of plates sliding down inclines into the mantle.

2 · MODEL GRAVITY

15 min

MATERIALS: science notebook, plastic bottle, funnel, water or sand, small whiteboard, books or blocks, painter's tape, Model of Movement in the Mantle poster from Lesson 6 (optional), chart paper, chart paper markers

Review the vector nature of gravitational forces. Present **slide B**. Use the prompt to elicit student ideas, as shown below.

Suggested prompt	Sample student response
<i>What do we know about how the force of gravity acts on objects?</i>	Gravity pulls down (inward toward Earth's center). Gravity acts on everything that has mass. Gravity is why things fall.

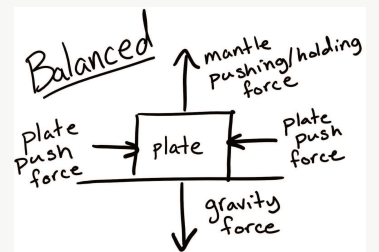
Use student ideas to review that forces, including gravity, are vectors that have both magnitude and direction, and that if an object is stable (stationary or moving at a constant velocity), the forces on it are balanced.

If students do not mention gravity, quickly ask them to recall the forces used in Lesson 6 to explain the movement of other systems, such as the mantle and mantle tank. Display the Lesson 6 Model of Movement in the Mantle poster and ask what forces in the mantle tank might also be affecting the stable plate. Guide students to determine that gravity would be present in both models.

Model forces on a stable plate. Present **slide C**. Say, *Let's model the force of gravity acting on Earth's plates, starting with a very simplified case.* Use the slide's prompts to guide students to draw a free-body diagram:

- Consider the simplified, stable plate system of a plate squeezed between two plates, all sitting on top of the mantle.
 - Draw a free-body diagram of the forces on the middle plate. *
 - If the plate motion is not changing, what do we know about the forces?

Give students 1-2 minutes to draw the free-body diagram in their notebooks. Have a couple of volunteers draw their diagrams on the board. Use these to come to an agreement on the diagram through a quick class discussion of similarities and differences. Be sure to establish that the forces are balanced, both vertically and horizontally. An example of this diagram is shown to the right.



* ATTENDING TO EQUITY

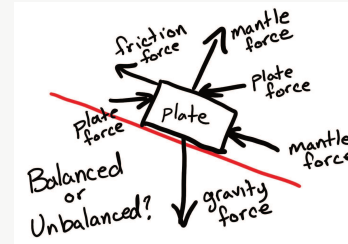
Universal Design for Learning: The representations used by students in free-body diagrams do not need to match any specific convention. What is important is to have a shared understanding of what each piece means. Allow students agency over these representations, and do not try to force them into any specific convention without an expressed need that the students understand.

 **Problemalyze the simplified model.** Say, *These free-body diagrams show a super-simplified scenario, but they're a good baseline for us to work from. Let's use them to expand to the more complex plate scenarios that motivated us to think about gravity in the first place.*

Present **slide D**. Have students work with a partner to draw a free-body diagram for a plate at a divergent boundary, and to consider whether the forces are balanced or unbalanced.

Ask a few pairs to draw their diagrams on the board. Facilitate discussion around these examples to highlight the complexity of the scenario and the unknowns, such as whether there is friction, what direction it points, and whether the forces are balanced. Do not try to build a correct or consensus model here; the purpose is to highlight complexity and unknowns.

Present **slide E**. Repeat the process for a convergent boundary. The force diagrams for these are likely to get very messy, and students are likely to have many questions or disagreements on details. An example of a proposed free-body diagram is shown to the right.



In the discussion about balanced versus unbalanced forces, highlight the need to know more about how the plates are or are not changing motion. Listen for students to reason about the temporal and spatial scale of the changes and what would tell us whether the forces are balanced.

Present **slide F**. Read the prompt aloud:

- *What do we think are the differences in the forces acting on the plate at points A and B?*

Mention that point A is an early convergent boundary and point B is a convergent boundary with significant overlap and subduction. Listen for students to offer ideas about gravity pulling on B differently because there is more of an incline.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Students to talk about:

- Using their **free-body diagram models** to **support their claims or explanations** about **plates**. (SEP: 2.3, 5.2; DCI: ESS2.A.2)
- The **force of gravity pulling on plate systems** and **affecting plate motion**. (SEP: 2.3; DCI: ESS2.A.2)
- That we cannot directly measure the force of **gravity on plates or their motion** because they are **too large and too slow**. (CCC: 3.2; DCI: ESS2.A.2)
- How the **mantle and plates interact** and how this changes based on how they are configured at plate boundaries (e.g., how tilted the plate is on the mantle). (SEP: 2.3; DCI: ESS2.A.2)

What to do: This formative assessment is followed by an individual written assessment near the end of the lesson. If students struggle with the connection between gravity and plate motion, support sensemaking about these ideas throughout the rest of the lesson. Use probing questions to elicit student thinking about the forces in the simplified setup, and how this connects to the plates.

Building toward: 12.A.1 Use **mathematical models to illustrate** the **force interactions** (including **gravity**) **between a plate** and other systems to explain stability and change of **plate motion** that is **too large and too slow to observe directly**. (SEP: 2.3, 5.2; CCC: 3.2; DCI: ESS2.A.2)

Define a simplified model for plates on inclines. Say, *Our models and thinking about these boundaries seem to confirm that we need to know more about gravity, especially how it behaves with inclines. Our models also highlight the complexity and unobservable temporal and spatial scales of the plates. To investigate how gravity acts on inclines, we need to use a simplified model.*

Present **slide G**. Display one of the bottles for the lab on a small whiteboard with a book or block in place of the spring scale, as shown on the slide and to the right. Explain that, because the surfaces of the bottle and whiteboard are both very smooth, we can ignore friction for this system. Ask students to individually follow the prompts on the slide:

- Draw a free-body diagram for the bottle.
- If the bottle stays sitting there, are the forces balanced or unbalanced?
- What would happen if the incline were increased?

Use student input to create a consensus on what this free-body diagram should look like (an example is shown to the right) and whether the forces are balanced. Create this model in a way that can be kept to reference during the next class, because students may want to revisit it during the *Midcontinent Rift Transfer Task*. If wall space is short, consider making this model on a whiteboard with dry erase markers. Listen for students to say that the forces might become unbalanced or change in some way if the incline is increased.

ADDITIONAL GUIDANCE

A major concept further developed across this unit is that of balanced and unbalanced forces. In this lesson, the concept of balanced forces being equal strengths and opposite directions is important. However, note that these are **not** Newton's third law force pairs, as these forces are acting on the same object. If students use language such as "action/reaction" or bring up Newton's third law, emphasize that those concepts are related to interaction forces between two objects as opposed to multiple balanced forces on the same object.

3 · DEVELOP A MATHEMATICAL MODEL FOR GRAVITY

10 min

MATERIALS: push-pull spring scale (5N)

Discuss how to measure forces. Present **slide H**. Say, *OK, we want to investigate the role of gravity acting on plates, but we know we can't investigate plates directly. Similarly to our Friction Investigation in the last lesson, we'll need to use a simpler object in the classroom.* Pose the slide's questions to the class, as shown in the table below.

Suggested prompt	Sample student response
What tools have we used to measure forces in the past?	A spring scale. A digital scale.
How could we use these tools to measure how much gravitational force is acting on an object?	We can hang the object on a spring scale and read the force. We put the object on a digital scale and it tells us how much it weighs.
How could we use them on the incline?	We could place the scale below the bottle on the incline.

If it is not brought up, talk about how, if you hang something from a spring scale, the scale reads the amount of force it pulls up with, which must be balanced with the force of gravity, therefore telling us the magnitude of the gravitational force. If necessary, draw a free-body diagram to illustrate.

If students do not mention a digital scale, or if they mention something like a bathroom scale, bring out a digital scale and show that when you press on it (gently), the number changes, so it seems to be measuring force too, but it is giving a readout in grams/kilograms.

Develop a mathematical model for gravity. Present slide I. Distribute spring scales to every pair/group of students, or use the image on the slide to elicit noticing and wonderings. Give students a minute to look at the spring scale before inviting them to share.

Students should recall from Lesson 2 that a spring scale gives readings in both grams and newtons. Ask them to now consider the relationship between grams and newtons on the scales. Expect them to notice that for any measurement, newtons are about 100 times larger than grams.

Ask what the unit grams is typically used to measure; listen for students to say mass. *Say, Mass and the force of gravity are related. We won't be investigating why this relationship exists until the Meteors Unit, but we can figure out the mathematical relationship between mass and gravity with the spring scales, using grams as a proxy measurement for the force of gravity.*

ADDITIONAL GUIDANCE

In previous lessons, students worked with spring scales and should have noticed that these use grams and newtons as units. When considering the relationship between these, they may notice that it is not exactly 100 grams = 1 newton. This is OK, but for the sake of the investigation, guide them into using the approximated value (alternatively, you could use 102 grams = 1 newton, which is more precise). Note that we are not converting to kilograms or taking the reciprocal to get to 10 N/kg. Although this is the traditional form, it is not necessary for establishing the proportionality of mass and the force of gravity, and could introduce confusion.

Then ask, *What do we mean that newtons are 100 times larger than grams? Can you give me a few examples?* After a few volunteers share, continue by asking, *Can we use this to write out a ratio that we can use to convert from grams to newtons?* Write the examples on the board as mathematical equations. For example:

$5\text{ N} \times 100 = 500\text{ g}$
 $10\text{ N} \times 100 = 1000\text{ g}$
 $1\text{ N} \times 100 = 100\text{ g}$

Say, Let's use our findings to write a mathematical model for the force of gravity based on mass. We can start by substituting variables for the values we read according to the units. Ask what variable the newtons should become, and write "Force of Gravity" on the board. Then write the " $\times 100 =$ " and ask what variable the grams should become, adding "mass" to the end of the equation when prompted by students. This should look like "Force of Gravity $\times 100 =$ Mass".

Continue, *Now let's figure out what the units of this 100 are.* Look for students to rearrange the equation to get 100 on its own; guide them to show that the units of 100 are g/N.

Say, Because we're developing a model for the force of gravity, we should solve for that. How should we rearrange the equation to solve for the force of gravity? When prompted by students, divide both sides of the original equation by 100 and rewrite the equation as "Force of Gravity = Mass/(100g/N)".

Reason about proportionality. Ask what would happen to the force of gravity on an object if its mass doubled, tripled, and so forth. Then introduce the term "directly proportional" to describe the relationship between the force of gravity on an object and the object's mass.

Say, We can measure many types of forces with the spring scales, but the mass markings on them assume that we're using a force of gravity measurement to find mass by hanging the object from a single scale. The markings don't read the mass of objects when using them for something like the friction forces we measured.

Continue, *Similarly, the digital scale assumes we're measuring mass by placing an object on it on a level surface. But really, it's measuring the force that it has to push back with to balance the gravity pulling down on the object. Therefore, even though the digital scale reads grams, we can use it to gather force data.*

ADDITIONAL GUIDANCE

Some students might be confused about the force of gravity being different on different objects, due to seeing things such as a feather and hammer being dropped on the moon. Affirm and keep track of questions, reassuring them that the phenomenon of how things fall will be addressed in the *Meteors Unit*. Then, to help them understand the relationship for how much the force of gravity pulls, talk about how it is the amount of force per amount of mass that is constant: every 100 g of mass is pulled on by 1 newton of gravitational force.

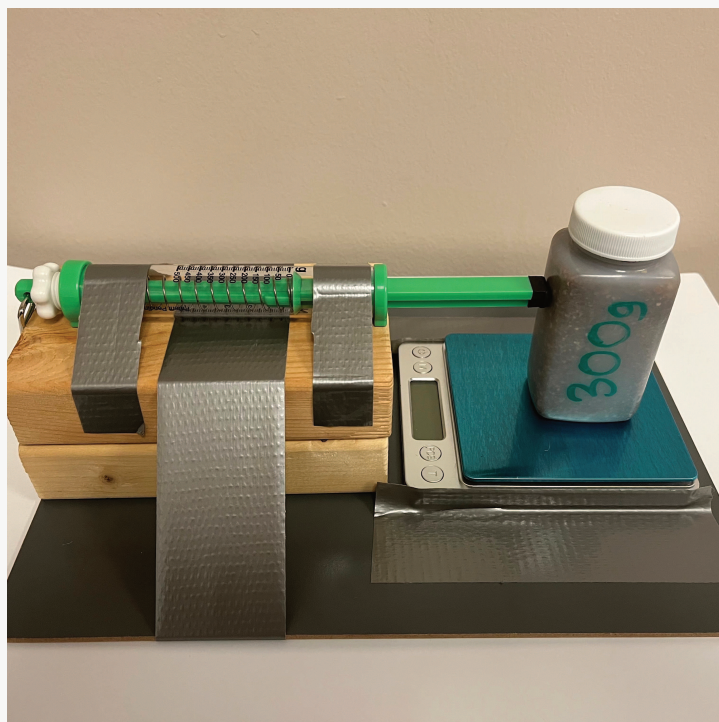
One way to help clarify this is to use “force of gravity” language as opposed to simply saying “gravity”. Students have not yet developed an understanding of the concept of acceleration, so it is best not to complicate things by discussing acceleration due to gravity; instead, concentrate on “gravitational field strength” or force of gravity per unit mass. Acceleration will be covered in the *Vehicle Collisions Unit*.

4 · PLAN AN INVESTIGATION ABOUT GRAVITY

8 min

MATERIALS: plastic bottle, funnel, water or sand, digital scale (3 kg max weight), push-pull spring scale (5N), protractor, small whiteboard, books or blocks, painter's tape

Orient to the lab setup. Present slide J. Introduce the setup, which is similar to the one shown in the image.



Show students how to use a protractor to measure the angles they will use. Use the slide's prompts to elicit ideas, as shown in the table below.

Suggested prompt	Sample student response
What force is the digital scale measuring?	The force the surface exerts on the object.
What force is the spring scale measuring?	How much force is on the bottle.
We said forces are vectors, and vectors have a magnitude and direction. What is the direction of each force?	The force the surface exerts on the object is perpendicular to the surface. The force down the incline acting on the bottle is parallel to the surface.
When are the forces acting on the bottle balanced?	When the object is not moving. When the force pulling down the incline is equal to the force of the spring scale pushing up the incline. When the force that the digital scale exerts on the bottle is equal to the force pulling the bottle into the incline (how much the incline is getting in the way).
Consider additional variables. Present slide K. Ask the question: Besides inclination (a.k.a. tilt angle), are there any other variables that could affect the forces we read with our scales? Listen for students to suggest the mass of the bottle. Say, <i>Because the mass was also a plate variable that we thought was connected to forces, we could investigate the role of mass as well. I have bottles between 300 and 500 grams. Your group needs to choose which mass to work with, and then compare your results with groups who investigated the other mass.</i>	
ADDITIONAL GUIDANCE	If students wonder why we have the digital scale measuring the force perpendicular to the incline, point out that when the incline is flat, it reads the force of gravity, and when the incline is 90 degrees, the spring scale measures the force of gravity. Use this to motivate looking at both values as the angle changes.

5 · CARRY OUT AN INVESTIGATION ABOUT GRAVITY

8 min

MATERIALS: Measuring Forces on Inclines Investigation

Carry out an investigation of gravity. Present slide L. Distribute the *Measuring Forces on Inclines Investigation* handout to each student. Orient them to the table in Section 1 where they will record their data. * This is a very short investigation, with only 5 data points to collect. Sample data for a 500-g bottle is shown below:

Angle	Force on Spring Scale (N)	Mass on Digital Scale (g)	Force calculated from Digital Scale (N)
0	0	500	5
30	2.5	433	4.33
45	3.5	354	3.54

* ATTENDING TO EQUITY

Students with physical disabilities may have a hard time holding the platform at a steady, specific angle while also reading the scales. For students who struggle with this task, provide additional books or blocks for them to set the platform at an angle. They may need an extra book to keep the platform from sliding as well.

60	4.3	250	2.5
Choose your own angle:	$(\text{mass}/100) \cdot \sin(\theta)$	$\text{mass} \cdot \cos(\theta)$	$[\text{mass} \cdot \cos(\theta)]/100$

6 · NAVIGATE

2 min

MATERIALS: None

Record noticings. Present **slide M**. Orient students to Section 2 of the *Measuring Forces on Inclines Investigation*, and have them record their noticings from their data collection so far.

End of day 1

7 · NAVIGATE

2 min

MATERIALS: None

Revisit noticings so far. Present **slide N**. Reorient the class to Section 2 of the *Measuring Forces on Inclines Investigation*, and to the investigation question at the top. Ask a student to remind the class what we were investigating and why. Allow others to suggest additional details or ideas. Be sure that the discussion talks about not only the bottle and gravity on an incline, but also the forces on plates that we are modeling.

Give students a moment to review their noticings from their data collection in the last class.

8 · REPRESENT FORCE DATA WITH COMPONENTS

13 min

MATERIALS: *Measuring Forces on Inclines Investigation*

Review force components. Revisit the free-body diagram for the bottle, either by displaying the version from day 1 or by recreating it. Relabel the forces as being applied by the digital and spring scales. Present **slide O**. Pose the question:

- *How have we dealt with forces at angles before?*

Listen for students to mention force components or ideas about splitting the force at an angle into pieces. If they do not, remind them about the foam and spring scales from Lesson 2 and how we drew the components of the forces that were at an angle. If needed, go through the Lesson 2 example again, drawing the dashed lines for the components of the angled force.

Turn back to the free-body diagram of the bottle and ask which force(s) we should break into components. If students say gravity, probe them to explain how. If they say the forces applied by the scales, point out that these are perpendicular, like the two that weren't split in Lesson 2. Say, *A convention that scientists came up with to make this process easier is to rotate the grids we use to consider the forces to align with the ramp. That way we only need to break the force of gravity into components.*

Represent data with force components. Present **slide P**. Ask students to use their data to draw free-body diagrams of the forces on the bottle for 30, 45, and 60 degrees. If they struggle to remember how to do this, draw the first one together using student data, or do an example with a bottle of a different mass. Give them a few minutes to complete their diagrams. An example diagram for a 500-g bottle at a 30-degree angle is shown.

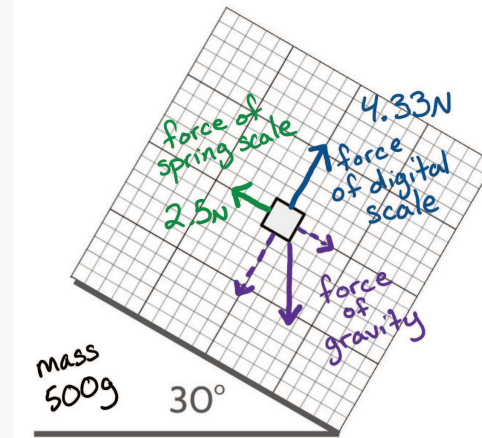
Present **slide Q**. Have students turn and talk about their free-body diagrams using the prompts:

- How do the forces of gravity at each angle compare?
- How do the components compare?

Ask a few pairs to share out. Listen for them to say that the force of gravity doesn't change from angle to angle, but the components change. Take a moment to discuss why this is. Be sure to note that how much the force of gravity pulls isn't changing, because the mass of the bottle doesn't change, but changing the angle changes which scale has to push more to balance out that component of gravity.

Calculate the force of gravity using its components. Remind students that when we drew force components, we could also use the Pythagorean theorem to combine these to determine the whole force. Present **slide R**. Ask them to complete the slide's tasks on the *Measuring Forces on Inclines Investigation* handout:

- Use the Pythagorean theorem to add the force components together to calculate the force of gravity that the two scales are balancing out.
- Compare these values to the force of gravity you measured/calculated at the beginning of the lab.



9 · MAKE SENSE OF DATA AND CONNECT TO PLATE MOTION

12 min

MATERIALS: *Measuring Forces on Inclines Investigation*

Make sense of how the angle changes the forces. Present **slide S**. Pose the questions:

- As the angle changes, what happens...
 - ...to the force of gravity acting on the bottle?
 - ...to the force on the bottle from the digital scale?
 - ...to the force on the bottle from the spring scale?

Listen for students to say that when the angle increases, the force of gravity stays the same, the digital scale force decreases, and the spring scale force increases.

Connect to mass. Present **slide T**. Ask students to turn and talk about the prompts:

- What would happen to the component of gravity pulling down the ramp if the mass were doubled?
- What if the mass were decreased to half?

Have a few pairs share out. Listen for them to say that doubling the mass would double the gravity, which would double both components of the force of gravity, and that halving mass would halve the components.

Present **slide U**. Take a moment to discuss how a plate could have more mass by being either thicker or more dense, using the first prompt:

- How could one plate have more mass than another?

Then, ask the second prompt:

- How can plates at convergent boundaries still slide down inclines when they are sliding into the mantle?

Guide students to make connections to the convection model from Lesson 6 through the density differences between the plates. Both plates are being pulled by gravity, but the bottom plate is denser and therefore is pulled down into the mantle.

Consider unbalanced forces. Say, *In the Measuring Forces on Inclines Investigation, the forces were always balanced, but we are trying to make sense of the plates and what they do when the forces are balanced and unbalanced.* Present **slide V**. Pose the questions on the slide:

- What happened to the foam plates squished between the spring scales in Lesson 2 when we removed one of the spring scales?
- What would this look like on an incline/with plates?

Listen for students to remember that when the spring scale was removed, the foam plates suddenly moved until they found a new resting position, and to propose that something similar would happen on an angle, likely with the bottle/plate starting to move down the incline.

 **Connect gravity to plate motion.** Present slide W. Reorient students to the *Measuring Forces on Inclines Investigation* handout and have them complete Section 4. Encourage them to use free-body diagrams, drawings, and words to map the connections made in this lesson's investigation to the stability and change of the plates. Collect the handout to review students' responses.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Look for student **models and explanations** to show (SEP: 2.3):

- The **force of gravity pulls plates** toward Earth's center/down, but a **component** of it also pulls things down inclines. (SEP: 2.3, 5.2; DCI: ESS2.A.2)
- **Component forces are mathematically related** to the force they make up according to the Pythagorean theorem. (SEP: 5.2)
- **Relationships between the systems** of the **plates, mantle, and gravity** can be balanced or unbalanced to keep plates stable or cause changes in **plate motion**. (SEP: 2.3; DCI: ESS2.A.2)
- **Plate motion and changes in motion** are too big and happen on timescales that cannot be directly observed, but **forces on plates** can be modeled at various scales. (CCC: 3.2; DCI: ESS2.A.2)

What to do: If students struggle with these connections to plate motion, take some time to review (as a class or in groups) the connections using the Plate Interactions Consensus Model poster updated at the end of this lesson, before moving on to the assessment in Lesson 13. Students will use the updated model poster in that assessment, so it is important to address confusion beforehand.

Building toward: 12.A.2 Use **mathematical models to illustrate** the force **interactions** (including **gravity**) **between a plate** and other systems to explain stability and change of **plate motion** that is **too large and too slow to observe directly**. (SEP: 2.3, 5.2; CCC: 3.2; DCI: ESS2.A.2)

10 • DEFINE FORCE PHENOMENA AT PLATE BOUNDARIES

7 min

MATERIALS: science notebook

Consider divergent and convergent plate boundaries. Present slide X. Pose the questions on the slide, referring students to the two images showing the development of a divergent boundary:

- How is an incline being formed at this divergent boundary?
- How is gravity acting on the plates at this boundary?

Listen for students to say things such as the magma pushing up causes a type of incline that thins the plate/crust, and gravity pulls the plates away from each other as the magma creates new crust.

Present slide Y. Repeat the process for convergent boundaries. Listen for students to say things such as gravity is pulling the plate under the other and into the mantle, and it would pull more as it becomes more slanted. They may also mention something about density of the plates and that the plate going into the mantle must be denser.

Add entries to Personal Glossary. Present slide Z. Say, *Scientists have terms for how the force of gravity pulls down on plates. At a subduction zone of convergent boundaries, they call it "slab pull". At a divergent plate boundary, they call it "ridge push".* Give students time to add definitions to their Personal Glossaries, which may include *slab pull* and *ridge push*.

ALTERNATE ACTIVITY

Extension opportunity: There is the opportunity to discuss how, within the *Friction Investigation* of Lesson 11, increasing the mass is really increasing the pressing forces between the surfaces, and decreasing this force (without changing mass) would decrease friction. This can be connected to the digital scale reading in this lesson's *Measuring Forces on Inclines Investigation*, and how increasing the mass increases the perpendicular component of the force of gravity. To extend this conversation, you could also discuss how increasing the incline made the perpendicular component of gravity read by the digital scale decrease, and how this means that friction would decrease as the angle increased.

11 · ADD TO THE PLATE INTERACTIONS CONSENSUS MODEL

11 min

MATERIALS: science notebook, Progress Tracker, Plate Interactions Consensus Model poster, chart paper markers

Revisit and revise the consensus plate model. Present **slide AA**. Be sure that the Plate Interactions Consensus Model poster is visible to everyone. Ask students to individually review the model for a couple of minutes, and consider what should be added from the friction and gravity investigations. Present **slide BB**. Say, *Let's bring our ideas together and add to or revise our consensus model*. Ask students to share and discuss their ideas for changes to the model, and update the poster.

Update the Progress Tracker. Present **slide CC**. Direct students to turn to their Progress Trackers and record what we figured out from investigating friction and gravity in Lessons 11 and 12. Give them the rest of the period to complete this update. Before they leave class, point out that we have learned a lot about the movement of plates. Suggest that next time, we can apply our ideas to explain a rift that occurred where the United States is located today!

Additional Lesson 12 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

Number and Quantity:

- **CCSS.MATH.CONTENT.HS.N-VM.1** Represent and model with vector quantities: Recognize vector quantities as having both magnitude and direction.
- **CCSS.MATH.CONTENT.HS.N-VM.3** Represent and model with vector quantities: Solve problems involving velocity and other quantities that can be represented by vectors.

Students review that forces are vector quantities and have both magnitude and direction. They also use the concept of vector components within the context of forces to solve for the force of gravity on an object from measured forces that balance with the components of gravity.

Geometry:

- **CCSS.MATH.CONTENT.HSG.SRT.C.8** Use trigonometric ratios and the Pythagorean Theorem to solve right triangles in applied problems.

Students use the Pythagorean theorem to identify the relationship between the components of gravitational force acting on an object on an incline. This builds on ideas developed at the end of grade 8, when they learned to apply the Pythagorean theorem to determine the unknown side lengths in right triangles in real-world and mathematical problems in two dimensions. Use mathematical and geometrical representations to support students' sensemaking of this relationship.

LESSON 13: How can we use our science ideas to explain what happened at the Midcontinent Rift?

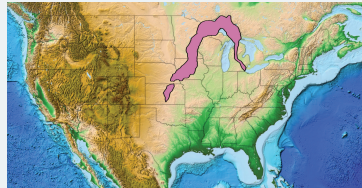
PREVIOUS LESSON

We modeled forces on the plates and investigated how gravity can be represented as components when objects are on an incline. We connected this to plate motion and updated our Plate Interactions Consensus Model poster and our Progress Trackers.

THIS LESSON

PUTTING PIECES TOGETHER

1 day



Data Source: ArcGIS

We revisit our Scale Chart poster and add processes from Lesson 12. We update connections on our Scale Chart poster and revisit our Driving Question Board. We reflect on our experiences in this unit and engage in a transfer task to explain why the Midcontinent Rift did not tear apart. We catalog our unanswered questions for future units.

NEXT LESSON

There is no next lesson.

BUILDING TOWARD NGSS

HS-PS1-8, HS-ESS1-5, HS-ESS2-1,
HS-ESS2-3



WHAT STUDENTS WILL DO

13.A Revise an explanation based on valid and reliable evidence to answer Driving Question Board questions that involve explaining the change over time in stability of the interactions between motions of the mantle and the plates. (SEP: 6.2; CCC: 7.1; DCI: ESS2.A.2, ESS2.B.2, ESS2.B.3)

WHAT STUDENTS WILL FIGURE OUT

- Many processes on the Scale Chart poster have effects on other processes at different scales.
- Processes that occurred at the Midcontinent Rift 1.1 billion years ago are similar to what is occurring at Afar today.
- Thermal convection and the interaction of forces with plates can be used to explain how the Midcontinent Rift failed.

Lesson 13 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	5 min		REVISIT THE SCALE CHART Revisit the Scale Chart poster. Add ridge push and slab pull. Take a final pass at identifying relationships between the components and mechanisms.	A	Scale Chart poster, 3x5 sticky notes, chart paper markers
2	10 min		REVISIT THE DRIVING QUESTION BOARD Return to the DQB to determine which questions we have answered. Reflect on experiences during the unit.	B-D	sticky dots (red), sticky dots (yellow), sticky dots (green), Driving Question Board, Takeaways poster, Scale Chart poster, chart paper markers
3	30 min		COMPLETE THE FINAL ASSESSMENT Complete an assessment comparing the processes that occurred at the Midcontinent Rift and the current processes in the Afar region, and predicting the future of Afar if it follows the same processes.	E	<i>Midcontinent Rift Transfer Task</i> , Scale Chart poster

End of day 1

Lesson 13 • Materials List

	per student	per group	per class
Lesson materials	• science notebook • sticky dots (red) • sticky dots (yellow) • sticky dots (green) • <i>Midcontinent Rift Transfer Task</i>		• Scale Chart poster • 3x5 sticky notes • chart paper markers • Driving Question Board • Takeaways poster

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 “Takeaways”.

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 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 *Midcontinent Rift Transfer Task* for each student. Review the *Failed Midcontinent Rift 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 13 • 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 (DCI)s:

- **ESS2.A.2: Earth Materials and 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)
- **ESS2.B.2: Plate Tectonics and Large-Scale System Interactions:** 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. (ESS2.B Grade 8 GBE) (HS-ESS2-1) (secondary to HS-ESS1-5)
- **ESS2.B.3: Plate Tectonics and Large-Scale System Interactions:** Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust. (HS-ESS2-1)

This lesson revisits the Scale Chart poster to identify that all components, mechanisms, and their interactions on the chart represent the Theory of Plate Tectonics.

This lesson also touches back on the questions posted on the Driving Question Board. Students can now answer questions based around the DCIs from prior lessons, using their understanding of Earth's internal processes and the interaction of forces, matter, and energy that cause the changes over time.

After a review of the Scale Chart poster and the Driving Question Board, students engage in a transfer task of modeling to explain why the Midcontinent Rift, which appears to have processes similar to what the Afar region is currently experiencing, did not result in a new ocean 1.1 billion years ago.

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

Within the assessment, students explain why the Midcontinent Rift did not create a new ocean 1.1 billion years ago. This process, however, is currently being debated by geologists. Some believe that a hotspot also existed under the rift, causing active rifting to occur as well, among other theories. This complex process is not included in this assessment, nor are theories unrelated to the outcomes of this unit. Students are to explain this rifting process and the failing of the rift based upon what they have learned in the unit. After the assessment, consider sharing the other possible reasons for this rifting process; emphasize that there is no definitive evidence for any of these, as this research is an ongoing geological endeavor.

Further, the theorized plate boundaries and other interactions that occurred around Amazonia and Laurentia are complex and uncertain. Because of this, the assessment explains the separation of Laurentia and Amazonia using a simplified model that removes other cratons believed to have been present on the same plate with Amazonia.

The assessment also does not use north, south, east, and west directions, instead using the terms “left” and “right” for the direction of movement. This is to make the assessment more accessible for students who may have trouble situating the continents with cardinal directions. In addition, Amazonia and Laurentia did not move cleanly in one direction or another. Referring to their movement as “left” and “right” can help students better explain changes in net force and how energy from the mantle is driving the tectonic processes.

Though the Midcontinent Rift is considered a fossil rift, it has many parallels to the processes occurring at Afar, and there is still uncertainty regarding its formation. Many online resources offer more information about the Midcontinent Rift. To learn more, consider visiting one of these sites:

- <https://www.youtube.com/watch?v=HO1FpJJGsgY>
- <https://eos.org/features/new-insights-into-north-americas-midcontinent-rift>
- <https://www.sciencedirect.com/science/article/pii/S0012825221002920>

LEARNING PLAN for LESSON 13

1 · REVISIT THE SCALE CHART

5 min

MATERIALS: Scale Chart poster, 3x5 sticky notes, chart paper markers

Reflect on the phenomena identified in Lesson 12. Project slide A. Bring students' attention to the Scale Chart poster, and ask them to reflect on their experiences in the prior lesson. Ask, *What processes did we identify last time that we can now add to our Scale Chart?* Guide students to recall that we identified slab pull and ridge push in the prior lesson. If they have difficulty remembering the last class period, direct them to look back at any of their artifacts from Lesson 12, including the updated consensus model.

Add these phenomena to the Scale Chart poster. Ask students to identify where ridge push and slab pull should go on the poster. They should say that these happen over a large time period and over a large space. The sticky notes for these processes should be placed somewhere between the deformation of plate material and new plate creation on the temporal axis, and to the right of the earthquakes (but not as far right as the mantle convection) on the spatial axis.

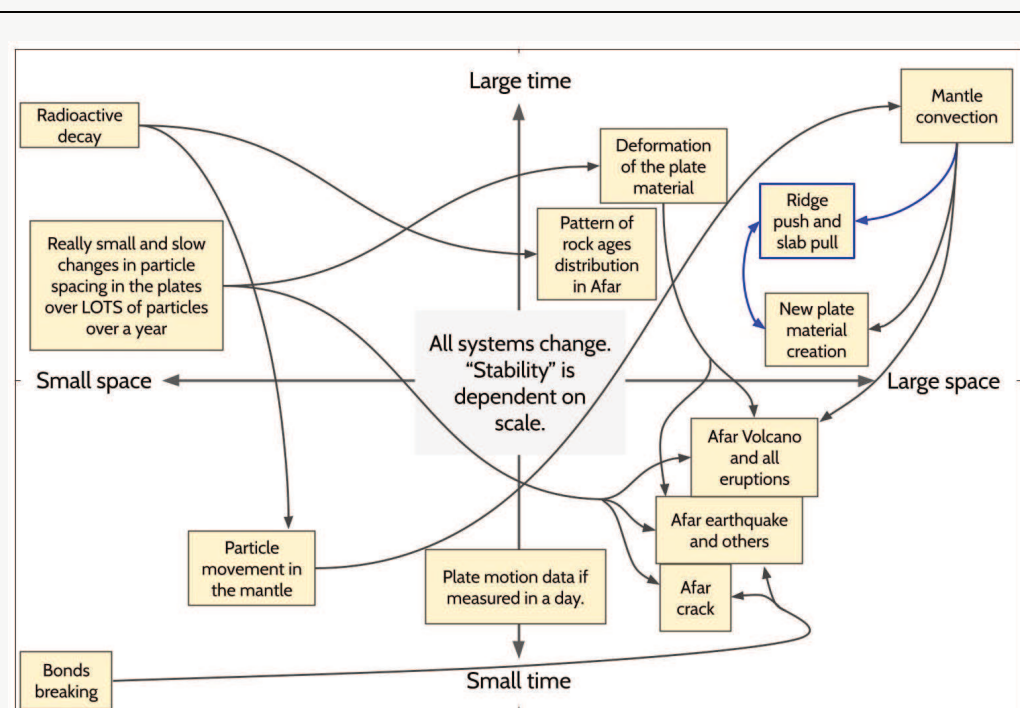
Connect these phenomena to other processes. Ask students to identify any connections between these processes and the others on the chart. They should say that mantle convection causes slab push and ridge pull, and that slab push and ridge pull (particularly ridge pull) create new plate material at the surface. This arrow should be double-headed, because this can create a feedback loop. See the image below for an example, with the new items outlined in blue.

Ridge push and slab pull were added to the chart. Depending on the class discussion, these could go anywhere by new plate material creation.

Connections were made between **mantle convection**, **new plate material creation**, and these two items.

Double arrows were added between **ridge push**, **slab pull**, and **new plate material creation**.

Additional arrows should be added at the class's discretion.



Make additional connections. Encourage students to continue looking at the chart and identify any other connections that they now see. Some may make further connections to ridge push, slab pull, earthquakes as well as cracks, and so forth. Ask students to explain the connections they are pointing out. Honor these connections, and draw arrows to show the relationships between these processes.

Ask, *What do you notice about the scales of these changes that were seemingly independent, but that we now see as connected?* Students should respond that many connections exist across the temporal and spatial scales, and changes at one scale have an effect on processes at other scales.

Consider the role of scale in processes. Point out that all of the connections on this chart really tell the story of plate tectonics on Earth. Summarize for the class that over the course of our lessons in this unit, we have explained the past and current movements of rocks at Earth's surface, and we now have a framework for understanding our geologic history by developing models and explanations and adding those mechanisms and interactions to our chart. Say that what we have explored is known as the Theory of Plate Tectonics. Use a marker to circle everything on the chart, and create a large label at the top saying "The Theory of Plate Tectonics".

2 · REVISIT THE DRIVING QUESTION BOARD

10 min

MATERIALS: science notebook, sticky dots (red), sticky dots (yellow), sticky dots (green), Driving Question Board, Takeaways poster, Scale Chart poster, chart paper markers

Frame the activity. Reorganize the class around the DQB. Present **slide B**. Say, *We've figured out so much! I bet we can answer many of our questions on the Driving Question Board.* *

Mark patterns in questions answered and unanswered. Facilitate identifying patterns in the DQB questions. Focus the discussion on identifying (1) questions we agree we can answer, (2) questions we have at least a partial answer to, and (3) questions we cannot answer at all. Explain that we will use a different color of sticky dots to mark each category. 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 categories 1 or 2 to answer individually in their science notebook, and then share their answer during the discussion.



Discuss the DQB questions we can answer. Present **slide C**. Gather the class in a Scientists Circle for a discussion of the questions we can now answer. Display the Takeaways 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.

As students share, put an emphasis on any questions that we have previously constructed an answer for but can now more fully explain. When this occurs, ask students to explain what evidence we collected has helped them revise the answer. Also ask them to identify the scale at which the process occurs, and whether that process has an effect on another part of the Earth system. When possible, make connections back to the sticky notes and arrows on the Scale Chart poster.

* ATTENDING TO EQUITY

Revisiting the Driving Question Board is important for helping students feel that their questions are valued and recognized. Though not all questions will have been addressed (it's more likely that 50–75 percent will be at least partially answered), this enables students to see the hard work they have done to answer many of their own questions.

ASSESSMENT OPPORTUNITY

What to look for/listen for:

- Look/listen for students to use multiple sources of evidence to explain a surface feature, or the motion of the mantle and the plates 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: ESS2.A.2, ESS2.B.3)
- Look/listen for students to use multiple sources of evidence to explain that changes that occur over a long time through the process of plate tectonics may appear stable over short time periods. (SEP: 6.2; CCC: 7.1; ESS2.B.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?*
- If students are uncertain as to the scale on which their answer occurs, have them map their question to the Scale Chart poster. Ask them to identify whether other connections made on the poster also apply to their answer, and whether any processes at a larger or smaller spatial or temporal scale would be affected or involved within their answer.

Building toward: 13.A Revise an explanation based on valid and reliable evidence to answer Driving Question Board questions that involve explaining the change over time in stability of the interactions between motions of the mantle and the plates. (SEP: 6.2; CCC: 7.1; DCI: ESS2.A.2, ESS2.B.2, ESS2.B.3)

Celebrate the class's accomplishments. Say, *I can't believe how far we've come since we first read about Afar in Lesson 1. We should be very proud of what we've accomplished.*

Have students reflect upon their experiences. Present slide D. Direct students to find a blank piece of paper 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?*

Ask each student to share out 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.

3 · COMPLETE THE FINAL ASSESSMENT

30 min

MATERIALS: *Midcontinent Rift Transfer Task*, science notebook, Scale Chart poster



Administer the assessment. Present slide E. Say, *In this unit, we've figured out not only why the crack in Afar happened, but also why other surface features happen elsewhere around the world. Did you know we have a rift system similar to Afar's in the middle of the United States? Scientists have said that this system, the Midcontinent Rift, began creating a new ocean like we see in the Afar region, but instead of opening into a new ocean, it failed. Let's see whether we can use our knowledge of Afar, along with more information about the Midcontinent Rift, to explain what might have happened.*

Distribute the *Midcontinent Rift Transfer Task* to each student. This task will take the remainder of the class period to complete. * Students should turn in their completed assessments for feedback.

* ATTENDING TO EQUITY

Universal Design for Learning: Consider allowing students to express their understandings of the Midcontinent Rift in various ways. Some students may benefit from orally responding to the prompts, or by using manipulatives such as the foam pieces to physically represent what they believe happened in North America 1.1 billion years ago. Online tools such as Flip can assist students in showing and explaining their ideas in more than just writing.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: See the accompanying 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, students who are linking ideas but not yet organizing them, and students who are organizing ideas and need an additional challenge.

This assessment is not building toward a lesson-level performance expectation. It is designed to assess a performance expectation (PE) from the NGSS, below.

Transfer Task HS-ESS2-1 Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features. (SEP: 2.3; CCC: 7.2; DCI: ESS2.A.1, ESS2.B.2)

As well as the SEP, CCC, and DCIs associated with this PE, this assessment addresses one additional CCC element and one additional DCI element:

- **5.4 Energy and Matter.** Energy drives the cycling of matter within and between systems.
- **ESS2.A.2 Earth Material and 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)

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 acceleration or gravity, 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 *Vehicle Collisions Unit*, students will explore the idea of Newton's second law in more depth, and in *Meteors Unit* and *Cosmology Unit*, they will learn more about the history of Earth and the universe. This will allow some resolution on these unanswered questions in the future.

Additional Lesson 13 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH

This is the CCMS-related idea that is used to support sensemaking in this lesson:

Number and Quantity

- **CCSS.MATH.CONTENT.HS.N-VM.1** Represent and Model with Vector Quantities: Recognize vector quantities as having both magnitude and direction.

In the assessment, students use vectors to describe the magnitude and direction of multiple forces acting on Laurentia and Amazonia before and after their separation.



Unit P.2 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	<i>Initial Afar Models</i> Driving Question Board	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 on day 2 of Lesson 1 is a good opportunity to pre-assess student understanding of the relationships between Earth systems to explain what causes land to crack, break, and move. 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 they 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 students practice turning these questions into open-ended questions when they relate to the investigations underway.
Lesson 2	<i>Investigations A&B</i> <i>Free-Body Placemat</i> <i>Key</i> <i>Investigations A&B Key</i>	Formative In Lesson 2, students carry out an investigation to explore the relationship between the magnitude of the forces acting on a system and the observed stability and change in motion. They use these results to develop a free-body diagram to predict the changes in an object's motion due to the forces acting on it. They use this model to evaluate whether the plate motion data presented in <i>GPS Plate Map</i> helps explain the apparent stability of the Caribbean plate.
Lesson 3	<i>Analyzing Rock Behavior</i> <i>Analyzing Rock Behavior Key</i> <i>Explaining Behavior</i> <i>KEY</i>	Formative In Lesson 3, students are asked to read about how scientists measure the forces acting on rocks, and respond to some questions. They then work collaboratively to explore the relationship between the magnitude of external forces acting on an object, its deformation, and the energy transferred into it. A key is provided to support the scoring of both tasks.

When	Assessment and Scoring Guidance	Purpose of Assessment
Lesson 4	<i>Evaluating Models</i> <i>Evaluating Models Key</i> <i>Particle Investigations</i> <i>Particle Investigations Key</i> L4 Electronic Exit Ticket <i>Electronic Exit Ticket Key</i>	Formative In Lesson 4, students complete a handout in which they evaluate the merits and limitations of two physical models to help explain matter, energy, and force interactions at the particle level. They also use a computer simulation to further investigate these interactions. A key is provided to support the scoring of this task. Summative This Electronic Exit Ticket addresses 3-D elements associated with the lesson-level performance expectations (LLPEs) for Lesson 4, which is a problematize/putting-the-pieces-together routine for the first lesson set of the unit. This assessment is designed to make it easy for you to gather information about where students are still struggling to put the pieces together.
Lesson 5	<i>How Do Scientists Explore Earth's Interior?</i>	Formative In Lesson 5, students read about S and P waves, and compare their calculated S and P wave arrival times at stations with the times from the graph in the reading. They then compare the patterns with what they have learned about wave speeds and how these are affected by the media through which they pass.
Lesson 6	<i>Afar Mantle Model</i>	Formative In Lesson 6, students create an initial model of the mantle under Afar. They then investigate a mantle tank model and create an explanatory model of the mantle tank, using a matter, energy, and/or forces perspective. They compare the model of the mantle tank to the mantle under Afar and use the mantle tank to test and revise their initial models of the mantle under Afar.
Lesson 7	<i>Radioactive Decay (Forces)</i> <i>Radioactive Decay (Matter) and</i> <i>Radioactive Decay (Energy)</i> <i>Cause-Effect Model Key</i> L7 Electronic Exit Ticket <i>L7 Electronic Exit Ticket Key</i>	Formative In Lesson 7, students put the pieces together to create a cause-effect model of how particle-scale interactions in Earth's mantle manifest as global-scale phenomena. A key is provided to support the scoring of this task. Summative This Electronic Exit Ticket addresses 3-D elements associated with the lesson-level performance expectations (LLPEs) for Lesson 7, which is a problematize/putting-the-pieces-together routine for the first lesson set of the unit. This assessment is designed to make it easy for you to gather information about where students are still struggling to put the pieces together.

When	Assessment and Scoring Guidance	Purpose of Assessment
Lesson 10	<i>Investigating Plate Interactions</i> <i>Investigating Plate Interactions Key</i> <i>Predicting the Future of Africa and Afar</i> <i>Predicting the Future of Africa and Afar Key</i>	Formative In Lesson 10, students investigate plate interactions. They also get a chance to apply what they have learned to predict the future of the land that makes up the African continent, and the Afar region in particular. A key is provided to support the scoring of this task.
Lesson 12	<i>Measuring Forces on Inclines Investigation</i>	Formative In Lesson 12, students create free-body diagrams to make sense of how the forces change with the angle, connect that to mass, and consider what would happen if the forces become unbalanced. Students apply this idea to the context of divergent and convergent plate boundaries.
Lesson 13	<i>Midcontinent Rift Transfer Task</i> <i>Failed Midcontinent Rift Key</i>	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, in which they will explain how the Midcontinent Rift failed to create a new ocean 1.1 billion years ago. This task is robust and will take approximately 30 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 notebooks as a resource for completing all assessments.
Embedded in each lesson	Lesson-by-Lesson Assessment Opportunities (below)	Formative Assessment Use this document to see which parts of lessons or can be used as embedded formative assessments.
Occurs in several lessons	<i>Progress Tracker</i> <i>Progress Tracker Examples</i>	Formative and Self-Assessment Progress Trackers are thinking tools designed to help students (1) keep track of important discoveries that the class makes while investigating phenomena and (2) figure out how to prioritize and use those discoveries to develop a model to explain phenomena. It is important that what students write in their Progress Trackers reflects their own thinking at that particular moment. In this way, the tracker can be used throughout the unit to formatively assess individual student progress or for students to assess their own understanding. Because a tracker is meant to be a thinking tool, we strongly suggest that it not be collected for a summative “grade” other than to note its completion. In this unit, students add to their <i>Progress Tracker</i> in Lessons 2, 5, 6, 9, and 12. Examples of models and ideas that students may include in this tracker are embedded in these lessons, and an example of potential responses can also be found in <i>Progress Tracker Examples</i> .

When	Assessment and Scoring Guidance	Purpose of Assessment
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 <i>OpenSciEd Teacher Handbook: High School Science</i>.
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 <i>OpenSciEd Teacher Handbook: High School Science</i>.

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
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Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 1	1.A Develop a diagrammatic model of relationships between Earth systems to explain what causes land to crack, break, and move, and to predict what will happen to the land in the Afar region in the future. (SEP: 2.3; CCC: 2.2; DCI: ESS2.B) 1.B Ask questions about the mechanisms driving changes in Earth's crust that arise from careful observation of patterns in the Afar region, in order to seek additional information from indirect evidence because aspects of the phenomenon are too slow and too large to study directly. (SEP: 1.1; CCC: 3.2, 3.3; DCI: ESS2.B)	1.A When to check for understanding: On day 2, when students develop initial models for change before, during, and after the events in Afar. What to look for/listen for in the moment: • Indication of movement, force, and/or energy transfer (e.g., arrows) between components of the model. (SEP: 2.3) • Modeling changes in the shape or composition of the matter that makes up material at and/or below the surface, related to the changes at the surface. (SEP: 2.3) • Discussion of different timescales and/or gradual versus sudden change, either in models or in written responses. (DCI: ESS2.B) • A cause-and-effect relationship between something happening inside Earth and something happening at the surface. (CCC: 2.2) 1.B When to check for understanding: On day 3, during the development of the Driving Question Board (DQB). What to look for/listen for in the moment: • Questions that arise from our work together about things that are too large, too slow, or too inaccessible to observe directly (e.g., properties and motion deep inside Earth). (SEP: 1.1; CCC: 3.2, 3.3) • Questions that arise from our work together at a variety of timescales (e.g., short-term effects versus long-term geologic change). (SEP: 1.1; CCC: 3.2, 3.3) • Questions that arise from our work together that connect observations of the Afar region to larger-scale tectonic phenomena. (SEP: 1.1; DCI: ESS2.B)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 2	2.A Plan and conduct an investigation to determine the contact force interactions that result in the observed stability and change in the motion of an object. (SEP: 3.2; CCC: 4.2, 7.1; DCI: ESS2.A.1) 2.B Develop and use free-body diagrams (models) to explain and predict how the magnitude of the force interactions applied to matter at different scales would impact the stability and changes within a system. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1)	2.A.1 When to check for understanding: On day 1, while displaying slides P and Q, as students discuss calibration protocols and then carry out their investigation and record their results on the <i>Investigations A&B</i> handout. What to look for/listen for in the moment: - A record of the direction and magnitude of force interactions from four spring scales labeled in newtons. (SEP: 3.2; DCI: ESS2.A.1) - A description of how the group decided they had carried out enough tests to determine what keeps the system stable in every condition. (SEP: 3.2; CCC: 7.1) 2.A.2 When to check for understanding: On day 3, with slides AA and BB, as students record the changes that result from removing or adding a force, and the new stable state of the system, on the <i>Investigations A&B</i> handout. What to look for/listen for in the moment: - Recording data using a free-body diagram for each condition, including the initial force conditions acting on the stable system, and labeling which force interaction was added or removed. (SEP: 3.2; CCC: 4.2; DCI: ESS2.A.1) - Recording the dynamic changes in the system (e.g., how much the object moved, in what direction, and for how long). (SEP: 3.2, CCC: 4.2; DCI: ESS2.A.1) - Repeated trials or measurements yielding consistent results for several contact force combinations to support the reliability of the results. (SEP: 3.2; DCI: ESS2.A.1) - Following the calibration protocols for gathering accurate results using the spring scales. (SEP: 3.2) - Recording the new stable state of the system (where the foam rectangle is in the end and/or the new interactions on each spring scale) for each measurement. (SEP: 3.2, CCC: 7.1; DCI: ESS2.A.1) 2.B.1 When to check for understanding: On day 2, with slide U, as students draw their first free-body diagram at the bottom of the <i>Investigations A&B</i> handout. What to look for/listen for in the moment: - Two arrows pointed in one direction and one arrow pointed in the other, each with the magnitude labeled in newtons. (SEP: 2.6; DCI: ESS2.A.1) - Negative values for any vector(s) pointed to the left and positive values for any vector(s) pointed to the right. (CCC: 7.1) - Each arrow length proportionally scaled to its magnitude. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1) 2.B.2 When to check for understanding: On day 3, with slide AA, as students record a free-body diagram for each condition they test on the graph paper on the back of <i>Investigations A&B</i>. What to look for/listen for in the moment: - Using the results collected as free-body diagrams to explain how force interactions applied to matter would impact stability and changes within a system. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1) - Using the free-body diagrams to suggest that this model does not help to explain the apparent stability of the Caribbean plate. (SEP: 2.6; CCC: 7.1; DCI: ESS2.A.1)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 3	3.A Make qualitative claims about how differences in the magnitude of forces (1) acting on different materials (cause) would produce similar effects in their structure (elastic deformation) and (2) acting on a single material would affect the amount of energy transferred into and out of it. (SEP: 6.1; CCC: 2.2, 5.2, 6.2; DCI: PS3.B.2) 3.B Ask questions arising from development of the M-E-F model to clarify (1) additional relationships related to energy transfer and storage in deformed matter and (2) the model's application to various dynamics and interactions occurring in Earth systems. (SEP: 1.2; CCC: 5.2, 7.1; DCI: PS3.B.2, ESS2.A.1)	3.A When to check for understanding: When students complete Questions 1-3 on the <i>Analyzing Rock Behavior</i> handout (slide J). What to look for/listen for in the moment: See the <i>Analyzing Rock Behavior Key</i>. (SEP: 6.1; CCC: 2.2, 5.2, 6.2; DCI: PS3.B.2) 3.B.1 When to check for understanding: When students complete Question 4 on the <i>Analyzing Rock Behavior</i> handout (slide J). What to look for/listen for in the moment: See the <i>Analyzing Rock Behavior Key</i>. (SEP: 1.2; CCC: 5.2, 7.1; DCI: PS3.B.2, ESS2.A.1) 3.B.2 When to check for understanding: When students add new questions to their sticky note(s) for the exit ticket/home learning (slide L). What to look for/listen for in the moment: Questions that clarify differences in the relationship between changes in matter, forces acting on the system, and energy transfer occurring along plate boundaries and in other plate locations. (SEP: 1.2; CCC: 5.2, 7.1; DCI: PS3.B.2, ESS2.A.1)
Lesson 4	4.A Evaluate the merits and limitations of different models using a crosscutting lens (stability and change, thinking across scales, and/or cause and effect) for understanding and explaining different phenomena (earthquakes) and mechanisms (elastic deformation, cracking/breaking). (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2) 4.B Use a computational model to explore stability and change and cause-and-effect relationships between the magnitude of external forces acting on a solid, the changes in matter given its mass (number of particles), and the changes in energy in the system across different scales. (SEP: 2.3; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS3.B.2, PS2.B.3, ESS2.B.2)	4.A. When to check for understanding: Toward the end of day 1, when you collect the <i>Evaluating Models</i> handout. What to look for/listen for: - Use evidence generated by the model to discuss the mechanism(s) the model helps explain in terms of matter changes and/or M-E-F interactions. (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2) - Use a crosscutting lens (stability and change, thinking across scales, and/or cause and effect) to discuss the advantages and limitations of the model to further explain or test plate changes, breaking, and elastic deformation. (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2) See the <i>Evaluating Models Key</i> for sample responses. 4.B.1 When to check for understanding: - On day 2, after the simulation investigation, in student responses on the <i>Particle Investigations</i> handout. What to look for/listen for: - See the <i>Particle Investigations Key</i>. It includes a brief explanation of the goal of each investigation (1-4) and what to look for in student responses. 4.B.2 When to check for understanding: - At the end of day 3, with slide BB, when students complete the Electronic Exit Ticket. What to look for/listen for: This Electronic Exit Ticket addresses 3D elements associated with a lesson-level performance expectation (LLPE) for Lesson 4. This assessment is designed to make it easy to gather information about where students are still struggling to put the pieces together.
Lesson 5	5.A Analyze mathematical representations of indirect data to reveal	5.A.1 When to check for understanding: On day 1, on the <i>How Do Scientists Explore Earth's Interior?</i> handout and as a class, when students consider connections across disciplines by discussing other systems they have learned about

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
	anomalies in the pattern of arrival times for seismic waves is apparent about the relationship between wave speed and the medium through which the wave is passing in Earth's interior. (SEP: 4.1, 5.2; CCC: 1.4, 3.2; DCI: PS4.A.1, ESS2.A.2) 5.B Analyze seismic velocity anomaly data at multiple scales and evaluate the impact of this data on our working model of Earth's interior to provide evidence for a causal link between local matter variation in Earth's mantle and surface features, such as mountains, volcanoes, and cracks. (SEP: 4.1, 4.5; CCC: 1.1, 1.2; DCI: ESS2.A.2, PS4.A.4)	that cannot be studied directly because they are too small, too large, too fast, or too slow. What to look for/listen for in the moment: - Students should list examples of systems at various scales, such as the solar system, the electrical grid, tectonic motion, or an atom. - Students should recognize and explain that scale affects our ability to collect empirical evidence. If something is too large, too small, or on too long a timescale, it is very difficult to observe directly. (CCC: 3.2) 5.A.2 When to check for understanding: When students work through <i>How Do Scientists Explore Earth's Interior?</i> in pairs and as a class, analyzing empirical data to reveal an anomaly in the pattern of seismic wave arrival times when the chord the waves follow through the globe is approximately 10,000 km or more. What to look for/listen for in the moment: - Students should recognize that the data points representing observed arrival times depart significantly from the expected times, with arrivals later than expected for P-waves and none at all for S-waves. (SEP: 4.1; CCC: 1.4) - Through discussion, students should make a connection between this pattern and the reading, which explains that wave speed is affected by the media through which the wave passes. (DCI: PS4.A.1) - Students should make and defend the claim that in Part 2 of the image on slide K, the pattern of speed anomalies indicates that the seismic waves have encountered matter that is not a solid. S-waves do not travel through liquid, which is why they disappear. P-waves slow down in a liquid, which is why they arrive later than expected. (SEP: 5.2; CCC: 1.4) 5.A.3 When to check for understanding: On day 1, in the exit ticket, when students use the working model of Earth's interior to make a claim about which layers cause P-waves to slow down and S-waves to disappear, supporting their claim with evidence from mathematical representations. What to look for/listen for in the moment: - Students should make the claim that the liquid outer core causes P-waves to slow down and S-waves to disappear. (DCI: ESS2.A.2) - Students may use the speed provided on the slide (9 km/s) to test at least one anomalous data point from the graph in the <i>How Do Scientists Explore Earth's Interior?</i> handout. For example, to test the dot at about 12,200 km, they should divide this number by the given speed to get 1,356 seconds, then divide by 60 to get 22.6 minutes. They can also divide the x-value (12,200 km) by the y-value (22 minutes = 1,320 seconds) to get 9.2 km/sec. They then compare that number to either the y-value of the tested point on the graph or the speed on the slide, and find that it is roughly equal; it should be a little off, because the waves are not passing exclusively through liquid iron. Students should use this test to support their claim that the liquid core causes the slow-down pattern in the P-wave data. (SEP: 4.1, 5.2; DCI: PS4.A.1) - Alternatively, students may choose to support their explanation without doing the calculations but still applying mathematical reasoning. For example, they may argue that because 9 km/s is slower than 11 km/s, it makes sense that the P-waves arrive later than expected. They may also point out that these data points move in an odd pattern, going up and then back down. This implies that at some point, the waves are no longer moving through as much liquid iron and may be moving through a more solid inner core, reducing the lag. (SEP: 4.1, 5.2; DCI: PS4.A.1) 5.A.4 When to check for understanding: At the end of day 1, during navigation into day 2, when students respond to a reflection question on how indirect empirical evidence and mathematical representations helped them identify patterns and anomalies in seismic velocities to support their reasoning.

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
		What to look for/listen for in the moment: Use this as a quick check-in to make explicit that by organizing the data as a graph, we could see patterns that might not have been clear, and by applying mathematical reasoning, we could quantify how anomalous certain patterns were and highlight patterns that helped us figure out what might be going on deep inside our planet. (CCC: 1.4) 5.B.1 When to check for understanding: On day 3, after the Building Understandings Discussion, when students add to their models. Collect the <i>Earth's Interior Model</i> handout to provide feedback before the next class. What to look for/listen for in the moment: - Look for students to add images or words to their models to indicate that the mantle layer is not all the same; rather, it varies on a relatively local scale. (SEP: 4.5; CCC: 1.2; DCI: ESS2.A.2, PS4.A.4) - Students may include information about temperature or seismic wave velocities. They may add surface features corresponding to heterogeneity in the mantle below (e.g., volcanoes above a warmer mantle location). They may also show that these differences create different unbalanced forces in different locations, which is why some regions have different kinds of surface features than others. (DCI: ESS2.A.2, PS4.A.4) 5.B.2 When to check for understanding: On day 3, when students return to the Driving Question Board and fill out their Progress Trackers. What to look for/listen for in the moment: - Listen for students to start answering questions about specific surface features (such as volcanoes) and events (such as earthquakes) by describing seismic anomalies in the mantle at a regional scale that were added to our working model of Earth's interior. (SEP: 4.5; CCC: 1.1; DCI: ESS2.A.2, PS4.A.4) - Look for students to describe in their Progress Trackers how scaling down from a global to a regional grain size allowed us to see patterns of differences in mantle matter that were important for understanding surface features. (CCC: 1.2) - Students still have a significant gap in the causal chain connecting surface features to mantle matter, because they have not yet connected temperature variation to convection, and thus to plate movement. This will be developed over the next several lessons. Do not look for students to be able to make that connection here.

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 6	6.A Develop a model to explain the relationship between energy transfer and the motion of matter in a solid material via thermal convection and the motion of particles. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)	6.A.1 When to check for understanding: At the beginning of day 1, when students complete their individual models on the <i>Afar Mantle Model</i> handout, predicting the interactions of the different temperature parcels in the mantle. What to look for/listen for in the moment: - Look for all models to predict the relationship between the particle nature of parcels of different temperatures and their movement in the mantle. (SEP: 2.3; DCI: PS3.A.4) - Models should include particle-level interactions at various locations in the mantle system. (DCI: PS3.A.4) - Models should include changes in the mantle's matter related to the energy transferred into and out of the mantle parcels. (CCC: 5.4) 6.A.2 When to check for understanding: At the end of day 1, when students complete their models on the <i>Mantle Tank Model</i> handout, explaining the movement of matter in the mantle tank. What to look for/listen for in the moment: - Look for all models to reference the observed motion of matter and the temperature readings in the mantle tank video as evidence about energy transfer and matter changes. (SEP: 2.3) - Models using the matter perspective should include particle-level interactions at various locations in the mantle tank system. (DCI: PS3.A.4) - Models using the energy perspective should include changes in the matter related to the energy transferred into and out of the mantle tank system. (CCC: 5.4) - Models using the forces perspective should include the forces acting on matter at various locations in the mantle tank system that could explain the convective motion of matter or energy transfer in the model. (DCI: ESS2.A.2; CCC: 5.4) 6.A.3 When to check for understanding: On day 2, when students revise their models on the <i>Afar Mantle Model</i> handout. What to look for/listen for in the moment: - Look for revised models to include density differences in the particle-level modeling of the matter based on thermal energy tomography data and evidence from the mantle tank and lava lamps. (SEP: 2.3; DCI: ESS2.A.2, PS3.A.4) - Models should include energy being transferred into and out of the system to heat/cool the matter in the mantle, causing motion in the mantle. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2) - Models should reference balanced and unbalanced forces to explain the convective motion of matter in the mantle due to density differences. (SEP: 2.3; DCI: ESS2.A.2, PS3.A.4)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 7	7.A Construct a cause-effect explanation for how radioactive decay provides the heat that drives mantle convection, using ideas from our previous investigations, new evidence from a set of complementary readings, and the assumption that our past observations about matter, forces, and energy hold true across contexts. (SEP: 6.2; CCC: 2.2; DCI: ESS2.B.1, PS2.B.2, PS1.C.1, PS3.A.2) 7.B Ask questions that arise from examining models for explaining how radioactive decay at the subatomic scale can cause thermal energy transfer at the macroscopic scale to clarify and seek additional information regarding the relationships between matter, energy, and forces. (SEP: 1.2; CCC: 3.3; DCI: PS1.C.1, PS2.B.2, PS3.A.2, PS3.A.4)	7.A.1 When to check for understanding: At the end of day 1, when you read students' responses to the cause-effect questions in their handouts (<i>Radioactive Decay (Forces)</i>, material:PF.L7.HO2], or <i>Radioactive Decay (Energy)</i>). What to look for/listen for in the moment: - Students distill ideas from the readings to explain that radioactive decay provides the heat that drives mantle convection. (SEP: 6.2) - Students link cause at the particle scale to effect at the macroscopic scale using mechanistic reasoning. (CCC: 2.2) - Students accurately describe radioactive decay according to the subject of the article they read (forces, energy, or matter). See the accompanying <i>Cause-Effect Model Key</i> for examples at various levels of proficiency. (DCI: ESS2.B.1, PS1.C.1, PS2.B.2, PS3.A.2) 7.A.2 When to check for understanding: On day 2, as you listen to students' ideas during the Building Understandings Discussion. What to look for/listen for in the moment: - Listen for the key ideas listed in the Key Ideas callout, all of which rely on evidence from a variety of sources (our previous investigations, new evidence from the readings, and the assumption that our past observations about the relationships between matter, forces, and energy hold true across contexts. (SEP: 6.2; DCI: ESS2.B.1, PS1.C.1, PS2.B.2, PS3.A.2) - Use the <i>Cause-Effect Model Key</i> (cause-effect chain) as an example of what a class consensus model explaining mantle convection at multiple scales might look like. (SEP: 6.2; CCC: 2.2) - Listen for students to explicitly identify how matter, energy, and forces interact as part of the class consensus model. (DCI: ESS2.B.1, PS1.C.1) 7.B When to check for understanding: At the end of day 1, when you collect the exit tickets. Remember to have these ready to return for students' use at the start of day 2. What to look for/listen for in the moment: Accept all ideas, but across the class, look for the following: - Students apply what they know about matter, energy, and forces in articulating their questions. For example, a student who reads about forces might ask, "What energy transfers when the forces are imbalanced?" A student who reads about energy might ask, "What changes can you detect in the matter when energy is released from atomic nuclei?" A student who reads about matter might ask, "What unbalanced forces cause the motion of the particles?" (DCI: PS1.C.1, PS2.B.2, PS3.A.2, PS3.A.4) - Students ask questions to clarify an understanding or seek additional information about nuclear processes to explain macroscopic thermal energy. Look for sentence stems like "How does ____ cause ____?" or "Why does ____ happen when ____?" (SEP: 1.2; CCC: 3.3) Electronic Exit Ticket: The Electronic Exit Ticket addresses the lesson-level performance expectation (LLPE) for Lesson 7. This assessment is designed to make it easy to gather information about where students are still struggling to put the pieces together.

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 8	8.A Sketch and describe graphs for percent of parent and daughter elements versus time; use a spreadsheet to graph and compare patterns across different crystal sizes and different parent elements and compare these to patterns predicted by an exponential decay law. (SEP: 5.2; CCC: 1.4; DCI: PS1.C.2) 8.B Analyze data using a spreadsheet and an exponential decay law to find the age of various rock samples using relationships (half-lives) discovered in prior investigations; interpret the patterns across the ages of these samples and the sites where these are located to reconstruct the geologic history of Afar over the last 700 million years. (SEP: 4.1; CCC: 1.5; DCI: PS1.C.2)	8.A.1 When to check for understanding: At the end of day 1, when you collect student predictions on the <i>Predicting Composition Trends</i> handout. What to look for/listen for in the moment: - A graph that shows a trend (linear or nonlinear) with a solid line of decreasing y-values as x-values increase for the percentage of parent element found in a crystal over time, and a dotted line of increasing y-values as x-values increase for the percentage of daughter element found in a crystal. (SEP: 5.2; CCC: 1.4; DCI: PS1.C.2) 8.A.2 When to check for understanding: At the end of day 2, when you collect student analysis on the <i>Analyzing Decay Trends</i> handout. What to look for/listen for in the moment: A summary of the following: - The patterns in the trends of the data and how they compare to the predictions. - That the estimated time for at least one parent element to reach 25% is approximately twice the time it took to reach 50%. (SEP: 5.2; CCC: 1.4) - How quickly or slowly various radioactive elements change into daughter elements. (SEP: 5.2; CCC: 1.4; DCI: PS1.C.2) 8.B.1 When to check for understanding: At the end of day 2, when students individually calculate and record the age of rocks in Afar on the <i>Analyzing Decay Trends</i> handout. What to look for/listen for in the moment: - Using the mathematical model of radioactive decay to calculate the age of the assigned group of rock samples. (SEP: 4.1; DCI: PS1.C.2) - A is 0.12–0.33 mya, B is 0.49–4.0 mya, C is 1.9–3.2 mya, D is 4.5–8.2 mya, E is 23–25 mya, F is 29–31 mya, G is 583–659 mya. 8.B.2 When to check for understanding: At the end of day 3, when students use evidence they recorded on the <i>Transcript: Plate Interaction and Earthquake Demonstration</i> handout to identify patterns in the age distribution of rocks in Afar. What to look for/listen for in the moment: - Using evidence from the group data recorded on the <i>Age of Rocks</i> handout and the map in the <i>Rock Sample Site Map</i> to interpret the geologic history of Afar. (SEP: 4.1; CCC: 1.5; DCI: PS1.C.2)
Lesson 9	9.A Ask questions that arise from careful observations of patterns across multiple empirical sources to refine our model of how new oceanic crust is formed at plate boundaries. (SEP: 1.1, 1.2; CCC: 1.5; DCI: ESS1.C.1)	9.A When to check for understanding: At the end of day 2, when students add their questions to the Driving Question Board. What to look for/listen for in the moment: - Assess whether students are asking questions intended to refine our model by looking for alignment with the question marks on the Initial Class Consensus Model: New Crust poster. (SEP: 1.1, 1.2) - Assess student understanding of the DCI by looking for questions about plate boundaries, oceanic versus continental crust, and the ages of rocks in the Afar region and elsewhere that require empirical evidence to answer. (CCC: 1.5; DCI: ESS1.C.1)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 10	10.A Use a computer model that simulates the movement of tectonic plates to produce data to serve as the basis for evidence that can support an explanation of how plate interactions at plate boundaries shape the planet's surface features. (SEP: 2.6; CCC: 4.3; DCI: ESS2.B.3) 10.B Construct an explanation about the patterns in radiometric data using a consensus model of plate interactions at convergent and divergent boundaries. (SEP: 6.2; CCC: 1.5; DCI: ESS2.B.1, ESS2.B.3) 10.C Construct and revise an explanation about the future of Afar and Africa based on valid and reliable evidence obtained from a variety of sources and the assumption that plate tectonics is the unifying theory that explains the past and current movements of the rocks at Earth's surface. (SEP: 6.2; CCC: 4.4; DCI: ESS2.B.2, ESS2.B.3)	10.A When to check for understanding: On day 1, when students complete the <i>Investigating Plate Interactions</i> handout. What to look for/listen for: Using the <i>Investigating Plate Interactions Key</i>, look for students to: • Rows 2 and 3: Use a model to generate data to serve as the basis for evidence that can support an explanation. In row 3 specifically, look for a description of plates' vertical and horizontal motion. This evidence will be central to the investigation in Lesson 11. (SEP: 2.6) • Row 4: Use ideas about density to explain how plate interactions at plate boundaries shape the planet's surface features. (DCI: ESS2.B.3) • Row 5: Use the simulation to describe the interactions between these components of the system's matter: moving plates, mantle material, magma, and surface features. (CCC: 4.3) 10.B When to check for understanding: On day 2, when students develop an explanation about the patterns in the radiometric data explored in Lesson 9. What to look for/listen for: Look for students to: • Explicitly use the consensus model of plate interactions to explain the patterns in radiometric data. (SEP: 6.2; CCC: 1.5; DCI: ESS2.B.1, ESS2.B.3) • Include the flow of magma through the system as a mechanism that influences the movement of rocks and explains the patterns in the ages of crustal rocks. (CCC: 1.5; DCI: ESS2.B.1, ESS2.B.3) • Include divergent and convergent plate boundary interactions to explain the differences in composition of the crust. (SEP: 6.2; DCI: ESS2.B.1, ESS2.B.3) 10.C When to check for understanding: At the end of day 2, when students complete the handout <i>Predicting the Future of Africa and Afar</i>. What to look for/listen for: Use the <i>Predicting the Future of Africa and Afar Key</i> to assess students' engagement with each of the three dimensions: • Question 1: Make a prediction about the future of Afar and Africa focused on surface features changes. (CCC: 4.4) • Question 2: Use multiple sources of evidence and the consensus model to construct and revise an explanation of how the plate interactions occurring under Africa will cause the predicted surface changes. (SEP: 6.2; CCC: 4.4; DCI: ESS2.B.2, ESS2.B.3)

Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 11	11.A Develop and revise models that predict the relationship between mass, surface area, or texture and the force of friction acting on Earth's plates due to mantle convection, which is a process that is too large and too slow to observe directly. (SEP: 2.3; CCC: 3.2; DCI: ESS2.A.2)	11.A.1 When to check for understanding: On day 1, when students create initial predictive models in small groups. What to look for/listen for in the moment: Models should include: - Interactions between the plates and other systems, such as the mantle (via friction) or Earth (via gravity). (SEP: 2.3; DCI: ESS2.A.2) - Mantle movement affecting the plates through system interactions. (SEP: 2.3; DCI: ESS2.A.2) - Earth-sized systems of plates and the mantle interacting and representing change that occurs over large timescales. (CCC: 3.2; DCI: ESS2.A.2) 11.A.2 When to check for understanding: On day 2, when students revise their initial predictive models into explanatory models. What to look for/listen for in the moment: Models should include: - Interactions between the plates and other systems, including the mantle (via friction) or other plates, influencing the motion of the plates. (SEP: 2.3; DCI: ESS2.A.2) - Mantle movement affecting the plates through friction force interactions between systems. (SEP: 2.3; DCI: ESS2.A.2) - Earth-sized systems of plates and the mantle interacting and representing change that occurs over large timescales. (CCC: 3.2; DCI: ESS2.A.2) - The relationship between mass (more mass, more friction), surface area (no relationship), or texture (rougher texture, more friction) and the force of friction between the plates and the moving mantle. (SEP: 2.3; DCI: ESS2.A.2)
Lesson 12	12.A Use mathematical models to illustrate the force interactions (including gravity) between a plate and other systems to explain stability and change of plate motion that is too large and too slow to observe directly. (SEP: 2.3, 5.2; CCC: 3.2; DCI: ESS2.A.2)	12.A.1 When to check for understanding: On day 1, when students draw free-body diagrams for gravity acting on plates. What to look for/listen for in the moment: Students to talk about: - Use their free-body diagram models to support their claims or explanations about plates. (SEP: 2.3, 5.2; DCI: ESS2.A.2) - The force of gravity pulling on plate systems and affecting plate motion. (SEP: 2.3; DCI: ESS2.A.2) - That we cannot directly measure the force of gravity on plates or their motion because they are too large and too slow. (CCC: 3.2; DCI: ESS2.A.2) - Talk about how the mantle and plates interact and how this changes based on how they are configured at plate boundaries (e.g., how tilted the plate is on the mantle). (SEP: 2.3; DCI: ESS2.A.2) 12.A.2 When to check for understanding: On day 2, when you collect the <i>Measuring Forces on Inclines Investigation</i> handout and review student responses. What to look for/listen for in the moment: Look for student models and explanations to show (SEP: 2.3): - The force of gravity pulls plates toward Earth's center/down, but a component of it also pulls things down inclines. (SEP: 2.3, 5.2; DCI: ESS2.A.2) - Component forces are mathematically related to the force they make up according to the Pythagorean theorem. (SEP: 5.2) - Relationships between the systems of the plates, mantle, and gravity can be balanced or unbalanced to keep plates stable or cause changes in plate motion. (SEP: 2.3; DCI: ESS2.A.2) - Plate motion and changes in motion are too big and happen on timescales that cannot be directly observed, but forces on plates can be modeled at different scales. (CCC: 3.2; DCI: ESS2.A.2)

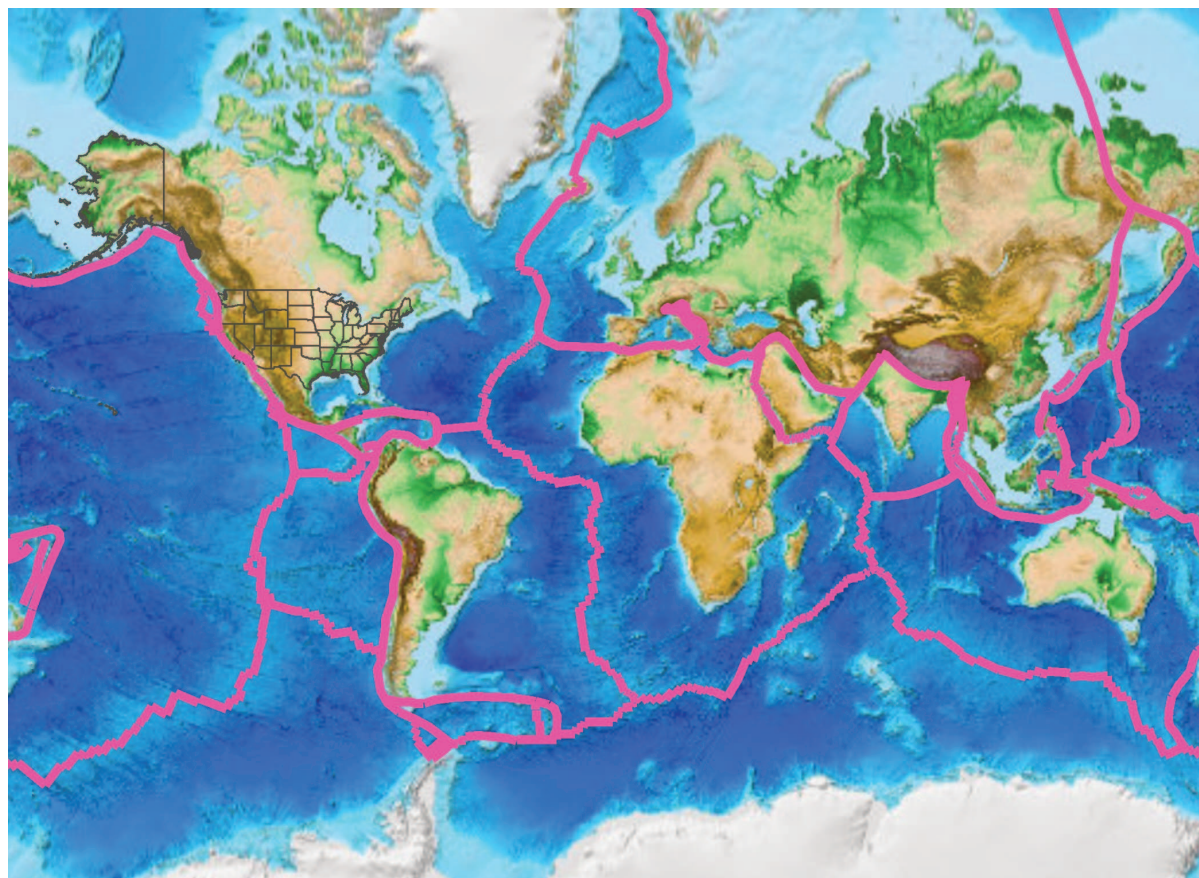
Lesson	Lesson-Level Performance Expectation(s)	Assessment Guidance
Lesson 13	13.A Revise an explanation based on valid and reliable evidence to answer Driving Question Board questions that involve explaining the change over time in stability of the interactions between motions of the mantle and the plates. (SEP: 6.2; CCC: 7.1; DCI: ESS2.A.2, ESS2.B.2, ESS2.B.3)	13.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 a surface feature, or the motion of the mantle and the plates 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: ESS2.A.2, ESS2.B.3) - Listen for students to use multiple sources of evidence to explain that changes that occur over a long time through the process of plate tectonics may appear stable over short time periods. (SEP: 6.2; CCC: 7.1; ESS2.B.2) Transfer Task PE: HS-ESS2-1 Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features. (SEP: 2.3; CCC: 7.2; DCI: ESS2.A.1, ESS2.B.2)



Lesson-Specific Teacher Materials



World Map



ArcGIS

Lesson 1 Teacher Reference

Local Case Creation

In this unit, students learn about intraplate earthquakes and the general processes that occur at these sites. Intraplate earthquakes occur in various places across the United States and the world, partly due to the ongoing stress and strain of tectonic plates from past and current geologic processes. Consider researching what earthquakes have occurred near your region and creating a localized earthquake case for students to investigate. The sections below detail what is needed to create an earthquake case to match the others in the unit, and what to be mindful of when selecting earthquake sites.

When constructing your earthquake case, make sure to detail the following information for future use in the unit. The bolded information is especially important for driving sensemaking in the anchor:

- **When the earthquake(s) occurred**
 - If there were swarms of earthquakes over a specified time period, include the size, number, and duration of the swarms.
- Where the earthquake(s) occurred
- **The magnitude of the earthquake(s)**
- How far away the earthquake(s) were felt
- How many kilojoules of energy were released by the magnitude of the earthquake(s)
 - How that amount compares to the average electrical energy used by a United States household in all of 2021 (3.8×10^7 kilojoules)
- The depth of the earthquake(s)
 - The *epicenter* is the spot on the surface above where an earthquake occurs.
 - The exact origin point underground is called the *hypocenter*.
- What damage occurred as a result of the earthquake(s)
- **Any accounts or data indicating cracking or shifting of the land**
 - The size of the shifting and cracking
- **Images of the earthquake region**
 - Images illustrating the damage or location
 - **Images illustrating any cracking or shifting of the land**
 - For any images, consider adding alt-text for students who would benefit from a description of what is shown in the image.
- **How frequently earthquakes occur in this region, and whether another earthquake is likely**
- **Information about the fault lines in the area and the seismic zone**
- To make the reading the same font as the other case readings, use OpenSans.

Fracking, Mining, Drilling, and Other Human Causes of Earthquakes

Earthquakes in your area may be due to human interactions with Earth's crust (fracking, drilling, mining, and so forth). However, these types of earthquakes are not directly addressed in this unit. The interaction of the biosphere with the crust is not included within the unit's performance expectations. If desired, however, these ideas could be intertwined in certain lessons to increase the local relevance of these types of earthquakes. If earthquakes in your area are related to those processes, consider making the connections below for incorporating those processes to explain those earthquake cases in Lessons 4 and 5:

- Lesson 4--When discussing forces on plates, consider how additional forces on different surfaces of the plate (from additional directions, including where items are being injected into the crust) could lead to bond breakage in the matter. Guide students to consider (1) how this would cascade across large sections of the plate material and (2) how this stored energy is transferred out of the compressed or stretched plate material in the form of an earthquake until the internal forces between the particles in the matter are balanced.
- Lesson 5--Add your earthquake case to the *Earthquake Cases* handout on day 3. This will allow students to see that there is no significant mantle anomaly also contributing to the earthquakes in your area.

Name: _____

Date: _____

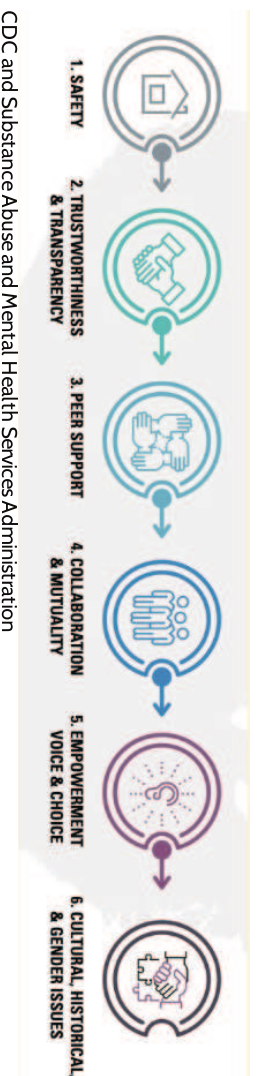
Lesson 1 Teacher Reference

Afar SEL Supports

In this unit, students explore events related to the 2005 Afar earthquake, cracking, and volcanic activity. Students are given space to share any earthquake-related stories with the class and learn about the impacts and causes of earthquakes, cracks, and volcanic activity worldwide. This unit focuses on Earth's internal processes and their manifestation on the surface. Students consider the spatial and temporal scales over which these events occur, and what interactions occur within Earth's systems.

It is important to keep in mind throughout this unit that earthquake- and volcano-related events can be traumatic, and recalling past experiences or learning about others' experiences can be triggering. Adolescents may develop symptoms following geologic hazards, such as difficult behaviors or emotions shown at home or school. According to the CDC, "Adopting a trauma-informed approach is not accomplished through any single particular technique or checklist. It requires constant attention, caring awareness, [and] sensitivity."

Below are some strategies to consider as you teach this unit, adapted from Transforming Education. <https://transformingeducation.org/>



Strategies to Strengthen Trauma-Informed Approaches in the Classroom

- 1. Safety**
 - The classroom environment feels physically and psychologically safe.
 - Interpersonal interactions between all educators and students promote a sense of safety.
- 2. Trustworthiness & Transparency**
 - Decisions about changes in the classroom are made with transparency.
 - Building and maintaining trust among teachers and students, and between peers, is a top priority.
 - Teachers openly acknowledge when they don't know an answer or when a subject could be hard to learn about for some people (adults and students alike).
- 3. Peer Support**
 - Peer support, mutual help, and collaboration are foundational for establishing safety and hope in the classroom.
- 4. Collaboration & Mutuality**
 - The identities and stories of members of the school and classroom communities are acknowledged and celebrated.
 - Partnering on work (between teachers and students, and peer-to-peer)
- 5. Empowerment, Voice, & Choice**
 - There is meaningful sharing of power and decision-making when possible.
 - Students' strengths and experiences are recognized and built upon.
 - The school and classroom communities believe in the students' resilience, empowerment, and ability to make good choices.
- 6. Cultural, Historical, & Gender Issues**
 - The school and classroom communities strive to move past cultural stereotypes and biases, promote culturally responsive teaching, and celebrate and welcome all students' identities.

Social and Emotional Learning (SEL) is the explicit teaching of skills to support emotion regulation and health relationships (CASEL). Trauma-informed approaches integrated with SEL work toward ensuring all students, including those who have experienced trauma, have the skills, knowledge, and attitudes to regulate their emotions and be productive, engaged learners (Osher et al. 2021; [Transforming Education, 2020](#)). The following skills support the development of self-regulation, a key principle of trauma-informed SEL ([Transforming Education, 2020](#)).

Engaging in Mindfulness

Below are several strategies to enable students to engage in mindfulness. This can help students who may have had negative experiences or trauma associated with geologic hazards and other themes in this unit. These strategies help to ground students and help them recognize that they are in a safe environment and ready to learn. The strategies can be utilized before a lesson, mid-lesson, or at any point that you feel students might benefit from them.

Strategy #1: 5-4-3-2-1

This can be conducted as a whole class, in partners, or in small groups.

- 5: Look at five things around you. Notice their qualities. What color are they? What shape are they? What other qualities do they have?
- 4: Acknowledge four things that you are touching, or could touch. How do they feel, or how would they feel?
- 3: Listen for three sounds. Tune into each of them individually.
- 2: Breathe in and identify two smells around you. What do these smells remind you of?
- 1: Identify one thing around you that you could taste. What would it taste like?

Note: Some alternatives to this approach can be found at <https://cognitiontoday.com/5-step-mindfulness-grounding-technique-to-ease-anxiety-why-it-works/>

Strategy #2: Check In

This works well at the beginning of a lesson.

- Have students reflect on these questions:
 - Think about the previous lesson. What went well? What was hard?
- Ask students to share their answers with peers, and consider how they can become more invested and present in the lesson today.

Strategy #3: Box Breathing

This can be used at any point in a lesson, and it can be helpful during or after any point when students show signs of stress or anxiety. Box breathing helps with stress management.

- Ask students to visualize a box with 4 equal sides in their minds. Guide them as each inhale or exhale takes them around the perimeter of the box.
- **Step 1:** Breathe in through the nose for a count of 4.
- **Step 2:** Hold the breath for a count of 4.
- **Step 3:** Breathe out for a count of 4.
- **Step 4:** Hold the breath for a count of 4.
- Repeat steps 1-4.

Note: The length of the steps can be adjusted to accommodate the individual (e.g., 2 seconds instead of 4).

Strategy #4: Progressive Muscle Relaxation

This exercise works well at any point during a lesson, either individually, in small groups, or as a whole class, while the teacher narrates. It guides students in tensing and relaxing their muscles in sequence through the body to foster relaxation.

- **Step 1:** Have students sit down and minimize distractions.
- **Step 2:** Starting at the feet, curl the toes under and tense the muscles in the feet. Hold for 5 seconds, then slowly release for 10 seconds. During the release, focus attention on the alleviation of tension and the experience of relaxation.
- **Step 3:** Tense the muscles in the lower legs. Hold for 5 seconds, then slowly release for 10 seconds. During the release, focus attention on the alleviation of tension and the experience of relaxation.
- **Step 4:** Tense the muscles in the hips and buttocks. Hold for 5 seconds, then slowly release for 10 seconds. During the release, focus attention on the alleviation of tension and the experience of relaxation.
- **Step 5:** Tense the muscles in the stomach and chest. Hold for 5 seconds, then slowly release for 10 seconds. During the release, focus attention on the alleviation of tension and the experience of relaxation.

- **Step 6:** Tense the muscles in the shoulders. Hold for 5 seconds, then slowly release for 10 seconds. During the release, focus attention on the alleviation of tension and the experience of relaxation.
- **Step 7:** Tense the muscles in the face (e.g., squeezing the eyes shut). Hold for 5 seconds, then slowly release for 10 seconds. During the release, focus attention on the alleviation of tension and the experience of relaxation.
- **Step 8:** Tense the muscles in the hand, creating a fist. Hold for 5 seconds, then slowly release for 10 seconds. During the release, focus attention on the alleviation of tension and the experience of relaxation.

Strategy #5: Guided Imagery

This can be done at any point in a lesson. Students visualize a relaxing environment, and walk through what they would sense in that environment, to help manage stress. Guided imagery can be practiced individually or with the teacher's support as narrator.

- **Step 1:** Have students sit down. Ideally, the space will have minimal distractions.
- **Step 2:** Visualize a relaxing environment by either recalling one from memory or creating one through imagination (e.g., a day at the beach). Elicit elements of the environment related to each of the five senses, using the following prompts:
 - What do you see? (e.g., the deep, blue color of the water)
 - What do you hear? (e.g., waves crashing along the shore)
 - What do you smell? (e.g., fruity aromas from sunscreen)
 - What do you taste? (e.g., salty sea air)
 - What do you feel? (e.g., the warmth of the sun)
- **Step 3:** Sustain the visualization as long as needed or able, focusing on taking slow, deep breaths throughout the exercise. Focus on the feelings of calm associated with being in a relaxing environment.

These five strategies are not the only mindfulness activities available. Consider using other mindfulness techniques suggested by your school counselors. As experts in their fields, they can recommend strategies that are relevant and targeted to your specific students.

Strategies #2-#5 were adapted from the following source for classroom-specific use:

Norelli SK, Long A, Krepps JM. Relaxation Techniques. [Updated 2021 Sep 6]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan-. Available from: <https://www.ncbi.nlm.nih.gov/books/NBK513238/>

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Name: _____

Date: _____

Lesson 2 Teacher Reference

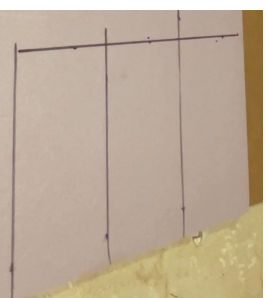
Preparing Foam Blocks

Gather the following supplies to prepare the foam blocks that students will use for Investigations A, B, C, and D:

- 2 sq. ft of $\frac{1}{2}$ " thick foam panel
 - These may be shipped in 1 sq. ft or 4 sq. ft sections, or you can start with a 4' x 8' panel available at a home improvement store.
- box cutter
- ruler or straight edge with a metal edge
- permanent marker

A video demonstrating the steps below is available at: <https://youtu.be/qtcSuxoThRU>

Mark lines to cut 4" x 8" rectangular sections out of the foam panel(s).



Use a box cutter to cut all the way through the foam along each cut line, keeping the blade perpendicular to the surface. If you have a ruler or straight edge with a metal edge, consider running the blade down the metal edge while it is on the foam to create a more defined cut.



Mark the corner of 1 side of each piece of foam as "A". Measure and mark to the midpoint of each edge of the shape. Use the ruler and marker to make a line between the midpoints of opposite edges.



Flip over the 7 pieces of foam, and measure and mark 2 points on the 4" side of each piece of foam, so each mark is 1" from the nearest shortest side and the marks are 2" apart.



Mark the corner of the side of the foam as "B".



Prepare 28 push-pull spring scales (5 N) with sticky tack tabs. Zero each scale. Attach 2 sticky tabs to each scale on the gram side at the 2 locations shown here.



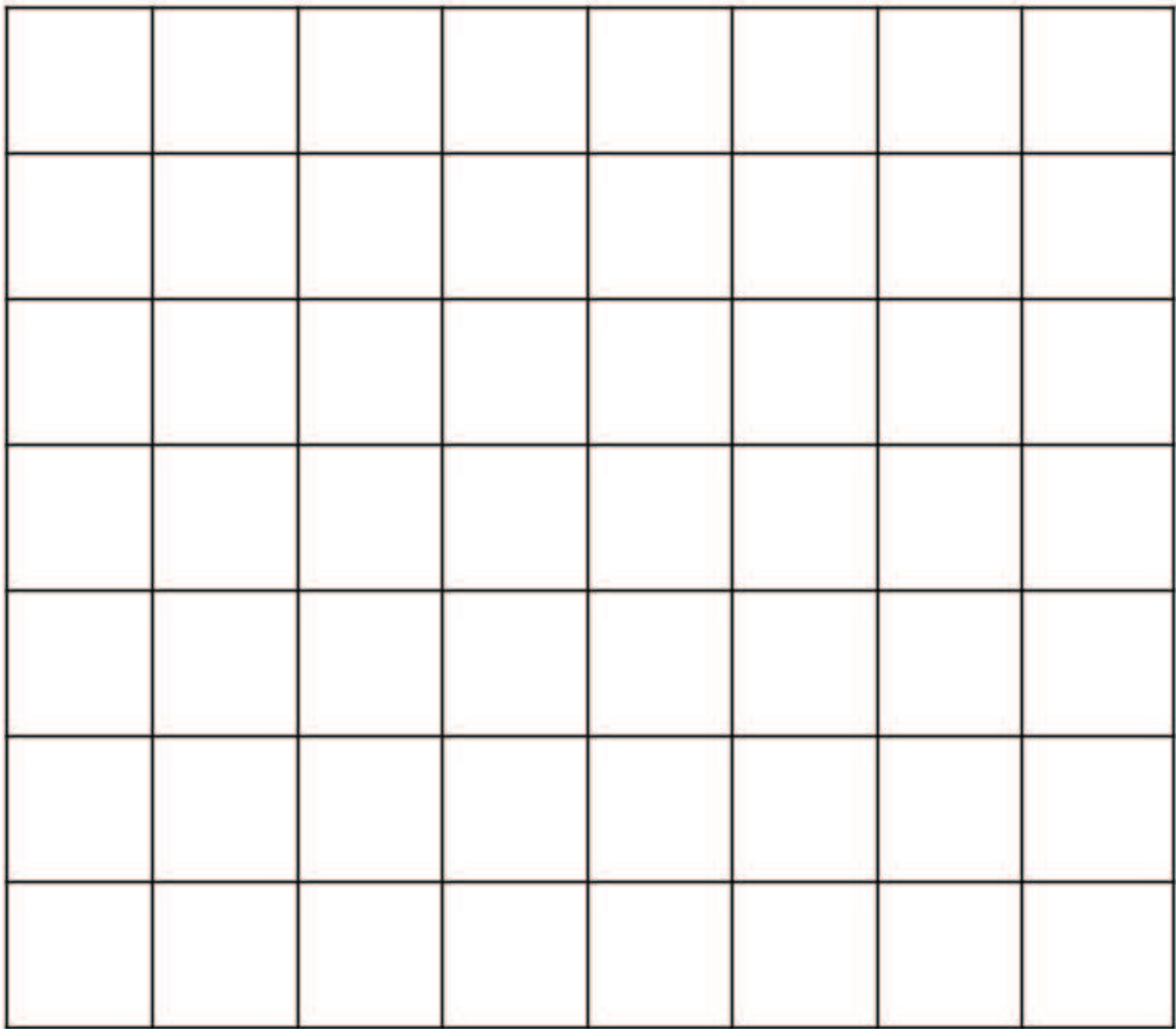
Teacher Background

Some amount of friction between the tip of the spring scale and the block produces additional shear forces along the contact face. These forces may contribute some level of error in student results. This variation, however, can be kept to a minimum and will appear insignificant if the force application is kept parallel to the aligned marks on either side of the foam. Watch for this as students work, and help them adjust their setup if you notice the spring scales are not parallel to these marks.

Understanding why this is, is beyond the high school level for students. Here is further guidance for the teacher who is interested in why this is:

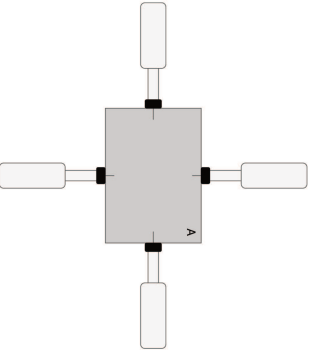
- Though the forces in Investigation A should pass through the block's center of mass, the forces in Investigation B do not.
- In Investigation B, the 2" spacing between the two pairs of parallel forces should ensure that the forces are being applied 1" away from the line that passes through the block's center of mass.
- This slightly off-center force application will produce a torque on the system (with each force applied on a radius arm of 1").
- In many cases that students test for Investigation B, the forces won't all be equal in magnitude. This is a desirable aspect of the investigation, as it will provide some interesting combinations to test. But in each of those cases, the torque on the system from the forces applied along the parallel line won't sum to zero. Additional shear forces due to friction will be produced where contact is made between the block and the tip of each spring scale. These shear forces will contribute to making the net torque on the system also equal zero, and the friction forces on the block due to the spring scales (which are perpendicular to the marked lines) also sum to zero. These additional forces contribute a small amount of error to students' results.
- In addition, some amount of friction force between the table and the foam block can contribute a small amount of error to student results. The calibration video, however, provides additional guidance on ways to limit this source of error.

Lesson 2 Teacher Reference
1" Grid Paper



Investigations A&B Key

Part 1: Data Collection / Observations

1. For each investigation, place the 4 spring scales provided to your group so they are pushing on the foam at the locations indicated by the arrows. 2. For each condition, increase or decrease the magnitude of the forces pushing on the foam, and record the force measurements when the system is stable (when the foam is not moving and nobody is touching it).	
Investigation	Results for each condition you tested
A	For both investigations, look for students to record different force combinations acting on the object. What to do: Make sure students are following the calibration protocols. If the recorded forces acting on the same axis are not similar, ask students to show you how they are calibrating their setup. Provide suggestions for how to improve data accuracy.
	
B	
	

Part 2: Data Analysis (Complete only *after* you have finished Part 1.)

1. How do the forces pushing on an object compare when it remains “stable”?

These are some possible answers students can provide to this question, and possible instructional moves to support their sensemaking:

- The forces are all different.

What to do: Suggest that students revise their calibration protocol and collect additional data.

- The forces are exactly the same.

What to do: Suggest that students compare their results with the results from other group(s).

- The forces are close in magnitude.

What to do: Encourage students to consider the factors causing variation in their data, and to think about the results they would obtain if these factors were removed.

2. How did you decide that you had tested enough conditions for either investigation (A or B)?

These are some possible answers students can provide to this question, based on their level of sophistication:

- We carried out three measurements, because three is enough.

What to do: This suggests that students are merely following a rule of thumb, rather than assessing the variability in their data. Encourage them to assess whether there is variation in their results, and to consider the factors that might be causing it. Ask them what they could do to reduce any large variation observed in the results.

- We did three measurements, because having more data provides more accurate results.

What to do: Although this answer suggests that students are making connections between data collection and data accuracy, they are not actually assessing the accuracy based on their actual results. Use the following prompts to encourage them to go a step further:

- **To reflect on variation:** *Think about the differences you observed in your measurements. Why might these variations have occurred?*
- **To consider factors affecting accuracy:** *What factors could contribute to the variability in your data? Are there any variables that might affect the force measurements you are getting?*
- **To explore sources of error:** *Can you identify any sources of error that might have influenced the differences in your measurements? How might these errors affect your overall findings?*
- We saw that the results were not exactly the same, but the forces we obtained were very close every time.

What to do: This answer suggests students are looking at the variation in their data to inform their data collection. Suggest that they compare and contrast their results with their peers by saying: *Compare your results with those of your classmates. Are there differences between your data? What could explain these differences? If not, what does our data suggest about the magnitude of the forces acting on a stationary object?*

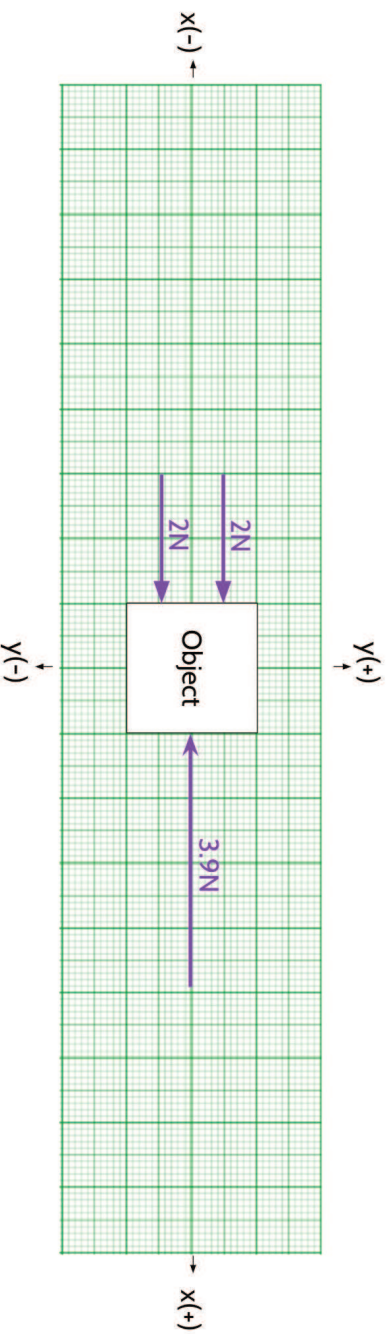
Part 3: Use a Model

Create a free-body diagram to represent a stationary object with 3 contact forces acting on it in the horizontal direction (along the x-axis).

Answers to this question will vary. If the forces acting on the object are not balanced, ask students some of the following prompts:

- *Can you tell me more about why you think the forces acting on this object will not make it move?*
- *What would be the net force acting on this object? Does that mean it would remain stable, or change its motion?*

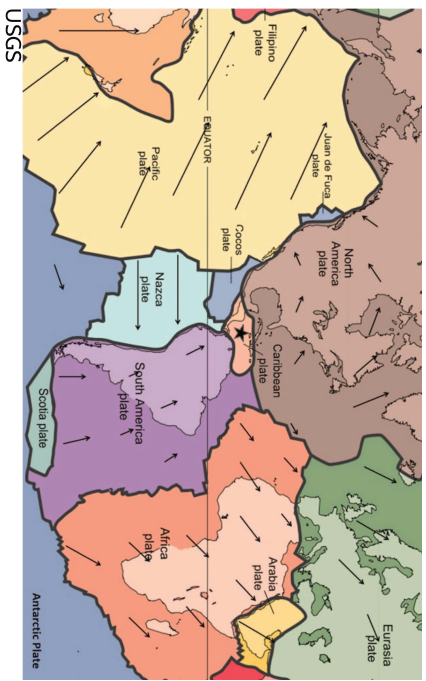
This is a sample response. Look for students to record the results they actually observe. Given the accuracy of the spring scales they use, it is very likely that the recorded net force will be slightly different from zero.



Then review the *GPS Plate Map*. Evaluate whether your free-body diagram is a reasonable model for explaining why the Caribbean plate (marked with a ★) might appear to be stable (not moving) relative to other plates. Why or why not?

These are some possible answers:

- No, the free-body diagram does not help explain why the Caribbean plate is not moving. The object does not move because the forces acting on it are balanced, but the map shows that other plates, like the South American plate, are actually pushing the Caribbean plate, so it should be moving north.
- No, the Caribbean plate is not moving, because the GPS map does not show any velocity arrows on it.



What to do: For students to understand that Earth systems are dynamic and interacting, it is important that they consider how one component of the system interacts with other components. If students suggest that the Caribbean plate is not moving because there are no GPS motion arrows drawn on it, suggest that they consider whether other plates are exerting forces on it, and whether those forces seem to be balanced or unbalanced.

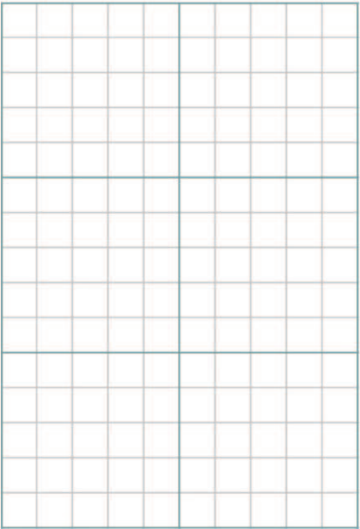
Investigations C&D Key

Procedure

- 1. Zero your 4 spring scales.
- 2. Set up the stable configuration you are testing for this condition (C or D).

Investigation C: Begin by placing 4 spring scales as shown in the image. Ensure that each scale is exerting a force on the foam (i.e., the force registered is not zero). 	Investigation D: Place 3 spring scales as shown in the image. Ensure that each scale is exerting a force on the foam (i.e., the force registered is not zero). 
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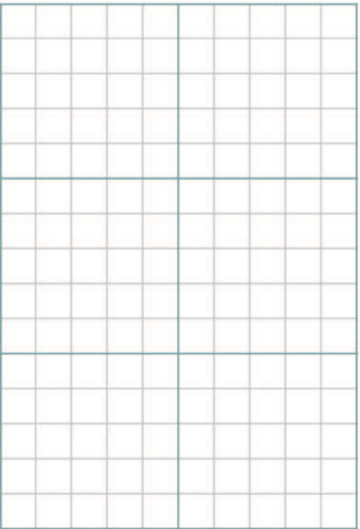
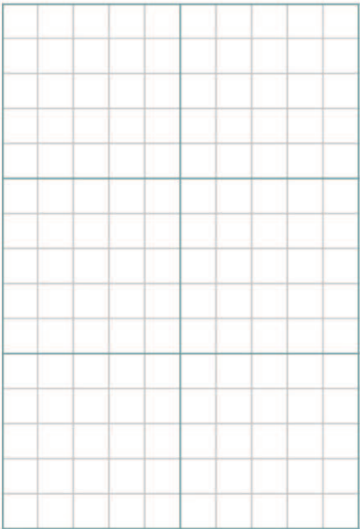
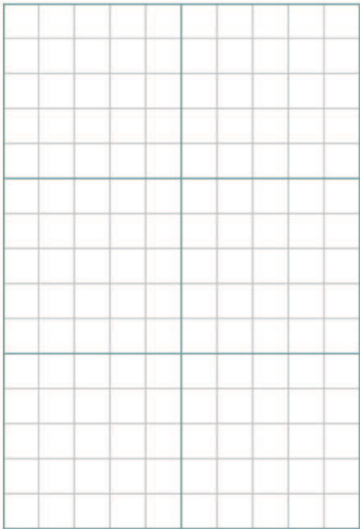
- 3. In the left column of the table below, draw a free-body diagram for the foam in its initial stationary condition that you set up.
- 4. Record the force vector you added or removed from that system using the protocol you saw in the video.
- 5. On the right column, record the changes you observed in the system and the force values of the new stable state the system reaches.
- 6. Repeat steps 2-5 for each condition you test, ensuring that the magnitude of the initial forces is different for each condition.
- 7. Keep an eye out for whether you think you need to modify your investigation plan as results come in.
- 8. Answer the questions at the end of this handout.

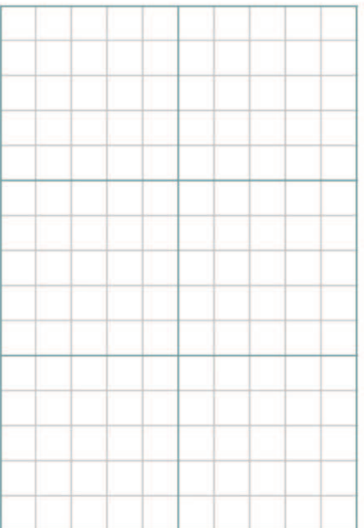
Trial	Forces acting on the system in initial stationary condition	Changes observed and new force values after adding or removing a spring scale
1	 Bobarino	For both investigations, look for students to: • Record data using a free-body diagram for each condition, including the initial force conditions acting on the stable system, and labeling which force interaction was added or removed. • Record the dynamic changes in the system (e.g., how much the object moved, in what direction, and for how long). • Repeated trials or measurements yielding consistent results for several contact force combinations to support the reliability of the results. • Follow the calibration protocols for gathering accurate results using the spring scales. • Record the new stable state of the system (where the foam rectangle is in the end and/or the new interactions on each spring scale) for each measurement. What to do: Ask students to consider the relationship between the change they made, the change they observed, and the new stable state of the system. Encourage them to think

about the forces acting on the object, and whether these forces are balanced or not before, during, and after the change.

See whether students use the scale calibration protocols on their own; this will be evidence that they are considering the relationship between data collection and the accuracy of their results. See the *Investigations A&B Key* for how to support data collection.

If students struggle to see any clear changes in the motion of the foam, use this as a motivation to watch the changes that happen in the system in slow motion.

2	Bobarino 
3	Bobarino 
4	Bobarino 



Bobarino

Use your results to answer the following questions:

1. What was the net force on the object initially, when it was stable?

The net force was zero when the object was stable

2. Why did adding or taking away a force make the object move?

Because by adding or removing a force changes the net force. If the net force is not zero, then the object moves.

3. What, if anything, can you now claim about how the net force on a stationary object and a moving object compare?

The net force of a stationary object is zero, while the net force of a moving object is not zero.

What to do: Some students might not get at this last idea from their investigations, as changes in the system are fast and hard to observe. If they have smartphones that can record slow-motion video, encourage them to record the changes in the system as they add or remove a spring scale acting on the foam.

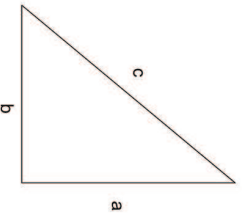
Name: _____

Date: _____

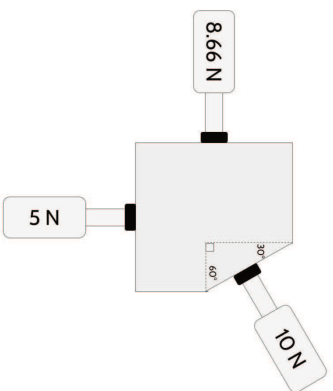
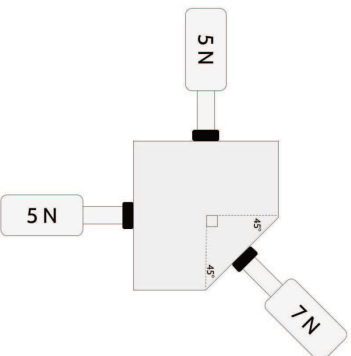
Lesson 2: Answer Key 3

Free-Body Placemat Key

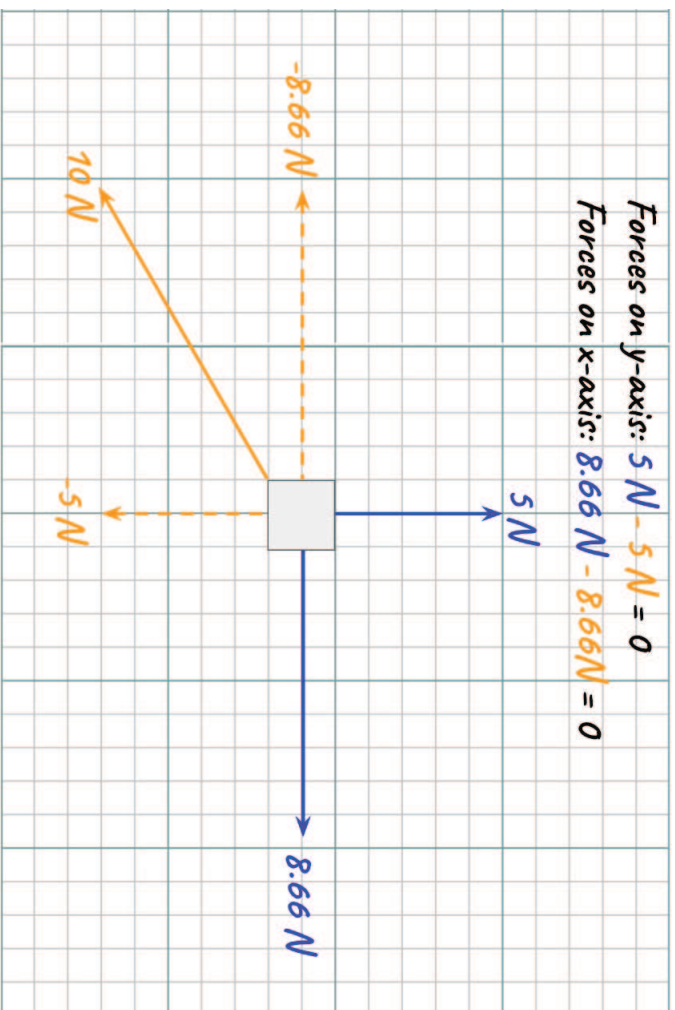
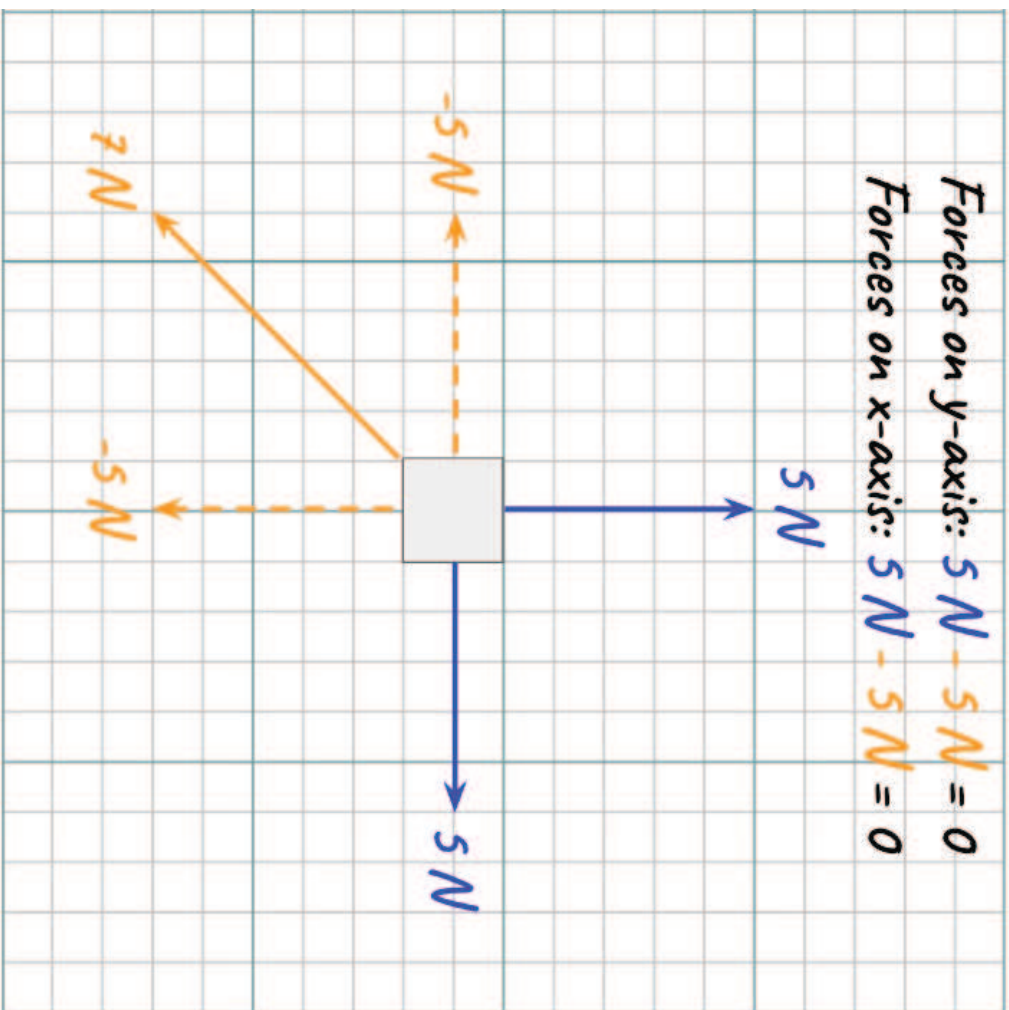
The Pythagorean theorem ($a^2 + b^2 = c^2$) describes the relationship between the 3 sides of any right triangle.



Use the manipulatives with the graph paper below to set up free-body diagrams representing the contact forces on the object for either of the 2 stable (stationary) conditions shown here:



Use these manipulatives to discover any additional relationships that can help explain why the object in the system would remain stable (stationary). Record your findings in your science notebook.



Lesson 2: Answer Key 4

Progress Tracker Examples

Below is an example of what students might add to their Progress Tracker. Please note that this is not an exact list of what a student should add, or an exemplar of how to fill out this chart. This is one example of many possible responses based upon how students have engaged in the lesson and their individual learning.

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?
2	<i>The net force on an object is all the forces on an object added together, with direction. Forces are vectors that can be broken into pieces called components. When all the forces on an object balance, it is stable. When forces become unbalanced, changes happen and things are no longer stable. All systems change, but some systems change quickly and some are stable for a long time</i>	☒ Stability over time or space ☐ Change over time or space ☒ Thinking at/across different scales	<i>We looked at foam plates with forces from spring scales all pushing from different directions. The plate was stable as long as the forces were balanced. When a scale was taken away, the block suddenly moved and then found a new stable spot. We connected this to Earth's plates and how they are stable for a really long timescale, but then maybe forces change and things like the crack in Afar and earthquakes happen.</i>
5	<i>The mantle has different temperatures in different places, which means the matter is different. This could create different unbalanced forces in different locations, which is why some regions have different kinds of surface features than others.</i>	☐ Stability over time or space ☐ Change over time or space ☒ Thinking at/across different scales	<i>Changing from the global scale of Earth's layers to regional differences within the mantle allowed us to see differences that might be causing matter differences and forces to be unbalanced, to cause different shapes on Earth's surface.</i>
6	<i>The mantle pushes on itself because of differences in density. These differences are caused by temperature differences and cause the matter in the mantle to move around like a lava lamp. Less dense mantle is pushed up by the matter around it.</i>	☐ Stability over time or space ☒ Change over time or space ☒ Thinking at/across different scales	<i>We saw how the matter in the mantle tank and lava lamps moved around over time, and saw that in the mantle tank this could be explained with temperature differences and density. We used the particle-level scale to explain how the matter of the whole mantle pushed on itself based on motion and spacing of particles.</i>

9	<i>Oceanic crust is younger and more dense than continental crust. In the middle of oceans, there are plate boundaries with the youngest rock, and it gets older as you move away from the plate boundary. The rock at Afar is the type of rock we see near these boundaries, young basalt.</i>	☐ Stability over time or space ☒ Change over time or space ☒ Thinking at/across different scales	<i>We saw that the space scales of distance from ocean plate boundaries also showed change over time because the rock got older when it got farther away. This showed that new rock seemed to be forming over time at the plate boundary and pushing the older rock away.</i>
11/12	<i>Gravity, like all forces, has magnitude and direction. When an object is on an incline, we can think of gravity as breaking into components that pull down the incline and into the surface. If the incline gets steeper, the component that pulls down the incline gets stronger. Gravity acts similarly to this at plate boundaries with ridge push and slab pull.</i>	☒ Stability over time or space ☐ Change over time or space ☐ Thinking at/across different scales	<i>We used balanced forces to indirectly measure forces. This was possible because the object was stable. Its motion was not changing. Therefore, the forces on it had to all be balanced, and we could measure the components of gravity by measuring the forces balancing gravity down and into the incline.</i>

Lesson 3 Teacher Reference

Developing the M-E-F poster

In order to explain many natural phenomena, students need to be able to connect their observations with evidence of mechanisms that they cannot see directly. These observations usually take the form of changes in matter within a system or between systems, and the mechanisms might involve energy transfer due to unbalanced forces acting in the system. To integrate these ideas into a sensemaking framework, we introduce a key anchor chart, the Matter, Energy, and Forces poster, abbreviated as the **M-E-F poster**. Over the course of this and subsequent units, this will become a public record of important ideas and questions that students ask to explore the dynamic interactions between matter, energy, and forces. Lessons 2, 3 and 4 include major additions to this poster.

The M-E-F is a tool to support developing explanations of many natural phenomena that we explore in OpenSciEd high school. This tool encourages students to answer different questions about changes that are happening in the system from a matter, energy, and forces perspective. By asking these questions over and over throughout this unit and other units, the goal of this tool is to support students developing productive lenses that can help them identify areas of a phenomenon that require further exploration.

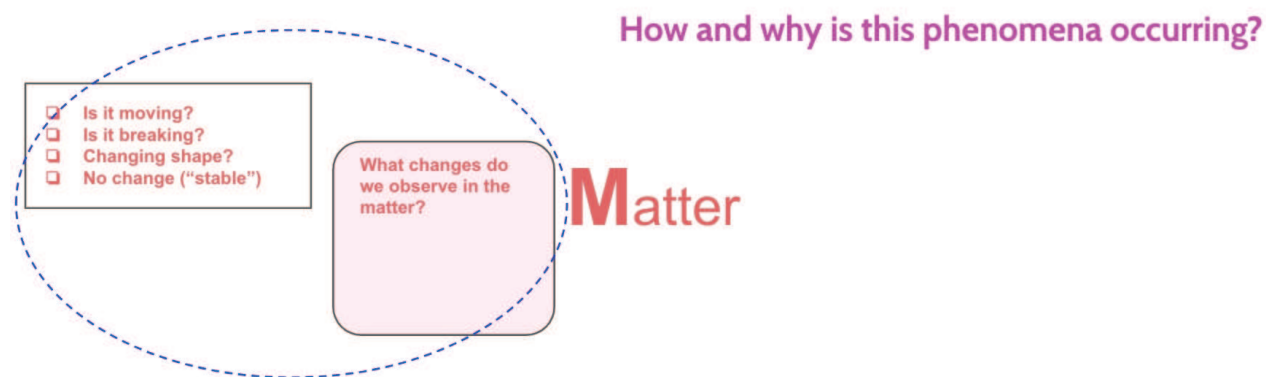
Development of the M-E-F poster in this unit

In **Lesson 2**, we introduce the idea that looking at changes in matter seems to be a first step to understand why a phenomenon is occurring. We add the following panel to the poster:

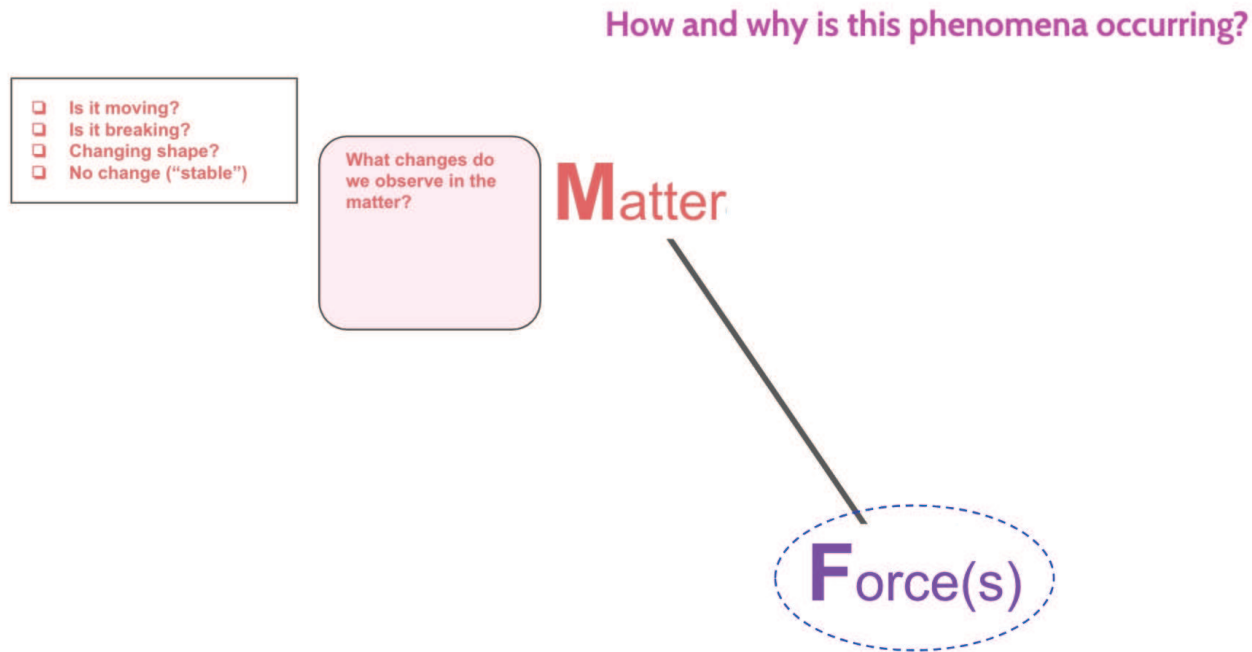
- “Matter” and “What changes do we observe in the matter?”

We also add the panel that lists the changes (in the form of questions) that students predicted we might observe in the matter:

- Is it moving?
- Is it breaking?
- Changing shape?
- No change (“stable”)



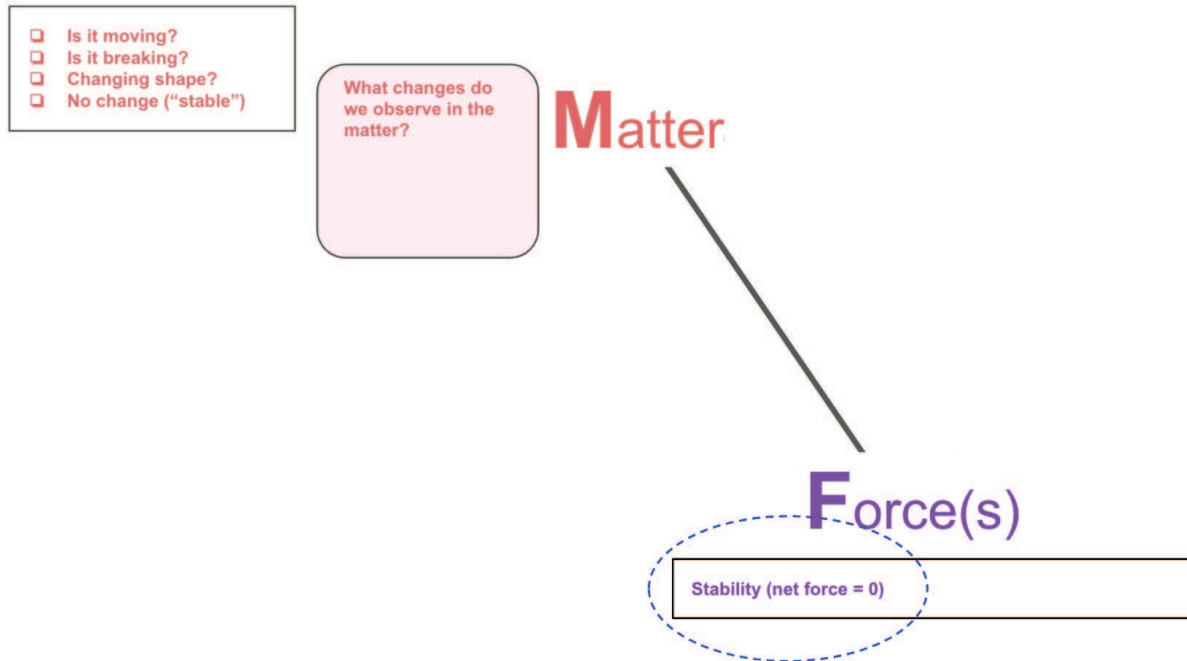
The investigations students carry out using forces acting on a physical system help us develop the idea that the changes in matter they are predicting (plate motion, Afar crack) are caused by forces, suggesting that forces are another important lens that can help us make sense of phenomena. We add the panel with “Force(s)” on it to the bottom black line that connects it to “Matter”.



Later in the lesson, we figure out how balanced forces or a net force of zero can produce stability in matter. We use these ideas to add the following annotation under the “Force” section of the poster:

- Stability (net force = 0)

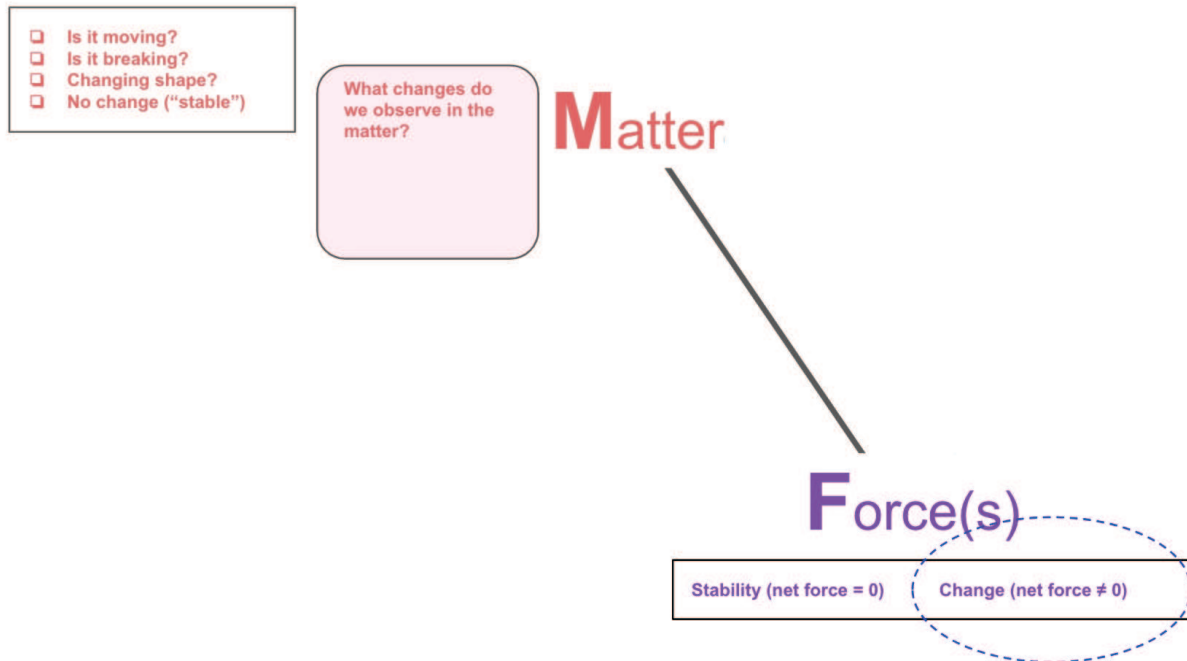
How and why is this phenomena occurring?



In addition, we determined that the changes in an object's motion were caused by the presence of a nonzero net force acting on it. We add the following annotation under the "Force" section of the poster:

- Change (net force $\neq 0$)

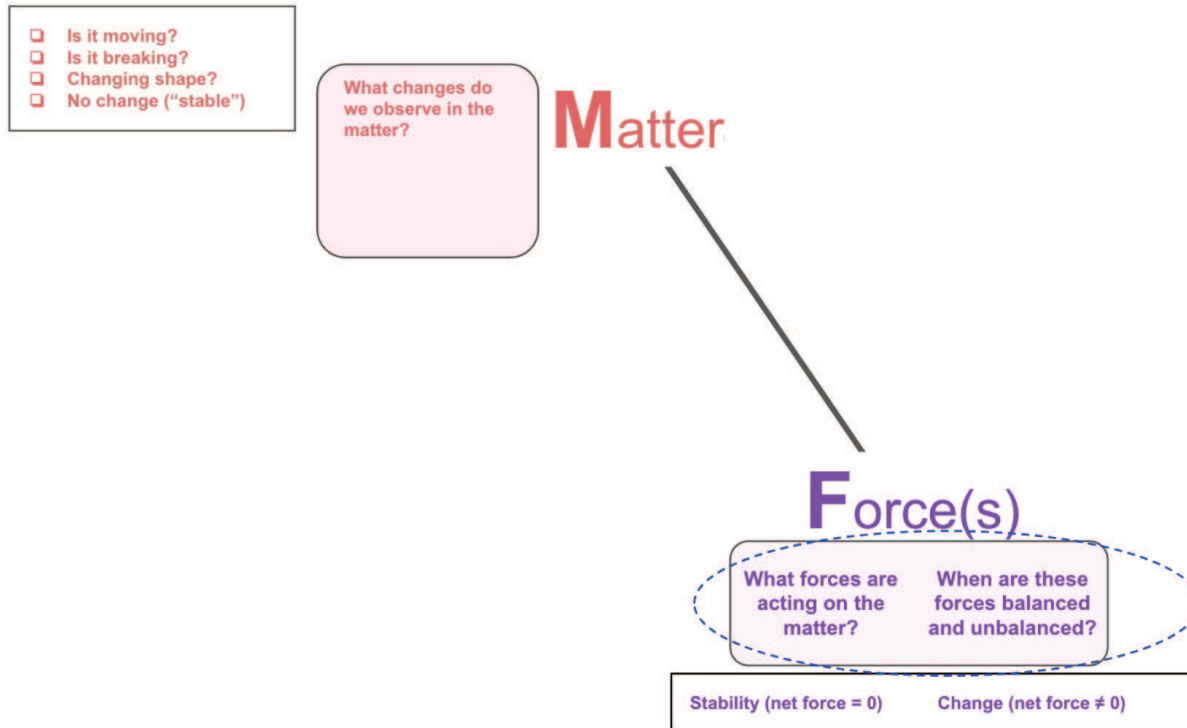
How and why is this phenomena occurring?



To synthesize the role of forces acting on a system, two prompts are added to the M-E-F poster:

- "What forces are acting on the matter?"
- "When are these forces balanced and unbalanced?"

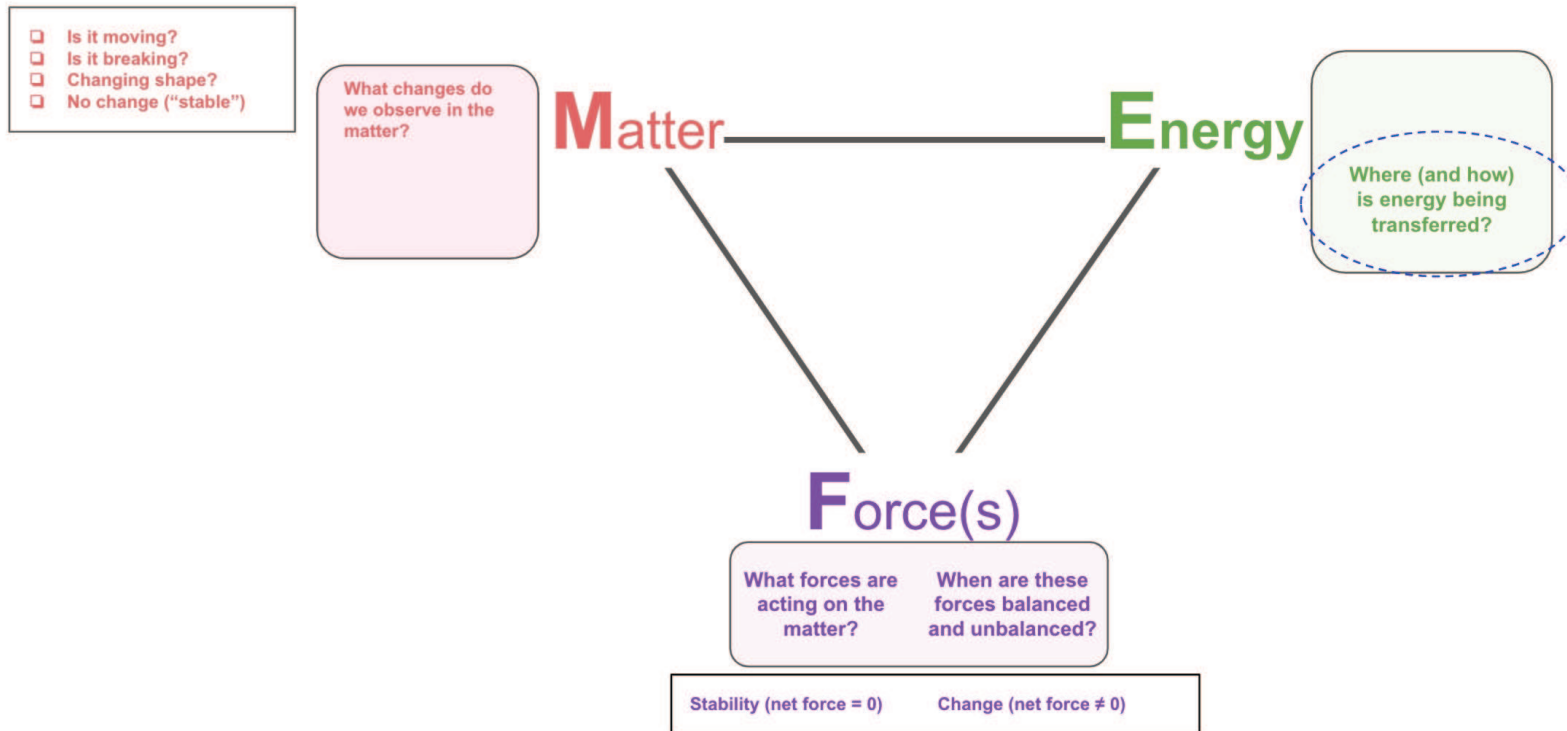
How and why is this phenomena occurring?



In the *Electricity Unit*, we explained many phenomena by thinking about energy transfer through the system. In **Lesson 3**, we use this lens again to try to explain what is happening in a foam model simulating how forces affect the matter in plates. We include a prompt that will help us make sense of energy transfer in a system:

- Where (and how) is energy being transferred?

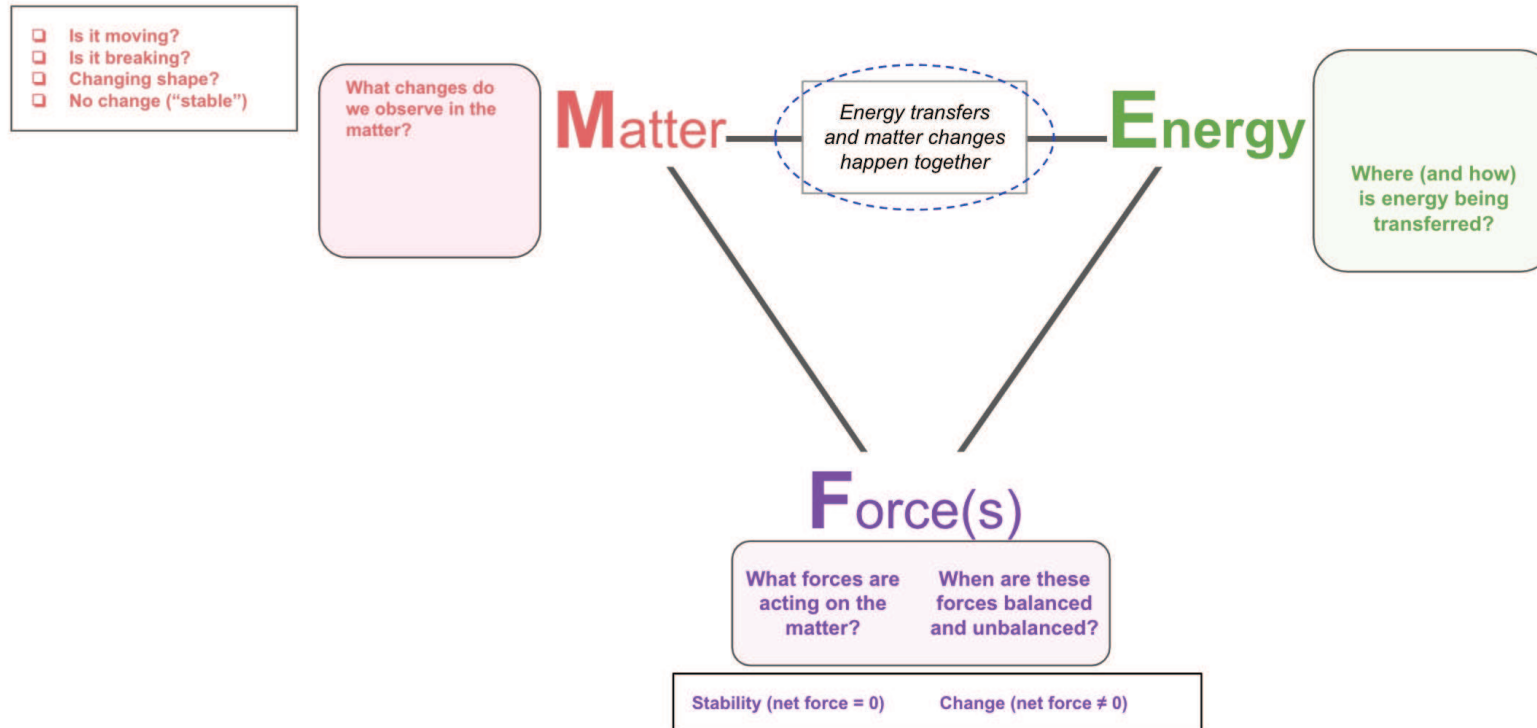
How and why is this phenomena occurring?



Based on the explorations with the foam model, we add the following idea to the poster on the line between the "Matter" and "Energy" panels:

- "Energy transfers and matter changes happen together"

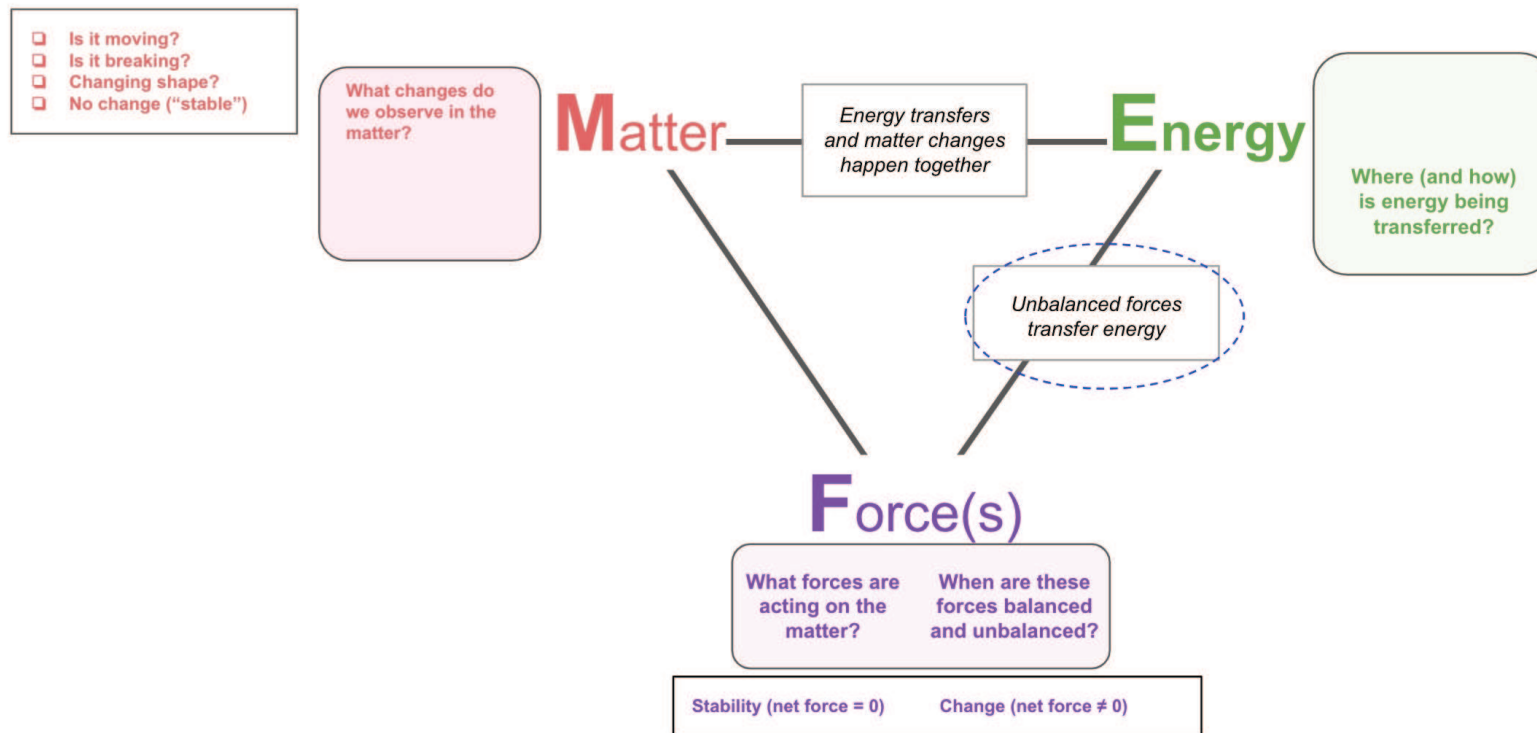
How and why is this phenomena occurring?



Later in the lesson, we will investigate the effects of changing the magnitude of the unbalanced forces applied to the system. From there, we will be able to reason out all the related changes in matter and energy. These ideas are used to add a new panel on the poster on the line between the "Forces" and "Energy" panels.

- "Unbalanced forces transfer energy"

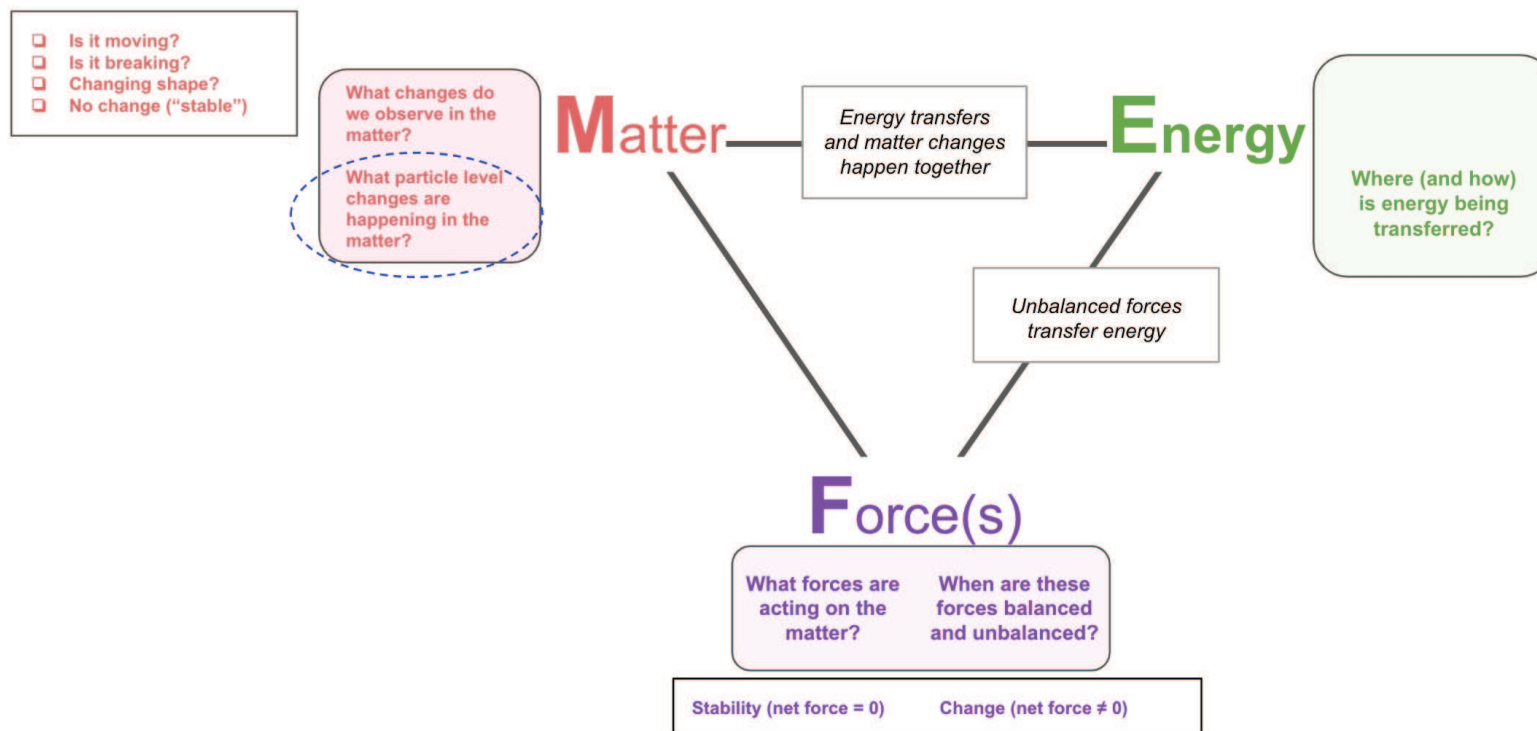
How and why is this phenomena occurring?



In **Lesson 4**, we bring the idea that paying attention to changes at the particle level helped us understand phenomena better in the past. We add the following panel to remind us of that going forward:

- "What particle-level changes are happening?"

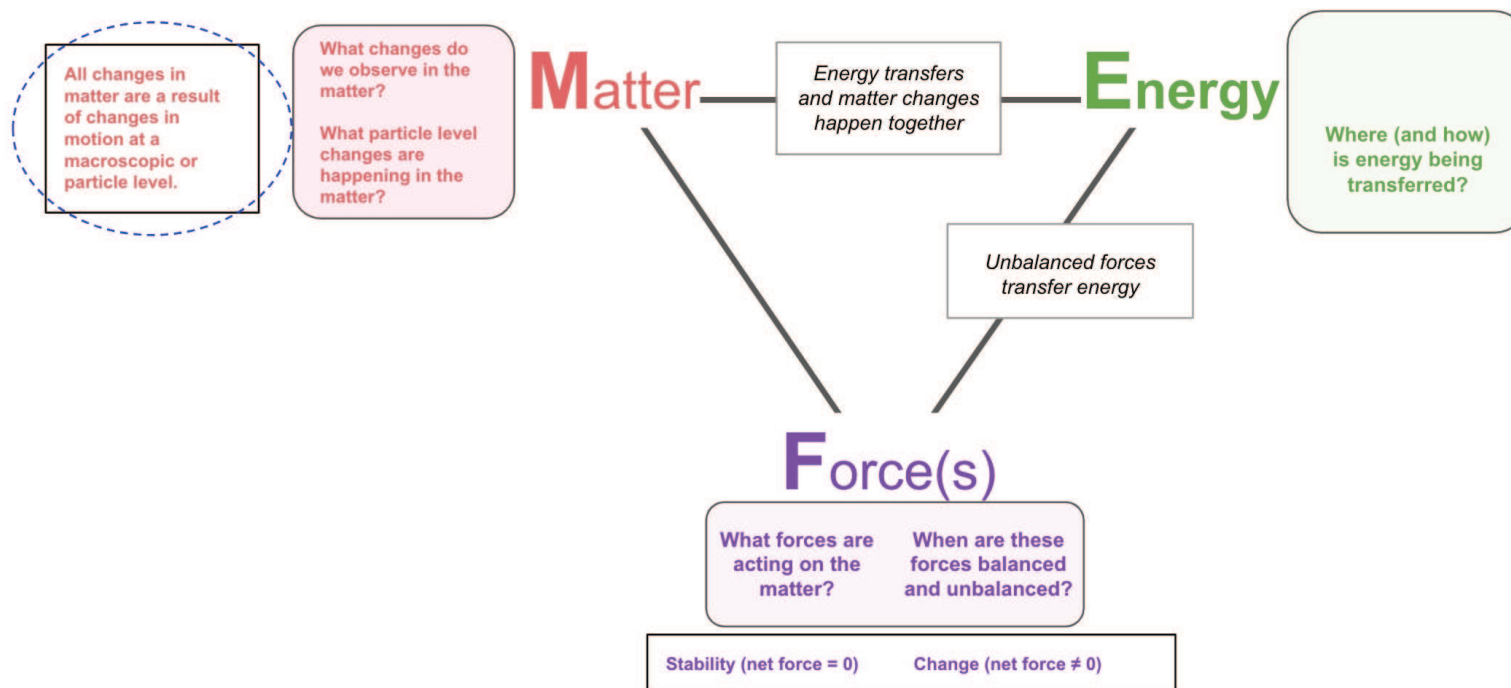
How and why is this phenomena occurring?



Up until this point, we have seen that unbalanced forces cause several types of changes: motion, shape change, and breaking. We use this insight to simplify the entire set of changes we listed under the “Matter” section on the M-E-F poster, as they are all changes in motion at different scales. The panel “Checklist of different matter changes,” is replaced by the following panel in the top left corner of the M-E-F poster”

- “All changes in matter are a result of changes in motion at a macroscopic or particle level”

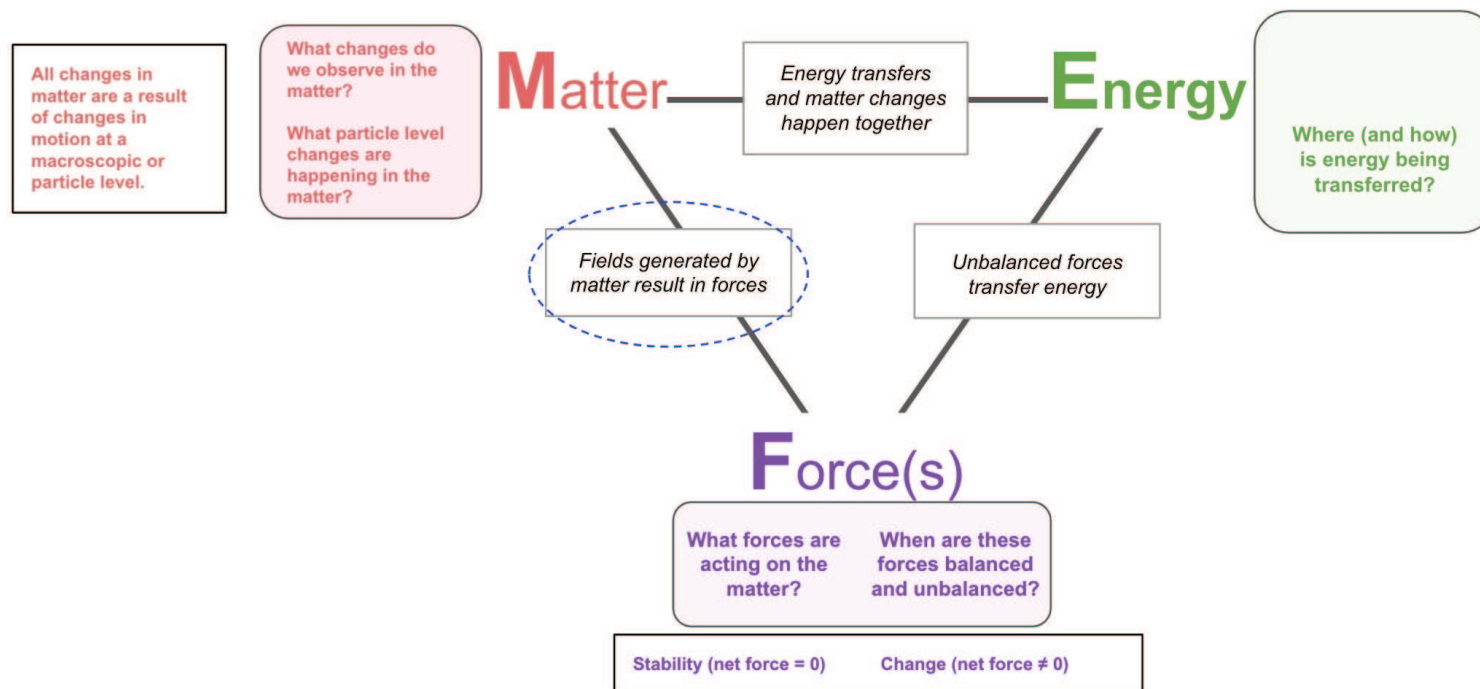
How and why is this phenomena occurring?



We use different models to investigate the interactions between matter, energy, and forces at the particle level. We develop the idea that in a solid, the electric fields produced by electrons and protons result in forces that act on neighboring particles in ways that explain all sorts of macroscopic behavior. Based on this, the following panel is added between the “Matter” and “Force(s)” panels on the line connecting them on the M-E-F poster:

- “Fields generated by matter result in forces”

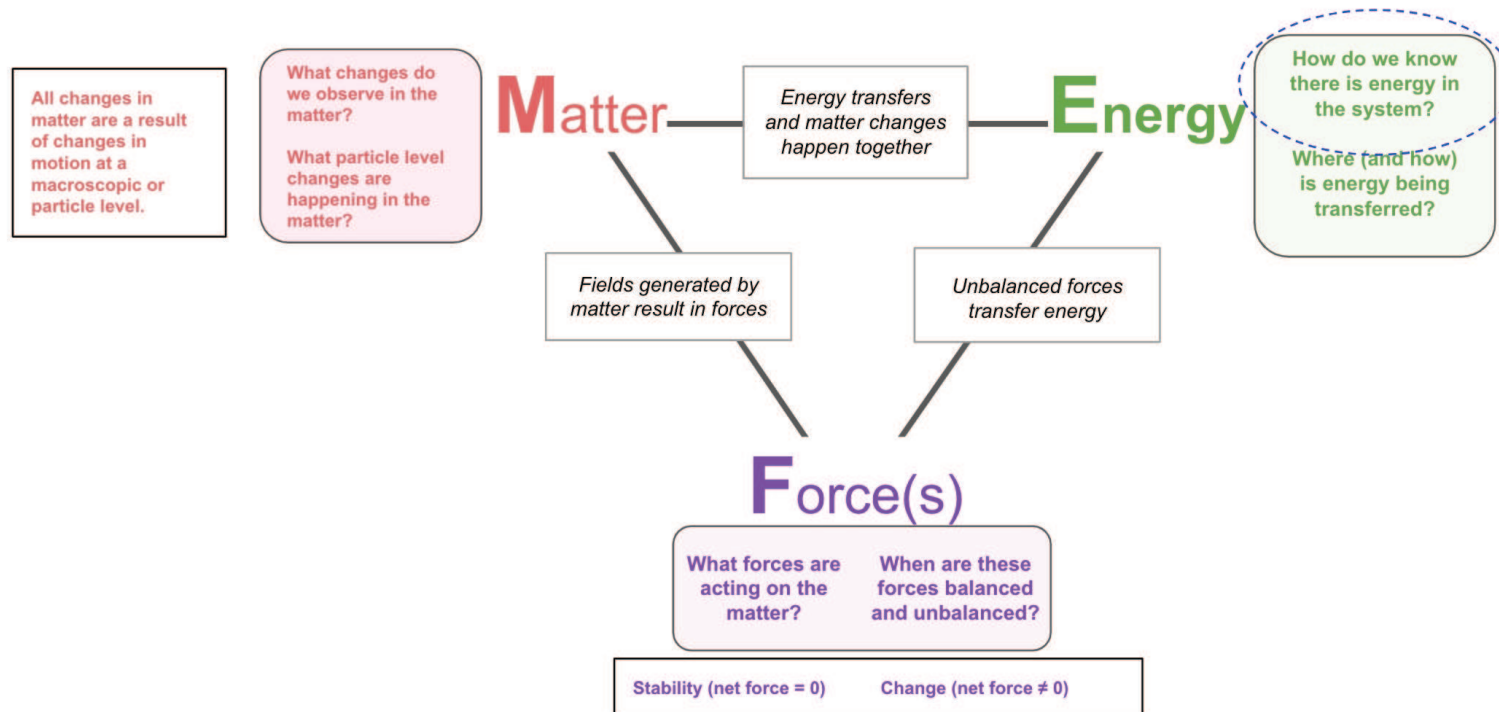
How and why is this phenomena occurring?



From an energy perspective, we elevate the idea that identifying evidence of energy in the system can help us make sense of changes that are taking place in a system. The following panel is added to the top right corner of the M-E-F poster:

- “How do we know there is energy in the system?”

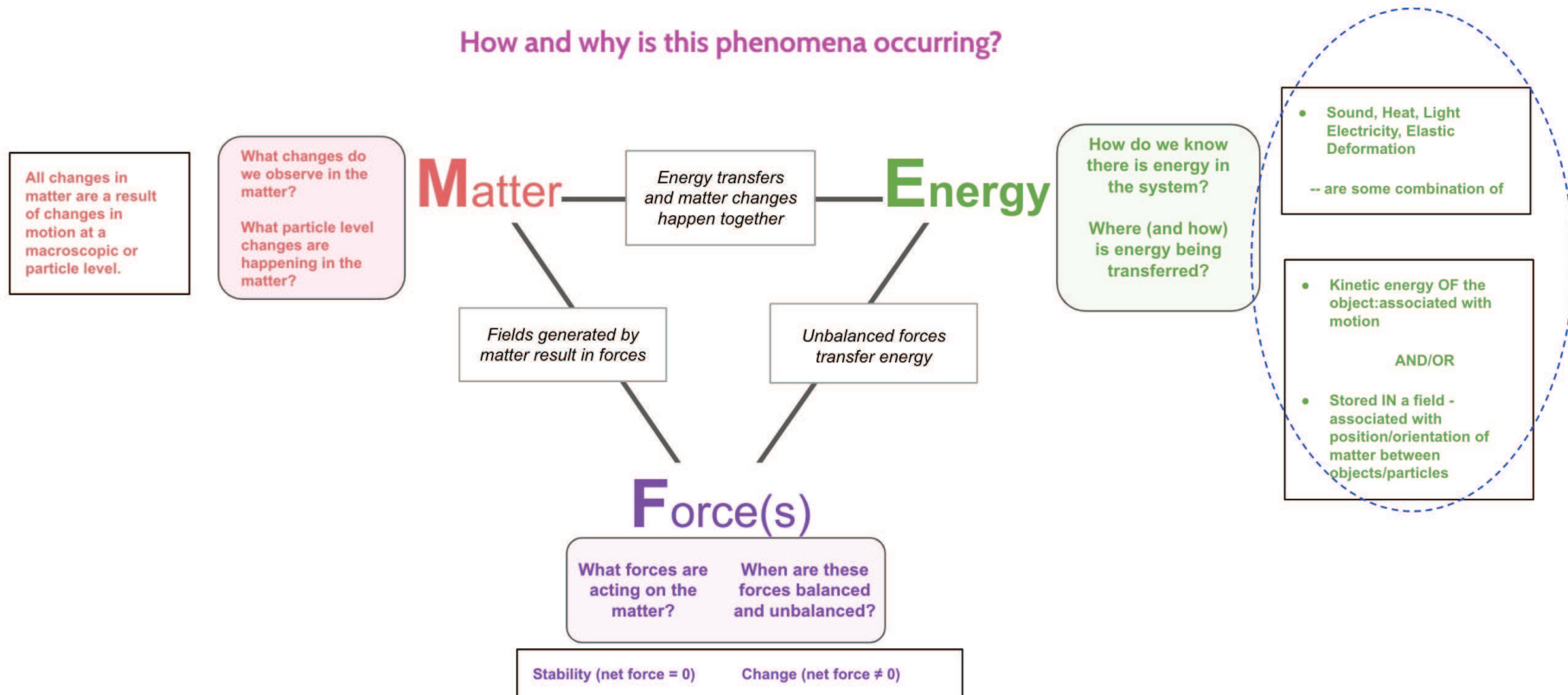
How and why is this phenomena occurring?



At the end of this lesson, we revise some of the manifestations of energy transfer in a system. Using these ideas, the remaining 4 panels are added to the right side of the M-E-F poster:

- “Sound, heat, light, electricity, elastic deformation ... are some combination of:”
- “Kinetic energy associated with the motion of objects or particles ”
- “ and/or”
- “Stored in a field associated with position/orientation between the objects /particles”

How and why is this phenomena occurring?



Lesson 3 Teacher Reference

L3 Investigation Extension

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. Though that was a focus of the first unit of the Chemistry course, *OpenSciEd Unit C.1: How can we slow the flow of energy on Earth to protect vulnerable coastal communities?* (*Polar Ice Unit*), it has not yet been a focus in this course. It will be introduced in Lesson 8, and it will become a larger focus of students' work in the next two units: *OpenSciEd Unit P.3: What can we do to make driving safer for everyone?* (*Vehicle Collisions Unit*) and *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity* (*Meteors Unit*).

Here are two options to consider that may better support the mathematical modeling required:

1. Offer the experimental design portion (Part 1) of this opportunity now and save the mathematical modeling (Part 2) until after Lesson 7.
2. Offer both parts of this opportunity after Lesson 7.

What practices will be needed for the first part of this opportunity?

Students will need to engage in these elements of *planning and carrying out investigations* for the experimental design portion of this work:

- 3.1 Plan an investigation or test a design individually and collaboratively to produce data to serve as the basis for evidence as part of building and revising models, supporting explanations for phenomena, or testing solutions to problems. Consider possible confounding variables or effects and evaluate the investigation's design to ensure variables are controlled.
- 3.2 Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- 3.3 Plan and conduct an investigation or test a design solution in a safe and ethical manner, including considerations of environmental, social, and personal impacts.
- 3.4 Select appropriate tools to collect, record, analyze, and evaluate data.
- 3.5 Make directional hypotheses that specify what happens to a dependent variable when an independent variable is manipulated.

Students will need to engage in these elements of *analyzing and interpreting data and using mathematics and computational thinking* to work with the data they collect:

- 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.
- 4.2 Apply concepts of statistics and probability (including determining function fits to data, slope, intercept, and correlation coefficient for linear fits) to scientific and engineering questions and problems, using digital tools when feasible.
- 5.3 Apply techniques of algebra and functions to represent and solve scientific and engineering problems.

Have students use a tool like CoDap or Google Sheets to plot their data and find the equation for a line of best fit.

How can I introduce Part 1 of the extension opportunity?**Identifying the question and variables**

Have students start by:

- articulating the question that their curiosity arose from (e.g., how much energy can be transferred into or out of a deformed material)
- identifying the independent and dependent variables related to the question
- articulating which Earth system phenomena this is relevant to (by the end of Lesson 3 or 4)

Identifying materials and measures

Have students refer to the list of the materials the class brainstormed in **slide 1**, note those that you have available, and discuss which of them might be useful to test energy transfer into or out of. These will likely include:

- the foam panel
- the spring scale
- rubber bands

Provide students possible ways to measure some of the energy transferred out of the system. Suggest that the material they launch from their elastically deformed material could be launched vertically, and explain that scientists have a way to determine the amount of energy (in joules) that a moving object has when it is relatively aerodynamic (with little air resistance). Tell students that this formula is the weight of the object (in newtons) times the height the object travels upward (in meters): $1 \text{ N} \cdot \text{m} = 1 \text{ J}$

Have students brainstorm some of the main materials/setup challenges to consider for both approaches before choosing one. They should also identify important controls. Examples of design challenges include:

- figuring out a way to set up the launcher system to ensure the entire change in deformation remains in contact with the object it is launching until the launch is complete
- determining an aerodynamic shape that is safe to launch
- calibrating the launch trials to yield launch heights within a measurable range

After brainstorming, students should outline a detailed plan (draft) for configuring the launcher, a way to measure its deformation before launch, the number of conditions they want to gather data for, and the number of trials they want to carry out for each condition. They should also know (without you instructing them) that before starting, they need to create a data table to record their data.

How can I support Part 2 of the extension opportunity?

Have students develop a mathematical model through these steps:

- Create a scatter plot of their independent variable (deformation distance) and energy (distance traveled).
- Determine whether the relationship is linear or nonlinear. It should appear nonlinear.
- Determining a nonlinear equation that best fits the data. This will be a quadratic relationship with a vertex at (0,0) [$y = kx^2$].
- Determine how close of a fit the mathematical function is to the data (R^2) – quadratic regression.
- Rewrite the equation using the names of the variables in the equation.
 - [energy in joules = k (deformation of the launcher material) 2]

Have students explain the relevance of the equation to the Earth system phenomena we are studying.

What further extensions are possible?

If students completed *OpenSciEd Unit 8.1: Why do things sometimes get damaged when they hit each other?* (*Collisions Unit*) in middle school, they saw an example of how to plan for and analyze an investigation with two independent variables in Lesson 4 of that unit. Such a challenge could be relevant here, too, as other variables listed below should also exhibit quantitative relationships. These include:

- Varying the thickness of the deformed material. Most materials will exhibit a directly proportional relationship to energy transfer into and out of it: twice as thick = twice as much energy.
- Varying how wide the deformed material is. Most materials will exhibit a directly proportional relationship to energy transfer into and out of it: twice as wide = twice as much energy.

Explaining Behavior KEY

Explaining the behavior of the matter in the system					
Over time...	At first	Then very quickly	In between	Then very quickly	At the end
Forces	balanced on each object	... unbalanced forces...	... balanced forces...	... unbalanced forces...	... balanced forces...
		<u>Cause</u>		<u>Cause</u>	
Matter	Stable: Stationary Flat shaped panel	Changes in motion, shape.	Stable: Stationary, curved shape panel	Changes in motion, shape	Stable: Stationary, Flat shape panel
Energy		Energy transfer into the system		Energy transfer out of the system	

Analyzing Rock Behavior Key

The responses to Questions 1, 2, and 3 on the *Analyzing Rock Behavior* handout are aligned to lesson level performance expectation (LLPE) 3.A.

The response to Question 4 is aligned to lesson level performance expectation (LLPE) 3.B.

3.A Make qualitative claims about how differences in the magnitude of forces (1) acting on different materials (*cause*) would produce similar *effects* in their *structure* (elastic deformation) and (2) acting on the same material would *affect the amount of energy transferred into and out of it*. (SEP: 6.1; CCC: 2.2, 5.2, 6.2; DCI: PS3.B.2)

3.B Ask questions arising from development of the M-E-F model to clarify (1) additional relationships related to energy transfer and storage in deformed matter and (2) its application to various *dynamics and interactions occurring in Earth systems*. (SEP: 1.2 CCC: 5.2, 7.1; DCI: PS3.B.2, ESS2.A.1)

Question 1. If an engineer tested similar-sized samples of two different materials from the data table shown here, which one of those materials would require application of higher-magnitude forces on it to produce the same amount of elastic deformation as the other material?

- *Write an evidence-based claim that answers this question. Make sure your claim references the variables in question and 2 materials in the data table:*

What to look for in the student response to this question:

- The claim states which material will require a higher force (*cause*) to produce the same amount of elastic deformation (*effect*). (SEP: 6.1; CCC: 2.2)
- The predicted relationship is qualitatively accurate (based on elastic deformation-to-force ratios). (SEP: 6.1; CCC: 6.2). Though students may reference quantitative data from the data table, it is sufficient (for qualitative relationships) to look only for whether the selected material that requires a higher-magnitude force is from a row in the data table that is below the row for the other material.

Question 2. How would doubling the external force applied to elastically deform a solid affect the amount of energy that could be transferred back out of it when the force is removed?

- *Write an evidence-based claim that answers this question. Make sure your claim references the variables in question and two materials in the data table. Use the ideas in the M-E-F poster your class developed to support your claim.*

What to look for in the student response to this question:

- The claim states how the magnitude of the forces (*cause*) acting on a material affects the amount of energy transferred into and/or out of it. (SEP: 6.1; CCC: 2.2, 5.2; DCI: PS3.B.2)
 - The predicted relationship is qualitative and accurate. Responses might look like the following examples:
 - Higher-magnitude forces would result in higher energy transfer. OR
 - Lower-magnitude forces would result in lower energy transfer.
 - Connecting matter changes to “Forces” or to “Energy” transfer for any part of the M-E-F poster. Here are three examples:
 - We determined that unbalanced forces cause energy transfer. So, a larger net force applied to a material should result in greater energy transfer into it.
 - Because higher-magnitude forces produce greater elastic deformation (a relationship stated in the reading), and changes in matter and energy happen together (a correlation stated in the M-E-F poster), there should be greater energy transfer occurring with this.
 - We saw (firsthand) that higher-magnitude forces on the foam board produced greater elastic deformation in it and also resulted in greater energy transfer out of the board (how far/fast a projectile was launched). So, if all materials share similar elastic behavior related to the changes in the matter, they should share similar elastic behavior in their energy transfers.

- **What to do:** Though the prompt asks for connections to the M-E-F poster (or a related phenomenon), such reasoning might not be readily expressible by students at this point. Treat what is included in (or left out of) this reasoning as a pre-assessment opportunity related to the use of this new tool

Question 3. If you were to extract rock samples from the plate from sites around the region *before* the crack appeared, what would you expect to see happen to those samples when they are brought to the surface? Why?

What to look for in the student response to this question:

- A claim about how the magnitude of the forces before and after the rock samples are extracted (*cause*) helps explain the expected changes in their shape (*effect*). (SEP: 6.1; CCC: 2.2)

Add a point for each of the following elements included:

1. A claim about the expected changes in the rock samples after the effect of the external forces acting on the plate is removed from the system. (SEP: 6.1)
 - The diameter of the rock samples will become smaller because the plate forces were stretching them.
2. Evidence that supports their claim. (SEP: 6.1)
 - If you look at the map, you can see that the forces where the crack showed up are pushing in opposite ways.
3. A *cause-and-effect mechanism* that links the expected changes in the rock samples and the evidence used to support these changes. (SEP: 6.1; CCC: 2.2)
 - Stuff can go back to its regular shape if it hasn't been stretched past its elastic limit. Like, if something is pulling on a piece of rock, then when that pulling stops, the rock will kind of shrink back to its normal size.
- **What to do:** Prepare a cylindrical container, such as a tube, and get a pliable material, such as a sponge or a pipe cleaner. Put the pliable material into the container to represent the rock under compressive forces. Use this as a demonstration to help students understand that when compressive forces work on a material, it can change its shape elastically, but it will bounce back once these forces stop. After that, you can ask:
 - *What kind of forces were on the plate in Afar before the crack appeared?*
 - *Were these forces pushing or pulling the rock material?*
 - *What would happen to the rocks if you take away these forces?*

Question 4. What new question(s) does this raise for you about what interactions might be happening below Earth's surface?

Examples include:

- *Are there different forces causing the differences in the motion across the plate at Afar?*
- *Are there differences in the type of material the plate is made of beneath different spots at Afar?*
- *Is the plate material at Afar stretching right now?*
- *Would rock samples taken from from the plate across different locations in the Afar region show different amounts of elastic deformation (or rebound) when brought to the surface?*
- *Is the reason a crack formed at Afar because the plate material there reached its elastic limit?*
- *How much energy was transferred out of the plate material when the earthquake at Afar happened?*
- *How long does it take to compress a plate enough to cause an earthquake?*
- *Is an earthquake the result of elastic deformation only, or is it the result of the matter reaching its elastic limit?*
- *Is the plate material beneath the surface elastically deformed right now? What if we don't typically get earthquakes where I live?*
- *Do previous breaks (fractures or cracks) in a material affect its elastic limit?*
- *Why do different types of materials have different elastic limits?*

- **What to do:** If students run out of time before they get to Question 4, remember that you will still collect their sticky note questions at the end of the lesson. One modification you can make to give them an opportunity to respond to Question 4 is to take off the third page of the handout and assign it as home learning: ask students to simply focus on Question 4 (as they have already answered Question 3), and to write their questions on sticky notes as part of the home learning, so they will be ready to share and add them to the Driving Question Board in the next class period. This use of their responses will be more motivational than typical home learning assignments.

Lesson 4 Teacher Reference

How to Create Electronic Exit Tickets

What are Electronic Exit Tickets?

These are short **formative** assessments that occur 2-3 times per unit, between other assessments. They include items to check for understanding of LLPEs, to make connections between content and students' lives, to elicit information about students' experiences, and to help them reflect on their own progress in focal SEPs and CCCs. **These exit tickets are built in Google Forms, but can be ported to any survey software.**

How to create Electronic Exit Tickets

In *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*, the unit's Electronic Exit Tickets are found:

- at the end of Lesson 2
- at the end of Lesson 4
- at the end of Lesson 7

Select the link for the Electronic Exit Ticket that corresponds with the lesson you are teaching:

- Lesson 2 Community Agreements Electronic Exit Ticket: https://docs.google.com/forms/d/1AB7Onbf_9qGMfkD1hqN7sARigc-ssTOjD1wHTY5izfA/copy
- Lesson 4 Electronic Exit Ticket: https://docs.google.com/forms/d/1d7mdn_MMObL_bFfLV3eRkazg-AETeohRiBhXX7Z7sDE/copy
- Lesson 7 Electronic Exit Ticket: <https://docs.google.com/forms/d/17GF27o2OWj5tnVHBuE9KXf7dqzpotb-ZZnJ7lUncOvs/copy>

Spanish versions are available here:

Lesson 2: <https://docs.google.com/forms/d/1VLhrPjlz3DLLwO32KOUEEkc01IV4ZcZVMTDdxbY7ME/copy>

Lesson 4: https://docs.google.com/forms/d/1H6YLjdr3_35EF_yAn4e4LbczrgZY70lO2dSTgRUIFPk/copy

Lesson 7: https://docs.google.com/forms/d/1hOXDoQ8-GJOicobl82n8i7zY5lumD7cZ7_Fljm5q4g/copy

Attending to Equity

Some students may benefit from completing the Electronic Exit Ticket on a printed version. Complete the steps below to create a digital copy of the Electronic Exit Ticket. Once you have created a copy in your own Google Drive, click on the three dots in the upper right side of the form next to the SEND button. This should give you an option to print a paper copy of the Electronic Exit Ticket.

When you select the link, it will ask you to make a copy in your own Google Drive.

Copy document

Would you like to make a copy of **Family and Friends MRE Survey**?

Make a copy



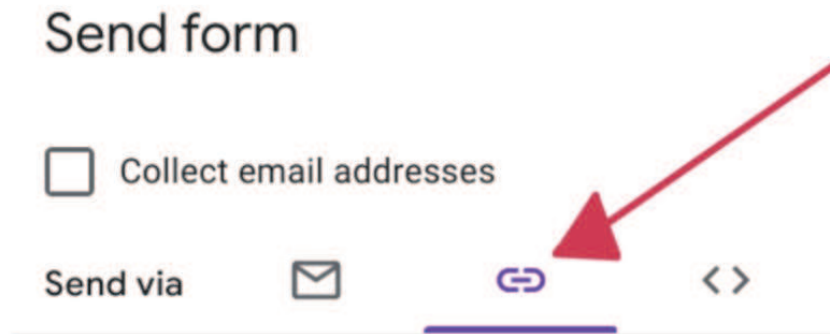
The student survey will open in your own Google Drive.



Select the “Send” button in the upper right corner to get a link to give to students.



In the “Send via” panel, select the middle icon to choose to send the survey via a link.



Copy the link it provides you or select the “Shorten URL” box and then copy the link. This second option creates a link that will be easier for students to type.

Link

<https://forms.gle/9YFjGS5FQhY3P7VR6>



Shorten URL

Press Ctrl+C to copy

Cancel

Copy

Once students submit responses, they will show up in your Google Form under “Responses”. Google will automatically provide you with some visualizations of these responses.

Questions

Responses

0 responses



Accepting responses 

Waiting for responses

If you want to see the data in a spreadsheet format, click the sheet icon to create a Google Sheet of your data. It will automatically populate when students respond to the survey.

For each Electronic Exit Ticket you create, you will need to repeat the process above. You can choose to make a separate ticket for each class or use the same one for all your classes.

Lesson 4: Answer Key 1

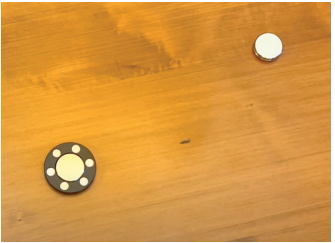
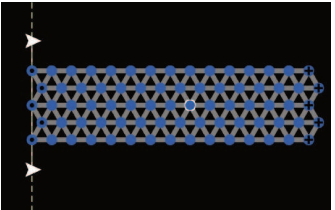
Evaluating Models Key

Every model has advantages (merits) and limitations. Understanding what these are can allow us to move more flexibly between different types of models, which can help us develop a more complete explanation of how and why phenomena occur.

What types of phenomena will we be trying to explain with the different models below?

Earthquakes, elastic deformation, breaking/crack, volcanic eruptions

	Which frame(s) are you using to evaluate this model?	What are some advantages (merits) of this model?	What are some limitations of this model?
Model 1 2 foam panels slipping/breaking 	☐ Stability or change over time or space ☐ Thinking across different scales ☐ Cause and effect in M-E-F relationships	• It allows us to see some changes near the boundaries--breaking in particular, like we see on Earth--fault lines. • We can test (and have tested) the effect of external forces on matter in different directions. • The foam's structure approximates our model of two plates. • We can see evidence of energy transferred into/out of the matter. • We can see the system go from stable to changing and back again.	• It is at a different scale--much smaller than Earth plates. • The elastic deformation is still at a very small scale. We would need to slow down the video and zoom in to see it. We can't see what actually breaks and when (too fast). • We cannot see the particle-level changes. • We cannot see where energy is stored in the matter.

Model 2 Inverter magnets 	☐ Stability or change over time or space ☐ Thinking across different scales ☐ Cause and effect in M-E-F relationships	• We can understand that two kinds of distance forces (repulsion and attraction) act on two bonded particles. • Magnetic and electric fields have a similar magnitude versus distance relationship--getting weaker with distance (but never reaching zero like Coulomb's law). • It helps us understand the particles that produce these forces (protons and electrons). • It helps us use net force thinking at a particle level to explain why the bond is a certain length and goes back to that length when the distance changes a little bit. • It helps us better explain why matter returns to its original shape after it has been elastically deformed and external forces are removed. • It helps us better explain how energy is transferred into/out of matter that is elastically deformed. • It helps us visualize that breaking a bond is a result of moving two particles far enough apart, which is related to reaching an elastic limit.	• We cannot use it directly to test our ideas. • Not all matter is magnetic. • Matter has more than two particles. • It seems hard to measure force magnitudes or energy with this model. • It is at a different scale--much smaller than Earth plates.
Model 3 Particle-Level Simulation (optional)  Wilensky, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL	☐ Stability or change over time or space ☐ Thinking across different scales ☐ Cause and effect in M-E-F relationships	• We can measure and study the net force acting on particles. • We can see changes in energy and how they relate to changes in deformation. • We can change the timescale (slow down or speed up). • We can collect data quickly. • We can study various changes in matter, including changes in shape and breaking.	• We cannot investigate the role of temperature. • There are probably other factors affecting real materials that are not simulated.

Particle Investigations Key

Part 1. Plan Investigations with the Simulation

Circle one of these independent variables you want to explore in the simulation:

- Material
- Sample length
- Sample thickness
- External force

What dependent variable(s) do you want to measure? Energy stored, highest net force, and/or deformation

Why would it be important to keep the other variables constant in your investigation?

- Because those variables can affect the values I am interested in. For instance, the type of material might influence how it responds to forces.
- If I don't keep those variables constant, the observed results can be due to the effect of variables different from my independent variable.

What to do: If students struggle to explain why it is important to keep the other variables constant, you can ask them: *How will you determine whether the results you observe are a result of changing your independent variable, rather than the other variables that you are also changing?*

Part 2. Carry Out Investigations:

Investigation 1. (4 minutes) Carry out your investigation and record your results for each condition you test in the table below.

Investigation 1 aims to engage students in the use of an independent variable (sample material, sample length, sample thickness, and magnitude of external force) for planning and conducting an investigation that can provide evidence about particle-level interactions. This evidence will support explanations about changes in matter, energy, and forces within Earth systems.

Investigation 2. (4 minutes) Rerun any of the prior conditions you tested until the matter reaches a new stable state. Then press REMOVE EXTERNAL FORCE. Record the changes you notice happening to the matter and energy stored in the system in the table below.

The goal of Investigation 2 is to help students consider energy storage and transfer out of the system when external forces are removed from it. This is an important part of the causal story behind the energy release in an earthquake.

Investigation 3. (3 minutes) Switch scales: select a single particle in the solid to inspect as you repeat Investigation 2. Record the changes you notice in the forces and the net force on a single particle over time as the matter transitions from one stable state to another in the table below.

The goal of Investigation 3 is to consider the changes in the net force experienced by a particle during stability and change cycles. This helps students see all shape changes and breaks in matter as another type of change in motion (at a smaller scale).

Investigation 4. (3 minutes) Find a state in which the matter goes just beyond its elastic limit. Record the changes you notice happening in the particles in the matter when this happens in the table below.

Investigation 4 is intended to help students observe how bond breaking is a form of force removal from within the matter. Seeing that this leads to a force imbalance at a particle level can help account for why larger macroscopic changes build up from this at the macroscopic level (e.g., permanent deformation, cracking, breaking apart).

What to do:

- Provide multiple means of representing these findings. In Investigation 1, students can record both qualitative and quantitative data. They can also use tables or graphs. If they record only quantitative data, encourage them to write a conclusion summarizing their findings. If they include only qualitative

data, encourage them to support their ideas with a couple of data points. For Investigations 2-4, which are brief, encourage students to record several observations at the very least.

- Adjust the simulation speed using the setting located at the top. Some students with disabilities might benefit from using a lower speed to more easily track changes in the system.
- For students who could benefit from added challenges or additional practice, encourage them to develop an additional investigation to test a different independent variable.

Observations/Data

Investigation 1 Sample investigation using external forces as the independent variable Controlled variables: material (= A); initial width (= 7); initial length (= 16) <table><tr><th>EF</th><th>ES</th><th>D</th><th>NF</th></tr><tr><td>-4</td><td>195</td><td>0.56</td><td>0.51</td></tr><tr><td>-2</td><td>62.6</td><td>0.353</td><td>0.23</td></tr><tr><td>2</td><td>82.3</td><td>0.473</td><td>0.32</td></tr><tr><td>4</td><td>246.2</td><td>0.763</td><td>0.74</td></tr></table> EF = external force ES = energy stored at new stable state D = deformation NF = largest net force experienced by particle The larger the force acting on the material, the more energy is stored, the more deformation, and the larger the highest net force experienced by particles.	EF	ES	D	NF	-4	195	0.56	0.51	-2	62.6	0.353	0.23	2	82.3	0.473	0.32	4	246.2	0.763	0.74	Investigation 2 • The matter goes back to its original shape. • The matter vibrates a bit. • The distance between particles goes back to the original distance. • There is a peak in deformation and energy stored in the electric fields.
EF	ES	D	NF																		
-4	195	0.56	0.51																		
-2	62.6	0.353	0.23																		
2	82.3	0.473	0.32																		
4	246.2	0.763	0.74																		
Investigation 3 • The forces are balanced at first (net force is zero). • The net force acting on the particle increases once the force is removed, and slowly goes back to zero again. • The forces are balanced at the end (net force is zero) in its new shape (or old shape) once the object is stable again.	Investigation 4 • The forces go much higher. • The net force is never zero, only after the matter breaks. • The bonds between some particles break. • The distance between particles increases a lot. • Chunks of matter fly apart!																				

Electronic Exit Ticket Key

This Electronic Exit Ticket addresses 3D elements associated with a lesson-level performance expectation (LLPE) for Lesson 4. This assessment is designed to make it easy to gather information about where your students are still struggling to put the pieces together.

The relevant LLPE is:

4.B Use a computational model to explore stability and change and cause and effect relationships between the magnitude of external forces acting on a solid, the changes in matter given its mass (number of particles), and the changes in energy in the system across different scales. (SEP: 2.3; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS3.B.2, PS2.B.3, ESS2.B.2)

The elements of the LLPE assessed in this exit ticket are:

3D Elements Addressed in the Assessment	1	2	3	4	5
2.3 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
7.1 Stability and Change. Much of science deals with constructing explanations of how things change and how they remain stable.			X		
2.2 Cause and Effect. Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system.	X	X			
From the framework: Understanding the forces that drive the transformations and cycles within a system, as well as the forces imposed on the system from the outside, helps predict its behavior under a variety of conditions.				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
PS2.B.3 Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects. (HS-PS2-6), (secondary to HS-PS1-1), (secondary to HS-PS1-3)	X	X			

Question 1

Interactions between these two plates transfer energy into the rock near the boundary. This causes pockets of rock to melt and become magma. Gases in the hot magma put pressure on the solid rock above as a result of particle collisions. The upward force from this pressure can cause the crust to deform over time, and eventually break, allowing magma to reach the surface.

Which **interactions** at the particle scale do we need in order to explain why the crust above the magma will break, allowing magma to reach the surface? (CCC: 2.2; DCI: PS2.B.3)

- The **repulsion due to electric forces (bonds) between the particles of rock will weaken when the particles are forced apart by the upward forces.**
- The **attraction due to electric forces (bonds)** between the particles of rock will get stronger when the particles are forced apart by the upward forces.
- The **attraction due to gravity** between the particles of rock and Earth will get stronger when the particles are forced apart by the upward forces.
- The **repulsion due to gravity** between the particles of rock and Earth will weaken when the particles are forced apart by the upward forces.

What to look for:

The correct answer is: **The repulsion due to electric forces (bonds) between the particles of rock will weaken when the particles are forced apart by the upward forces.**

What to do:

- Encourage students to look back in their *Progress Tracker* to find the particle-level models they made in Lessons 2-3.
- If a large number of students select other answers, consider discussing this question as a class, exploring the force interactions described in each option.

Question 2

Using this model, which of the following do you predict about stability and change in the system at this scale? (SEP: 2.3; CCC: 7.1)

- There are many forces acting on the matter at this scale, so the system will be unstable.
- **The forces on each cube of matter are roughly balanced at this scale, so the system will be stable.**
- The upward forces from the magma are much stronger than the forces from the weight of the rock at this scale, so **the system will be unstable.**
- There are no forces acting on the system, so **the system will be stable.**

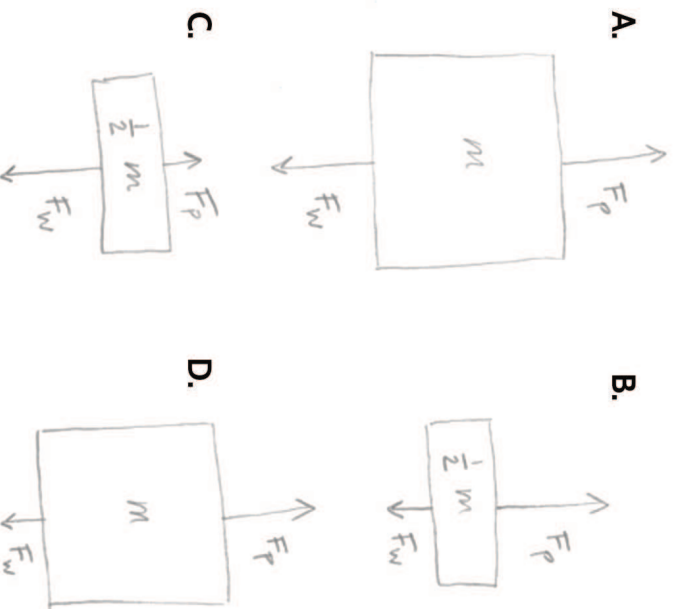
What to look for:

The correct answer is: **The forces on each cube of matter are roughly balanced at this scale, so the system will be stable.**

What to do: Encourage students to estimate the net force acting on the blocks according to this model. Then encourage them to look for ideas related to stability and change in the M-E-F poster.

Question 3

The physics student made a new model to represent one of the cubes of mass on the volcano in the minutes **after** the landslide, but **before** the explosion.



Which of the **free-body diagram** models above can help explain why the landslide triggered the explosion? (SEP: 2.3; **framework understanding**)

What to look for:

The correct answer is: **B**

What to do: Encourage students to consider the changes in matter first. Then ask them to consider whether those changes could result in changes in any of the forces acting on a block of matter, as represented in Question 2.

Question 4

Use the model you chose to explain what might have happened to trigger the explosive **transfer of energy** after the landslide. (SEP: 2.3; DCI: PS3.B.2)

- The magnitude of the forces upward from the magma became larger (F_p). The resulting unbalanced forces upward from the magma transferred energy out of the system.
- The magnitude of the force downward from the weight of the crust (F_w) became larger. The resulting unbalanced forces downward transferred energy out of the system.
- The magnitude of the forces upward from the magma became smaller (F_p). The resulting unbalanced forces downward transferred energy out of the system.
- The magnitude of the forces downward from the weight of the crust (F_w) became smaller. The resulting unbalanced forces upward from the magma (F_p) transferred energy out of the system.

What to look for:

The correct answer is: The magnitude of the forces downward from the weight of the crust (F_w) became smaller. The resulting unbalanced forces upward from the magma (F_p) transferred energy out of the system.

What to do: Encourage students to estimate the net force acting on the block in each of the free-body diagram models from Question 3. Then ask them to select the model that would explain an explosion, and use it to find the answer that better describes that model.

Question 5-7

Geysers, landslides, and ice chunks breaking off of a glacier are all processes on Earth's surface that happen very suddenly, like volcanic eruptions do. Choose one of these processes that you think you could explain using ideas from the M-E-F triangle.

- Geysers that erupt every few hours
- Landslides right after a rainstorm
- Ice chunks breaking off of a glacier a few days after the warmest month on record

Which lens(es) would be the most useful to explain why the process you chose could occur so suddenly after a long period of no change?

- Stability and change over time or space
- Cause and effect
- Thinking at/across different scales

How could the lens(es) you chose help you explain the process you chose?

What to look for:

Do not assign a score to Questions 5 and 6. For Question 7, look for students to explain why crosscutting concepts like stability, change, and scale are useful for explaining sudden changes to systems that typically change very slowly over time. Examples include:

- Stability and change is important for explaining geysers because they are very stable for a few hours, and then they suddenly change.
- Cause-and-effect is important for explaining landslides, because a storm probably caused something to happen, and that caused something to happen, and the effect was a landslide, and we need to know how in order to explain the landslide.
- We need scale and stability and change to explain ice chunks, because the glaciers have been through changes in temperature over a long time, but the change was so much bigger last month that a chunk broke off.

What to do:

- Encourage students to use a lens they have used in their *Progress Tracker* and a lens they have not used before.
- Because these questions are not scored, students might feel motivated to take risks.
- Examine the distribution of students who selected each of the lenses. This will provide you with an idea of the lenses your students are feeling more comfortable with and the ones for which they might need additional scaffolding.

Question 8

Over the course of our Lesson 4 investigations, who helped push your thinking forward? What did that person do to push your thinking?

What to look for:

Do not assign a score to this question.

What to do: Identify a few examples of how a student pushed others' thinking that you think might be worth sharing with the class as an example of productive and positive interactions that benefit the work of the classroom community. Avoid mentioning student names, as some might feel uncomfortable being on the spot.

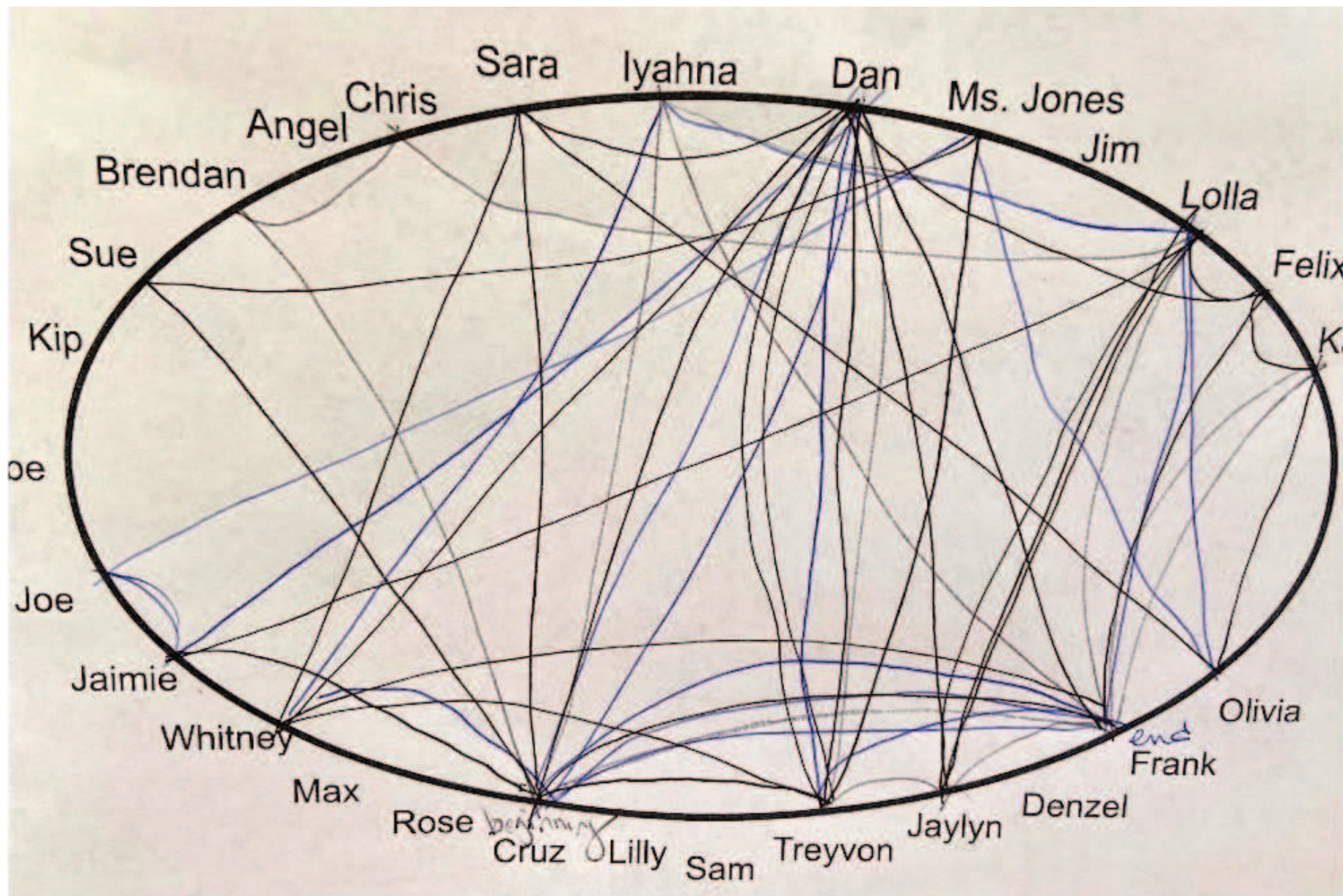
Lesson 7 Teacher Reference

Discussion Mapping Tool

Discussion Mapping Procedure

1. Print one copy of the second page of this tool for each class.
2. Add students' names to the circle in the order that students are sitting. Alternatively, you may want to write students' names on the circle ahead of time and then ask them to sit according to the map.
3. Write the question that we are trying to answer at the top of the page.
4. Select a student mapper who will map the discussion as it happens. Decide ahead of time whether you will have students take turns mapping, and when you will move the map to a new student mapper.
5. If this is the first time you are using a discussion map, explain to students that each time someone speaks, the recorder will draw a line from the previous speaker's name to the new speaker's name. You may want to mark where the conversation begins and ends, but the goal is to map the overall conversation patterns rather than to be able to retrace the entire conversation.
6. Once the discussion begins, have students take the lead in moving it forward. You may decide to sit in the circle as a participant rather than standing in front of the class as a facilitator. This allows students to practice building on each other's ideas directly. You may also take a recorder role, keeping track of student ideas.
7. Be mindful of group dynamics, especially when displaying the map and discussing patterns of contributions. Avoid focusing on the contributions of single students, and instead redirect the class to notice class-level patterns.

An example of a completed discussion map is shown below:



The key at the bottom of the map contains codes that can be used to label the types of student contributions. The first few times that you create a discussion map with the class, you should focus only on recording the flow of the conversation. This allows students to get comfortable with the process. Once they have experience recording and interpreting those initial patterns, you can use the discussion mapping codes in future maps. There is an extra column for adding your own discussion codes as needed, based on individual class needs and agreements. You may also choose to use only some of the codes, based on the type of discussion your students are having. In this case, be sure to cross out the codes you are not using in the key, so the student recorders know not to include them.

Key Ideas

There is space on the tool to list up to three key ideas that emerge from the discussion, so the class can keep track of them. If you choose to use codes to annotate student contributions, you can also use the codes “1”, “2”, and “3” to map when those key ideas are talked about.

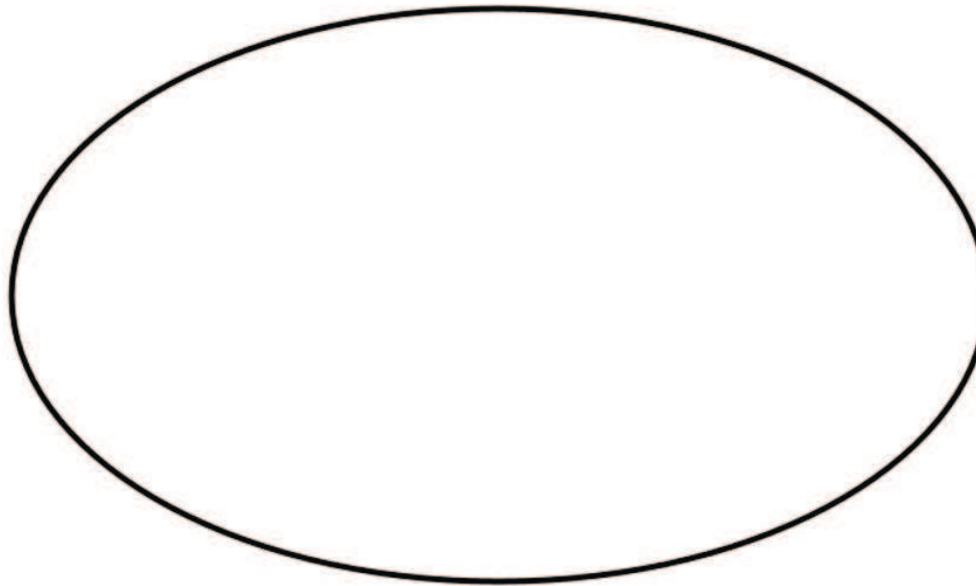
Question we are trying to answer:

Directions:

Write your students names around the circle, according to where they are sitting in the room.

Tip:

Find a landmark for you and add it to your image!



Key Idea 1:

Key Idea 2:

Key Idea 3:

Discussion Mapping Codes					
C - claim given	CL - clarified idea	? - asked question	T - tied ideas together	I - interrupted	1- Key Idea 1
E - gave evidence	A - affirmed/agreed	NI - new idea added	RP - related phenomena		2- Key Idea 2
OT - off topic	D - disagreed	R - repeated idea	* - idea ended		3- Key Idea 3

Lesson 7: Answer Key 1

Cause-Effect Model Key

Building toward: 7.A Construct a cause-effect explanation for how radioactive decay provides the heat that drives mantle convection using ideas from our previous investigations, new evidence from a set of complementary readings, and the assumption that our past observations about matter, energy, and forces hold true across contexts. (SEP: 6.2; CCC: 2.2; DCI: ESS2.B.1, PS3.A.2, PS2.B.2, PS1.C.1)

3D Elements Addressed in This Assessment	
SEPs	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.
	Obtaining, Evaluating, and Communicating Information. Compare, integrate and evaluate sources of information presented in different media or formats (e.g., visually, quantitatively) as well as in words in order to address a scientific question or solve a problem.
CCCs	Cause and Effect: Mechanism and Prediction. Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system.
DCIs	ESS2.B.2 The radioactive decay of unstable isotopes continually generates new energy within Earth's crust and mantle, providing the primary source of the heat that drives mantle convection. Plate tectonics can be viewed as the surface expression of mantle convection. (HS-ESS2-3)

	Foundational Pieces	Linked Understanding	Organized Understanding
3D Elements	In this cause-effect model, look for: Students include ideas about matter, energy, and/or forces. Students list some of the science ideas in purple in the key below.	In this cause-effect model, look for: Students integrate ideas about matter, energy, and/or forces into a single row. Students string together some ideas coherently, so that the effects described in one row are related to or integrated into the cause listed in the next row. Students list some of the science ideas in purple in the key below.	In this cause-effect model, look for: Students integrate ideas about matter, energy, and forces throughout the table. Students string together ideas coherently, so that the effects described in one row are related to or integrated into the cause listed in the next row. Students list most or all of the science ideas in purple in the key below.
Example	See key below.		
Feedback/ What to Do	<i>Linking:</i> When reviewing students' handouts at the end of day 1, use the key below to provide feedback that better supports students' construction of the cause-effect model. Ask clarifying questions to encourage them to think about the mechanisms that will be important links in the chain, such as, <i>What else is going on in the system that might cause this more directly?</i> During the Scientists Circle, use the key to point students to places in the reading where they can find important science ideas that may not have made it into the model.	<i>Organizing:</i> When reviewing students' handouts at the end of day 1, use the key below to provide feedback that better supports students' construction of the cause-effect model. Point to places where students have left out "because" clauses. During the Scientists Circle, use the key to point students to places in the reading where they can find additional links in the chain.	<i>Extending:</i> Ask students to link the diagrammatic model they created to the cause-effect chain.

- Below is an example of a completed cause-effect table. In the more highly scaffolded version of the handout, the text in blue is provided. In both versions, the text in black is provided. Students do not need to match every detail in every box. They may use different words, or a different combination of frames (energy, forces, matter).
- The words in red are suggestions of where the class might identify the frames from the M-E-F triangle during the Consensus Discussion in a Scientists Circle on day 2.
- Some causes may have multiple effects or vice-versa. If this comes up, make this explicit during the Consensus Discussion.
- If students struggle with an idea, ask them to go back into the readings together as a Jigsaw group to look for missing puzzle pieces. The questions from the readings (or review from previous lessons) that will help scaffold students' responses are included in this key above each row, in gray. Use these to help direct students toward these answers if they are struggling with a row, during either the Jigsaw or the Consensus Discussion.

Forces Q1: How does the size of the atom cause the forces to be either balanced or unbalanced?				
1	Larger atoms (or unstable nuclei) (<i>MATTER</i>)	causes	<i>the forces to be unbalanced (FORCES)</i>	because the particles in the nucleus (protons and neutrons) (<i>MATTER</i>) are farther away from each other, so the strong force will be weaker than the E-M force (<i>FORCES</i>).
Forces Q2: What is the effect on the protons and neutrons in the nucleus when the forces become unbalanced, and why?				
2	<i>Unbalanced forces (FORCES)</i>	causes	protons and neutrons (<i>MATTER</i>) to be released from the nucleus, or electrons (<i>MATTER</i>)	because the forces (<i>FORCES</i>) holding them together won't be as strong anymore as the forces (<i>FORCES</i>) pushing them apart.
Matter Q1: How can radioactive decay cause the atom to become smaller, and change its properties?				
3	Particles leaving the nucleus (<i>MATTER</i>)	causes	<i>the atom to change (MATTER) into a new atom in a predictable way</i>	because every atom has a unique atomic number that determines what element it is (<i>MATTER</i>).
Matter Q2: How do particles leaving the nucleus cause energy to be transferred out of the system?				
4	Particles leaving the nucleus (<i>MATTER</i>), or energy transfer out of the nucleus (<i>ENERGY</i>), or the atom changing	causes	<i>particles with high kinetic energy to move into the space between atoms (KE=1/2mv²) (ENERGY)</i>	because the energy that was in the mass of the nucleus is now in the kinetic energy of the escaping particles (<i>ENERGY</i>) (optional: and the recoil of the nucleus itself).
Energy Q1: When mass is converted into energy in the atomic nucleus, where does energy transfer, and why?				
5	The high-kinetic energy particles leaving the nucleus	causes	<i>collisions with surrounding atoms (MATTER)</i>	because the neutrons and protons move fast and collide with other atoms (<i>MATTER</i>).
Energy Q2: What happens to the surrounding atoms when particles leaving the nucleus collide with them?				
6	<i>Particles colliding with the surrounding atoms (MATTER)</i>	causes	heating of surrounding particles (vibrating particles, thermal energy, particles with high average kinetic energy) (<i>ENERGY</i>)	collisions transfer energy. The kinetic energy of the escaping particles transfers into the vibration of the surrounding particles when they collide (thermal energy) (<i>ENERGY, MATTER</i>).
Lessons 6 and 7 review				
7	Heat from radioactive decay (<i>ENERGY</i>)	causes	<i>material from the mantle to move upward into the crust, and material from the crust to move down into the mantle (MATTER)</i>	because parcels of hot material are less massive per volume, so cooler material higher up is pulled down, pushing the hot material up--this is called convection (<i>MATTER</i>).

Lesson 7: Answer Key 2

L7 Electronic Exit Ticket Key

This Electronic Exit Ticket addresses 3D elements associated with a lesson-level performance expectation (LLPE) from Lesson 7. This assessment is designed to make it easy to gather information about where students are still struggling to put the pieces together.

The relevant LLPE is:

7.A Construct a cause-effect explanation for how radioactive decay provides the heat that drives mantle convection, using ideas from our previous investigations, new evidence from a set of complementary readings, and the assumption that our past observations about matter, forces, and energy hold true across contexts. (SEP: 6.2; CCC: 2.2, 3.3; DCI: ESS2.B.1, PS3.A.2, PS2.B.2, PS1.C.1)

The elements of the LLPE assessed in this exit ticket are:

3D Elements Addressed in This Assessment	1	2	3	4	5
6.2 Constructing Explanations and Designing Solutions. Construct and revise an explanation based on valid and reliable evidence obtained from a variety of sources and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future.	X	X	X		
2.2 Cause and Effect. Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system.				X	
ESS2.B.1: Plate Tectonics and Large-Scale System Interactions. The radioactive decay of unstable isotopes continually generates new energy within Earth's crust and mantle, providing the primary source of the heat that drives mantle convection.			X		
PS1.C.1: Nuclear Processes. Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process. (HS-PS1-8)			X		
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)	X	X		X	
PS2.B.2 Types of Interactions. 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			

Questions 1 and 2

What physics principle best describes how Jupiter's gravity could cause sufficient heat in Europa's interior to fuel volcanism?

- Energy transfer and matter changes happen together.
- Unbalanced forces transfer energy.
- Fields generated by matter result in forces.

Explain how the principle you chose could describe how Jupiter's gravity causes heat in Europa's interior. (SEP: 6.2; DCI: PS3.A.2, PS2.B.2)

What to look for:

Accept all responses to Question 1. Then look for students to use the principle they selected to explain the mechanism by which Jupiter heats Europa's interior.

- If students chose "energy transfer and matter changes happen together", they should explain that as Europa stretches and compresses (a change in matter), energy transfers into the matter.
- If students chose "unbalanced forces transfer energy", they should explain that Jupiter's gravitational forces must be stronger than the electric forces keeping the matter on Europa together, transferring energy.
- If students chose "fields generated by matter result in forces", they should explain that Jupiter's gravitational field causes forces, or that forces generated by the matter of Europa change as the matter flexes, which could transfer energy.

What to do: Point students to the M-E-F triangle, and ask them to consider other examples that describe these mechanisms.

Question 3

Unlike Europa, at least half of the heat in Earth's interior is caused by radioactive decay. The cause-effect mechanism driving this process can be described by:

1. Larger atoms cause the balance of forces holding a nucleus together to be unstable, because the particles in the nucleus are farther away from each other.
2. When the strong force is weaker than the E-M force, the unbalanced forces transfer energy.
3. Radioactive decay causes a particle to be suddenly released from the nucleus, which restores the balance.

Which of the following best describes the next step in this cause-effect explanation? (SEP: 6.2)

- **The particles leaving the nucleus collide with surrounding atoms, transferring energy in the form of heat.** (DCI: ESS2.B.1, PS1.C.1)
- The particles leaving the nucleus collide with surrounding atoms, pushing them upward toward Earth's surface.
- The particles leaving the nucleus collide with surrounding electrons, causing an electric current.

What to look for:

The correct answer is: **The particles leaving the nucleus collide with surrounding atoms, transferring energy in the form of heat.**

What to do: Encourage students to refer to the class's consensus cause-effect model, by pointing them to either the public record or the copy in their science notebook.

Question 4

Cause-and-effect relationships can be suggested and predicted for complex natural systems by examining what is known about smaller-scale mechanisms within the system. If NASA's Clipper mission finds evidence of volcanoes on Europa's seafloor, which cause-effect relationship does this suggest for life on this moon of Jupiter? (CCC: 2.2)

- Radioactivity in Europa's core -> energy transfer in Europa's mantle -> convection -> underwater volcanoes -> plate tectonics -> a mountainous terrain that can sustain life
- Jupiter's gravitational pull -> Europa stretches and compresses -> energy transfer in Europa's mantle -> underwater volcanoes -> chemical energy produced by the interaction of magma and seawater sustains life (DCI: PS3.A.2)
- Underwater volcanoes -> energy transfer in Europa's mantle -> Jupiter's gravitational pull -> chemical energy produced by the interaction of magma and seawater sustains life

What to look for:

The correct answer is: Jupiter's gravitational pull -> Europa stretches and compresses -> energy transfer in Europa's mantle -> underwater volcanoes -> chemical energy produced by the interaction of magma and seawater sustains life

What to do: This question requires students to link ideas about a process they have not learned about before. Support them by asking them to reread the paragraph above and underline anything they see that links a cause to an effect. Ask them to list these underlined clauses in order, and then look for the answer that matches their list.

Question 5

Radioactivity drives mantle convection deep inside Earth. But there is also naturally occurring radioactive material on Earth's surface, and humans use radioactive materials in technology. Where else have you heard about radioactivity occurring naturally or being used?

What to look for:

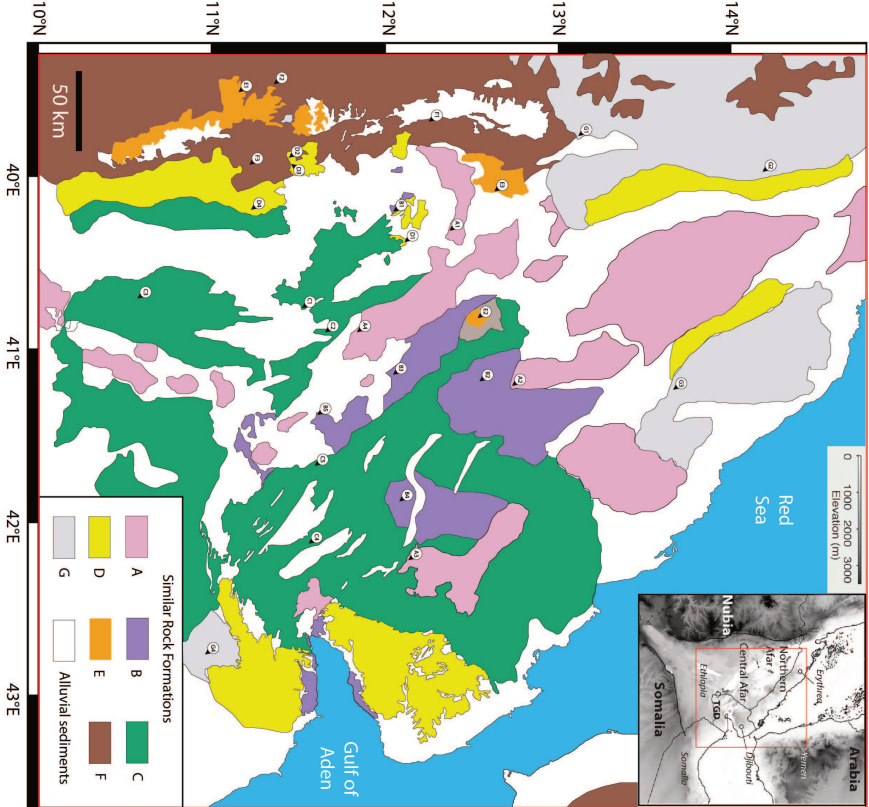
Listen for students to mention:

- nuclear power plants
- medical technologies, such as tracers and cancer therapy
- nuclear weapons
- radon mitigation systems

What to do: Accept all ideas. This is an opportunity for students to expand their thinking about radiation to related phenomena, and is not meant to be scored.

Site Location Modifications

The image on the right is used on slide E and in the *Age of Rocks* handout. It is a redrawn image that represents an approximation of the two maps in *Modes of rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar*. One of the maps used for this approximation is Figure 1 on page 4. That map covers 4 or more degrees of latitude and longitude. The second map used for this approximation is Figure 2 on page 6. It is a smaller-scale map that covers close to 1 degree of latitude and longitude. The locations of all the sample sites are based on best estimates of where they are located in Figure 6, except for these: G1, G2, G3, and G4. These last four sites were added by the authors of the lesson for educational purposes of the field test. The OpenSciEd development team intends to do further research on these to find published site locations for equivalent samples for the public release. The related radiometric composition of those samples for those sites is as cited in *Zircon U–Pb ages, $\delta^{18}O$ and whole-rock Nd isotopic compositions of the Dire Dawa Precambrian basement, eastern Ethiopia: Implications for the assembly of Gondwana*.



The table to the right is used on slides F, G, N, EE, and HH, as well as in *Rock Transformation Process*. It includes data from four samples reported in Table 1 on page 10 and two samples reported in Table 2 on page 11 of *Modes of rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar*. The first five samples had 2–3 aliquots that are measured and reported in the original paper. The measurement for the first aliquot listed is the only one included in the table to the right. Potassium (K–40) concentration is reported under a column heading of K (wt %) in table 1 in the original paper, rather than K–40 (ppm). This was converted by this relationship: ppm = 10,000 x % wt to provide a consistent unit for the last two columns. For example, in the original table sample, AF12–O2 is reported as K–40 (wt %) of 1.167, whereas in this table, that value is reported as K–40 (ppm), which is 11,670.

		Radioactive elements	
Sample	Label	K–40 (ppm)	U–238 (ppm)
AF12–O2	C1	11,670	N/A
AF12–11	D1	1260	N/A
AF13–98	D2	890	N/A
AF13–102	E3	5650	N/A
AF12–15	B1	N/A	163.58
AF12–21	D3	N/A	216

Lesson 8 Teacher Reference

Rock Composition Modifications

The first and fifth columns of data in the table below are derived from the age of the rock reported in Table 1 on page 10 of *Modes of rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar*. The ages reported in the article are based on measured amounts of K-40 and Ar-40 for the samples shown here. The calculated columns were derived by the OpenSciEd authors of this lesson, using a known half-life for K-40 to Ar-40 of 1250 million years.

Sample	Label	Calculated: extrapolated for educational purposes in this lesson		Reported	Summary of accuracy of the data students are using	
		Ratio of K-40 / Ar-40	Ratio of K-40 now / K-40 at formation	Age of rock (mya)	Label location of this sample shown on map is accurate	Ratio of these two elements is exact or is simplified based on other results
AF12-02	C1	624.00	0.99840	2.89	yes	Simplified based on other results
AF12-11	D1	399.00	0.99750	4.51	yes	Simplified based on other results
AF13-98	D2	218.78	0.99545	8.23	yes	Simplified based on other results
AF13-102	E1	73.404	0.98656	24.4	yes	Simplified based on other results

The first and fifth column of data in the table below are reported in table 2 on page 11 of *Modes of rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar*. The ages reported in the article were based on measured amounts of U-238, Th-232, Sm-147, and He-4, for the samples presented here. The authors of this lesson recalculated the data based on the known half-life of U-238 to He-4, which is 4,500 million years, and they disregarded the contribution of any other intermediate decay products. This simplification was made so students can use the results of their investigation to calculate the estimated age of these rocks themselves, based on a single radioactive parent/daughter decay relationship.

Sample	Label	Calculated: extrapolated for educational purposes in this lesson		Reported	Summary of accuracy of the data students are using	
		Ratio of U-238 / He-4	Ratio of U-238 now / U-238 at formation	age of rock (mya)	Label location of this sample shown on map is accurate	Ratio of these two elements is exact or is simplified based on other results
AF12-15	B1	1611.9	0.99938	4.0	yes	Simplified based on other results
AF12-21	D3	868.57	0.99885	7.5	yes	Simplified based on other results

The first, second, and fifth columns of data in the table below are values reported from the map and related key (Figure 2) on page 6 of *Modes of rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar*. The key cites the original published study for the sites chosen for the related student activity sheet. That original published study is included as a reference below. All the original published studies appear to have used the K-40/Ar-40 decay dating method, except for the F2* site, which used an Ar-40–Ar-39 dating method. For the purposes of the student activity, the reported age of rock was converted to an equivalent age based on a ratio of K-40/Ar-40 to reduce the complexity of the data analysis. In the revision, this may end up being replaced with an equivalent K-Ar ratio as time permits, to find a related rock sample site reported in the research base using this method. The calculated columns were derived by the OpenSciEd authors of this lesson, using a known half-life for K-40 to Ar-40 of 1250 million years.

Citation made to this other source	Site label	Calculated: extrapolated for educational purposes in this lesson		Reported	Summary of accuracy of the data students are using	
		Ratio of K-40 / Ar-40	Ratio of K-40 now / K-40 at formation	age of rock (my)	Label location of this sample shown on map is accurate?	Ratio of these two elements is exact or is simplified based on other results
Kuntz et al., 1975	D4	294.86	0.99662	6.1	yes	Simplified based on other results
Barberi et al., 1975	E3	78.618	0.98744	22.8	yes	Simplified based on other results
	E2	71.622	0.98623	25.0	yes	Simplified based on other results
Coulié et al., 2003	F1	61.267	0.98394	29.2	yes	Simplified based on other results
	F3	57.824	0.98300	30.92	yes	Simplified based on other results
Ukstins et al., 2002	F2*	60.387	0.98371	29.61	yes	Simplified based on other results
Kidane et al., 2003	B3	2271.7	0.99956	0.79	yes	Simplified based on other results
	B4	2126.7	0.99953	0.84	yes	Simplified based on other results
	C2	924.93	0.99892	1.94	yes	Simplified based on other results
	C5	883.96	0.99887	2.03	yes	Simplified based on other results
Lahitte et al., 2003a & 2003b	A1	6249.0	0.99984	0.290	yes	Simplified based on other results
	A2	6249.0	0.99984	0.290	yes	Simplified based on other results
	A3	5554.6	0.99982	0.332	yes	Simplified based on other results
	B2	1885.8	0.99947	0.959	yes	Simplified based on other results
	B5	3845.2	0.99974	0.489	yes	Simplified based on other results
	C3	557.65	0.99821	3.222	yes	Simplified based on other results
Lahitte et al., 2001	A4	14284	0.99993	0.12	yes	Simplified based on other results
Zumbo et al., 1985	C4	942.39	0.99894	1.90	yes	Simplified based on other results

The first, third, and fifth columns of data in the table below are the first four samples reported in Table 1 of *Zircon U–Pb ages, $\delta^{18}O$ and whole-rock Nd isotopic compositions of the Dire Dawa Precambrian basement, eastern Ethiopia: Implications for the assembly of Gondwana*. These samples were measured at different locations than those indicated in G1, G2, G3, G4. They are samples taken at 9°27'02.5"N, 41°49'59.4"E, which is south of the area shown in the student map. Rocks that are from the same formation are all the same age. These samples were taken from similar basement rock types as shown in G1, G2, G3, and G4 at Afar. This is why the OpenSciEd authors of this lesson included them in the new locations on the student map--so students could have data to draw comparisons to determine how much older the surrounding basement rock is in the region they are studying (Afar) than in the rest of the samples. The intent in the revisions was to replace this data with actual sample sites taken from the basement rock on the Afar region map.

Published in	Sample	Label	Measured	Calculated: extrapolated based on prior column	Reported	Summary of accuracy of the data students are using	
			Ratio of U-238 / Pb-206	Ratio of U-238 now / U-238 at formation	Age of rock	Label location of this sample shown on the map is accurate?	Ratio of these two elements is exact or is simplified based on other results
Yeshanew F, Pease V, Abdelsalam M, Whitehouse M. (2016) Table 1	n4737-02	G1	10.55	0.9134	583.8	no	exact
	n4737-12	G2	10.39	0.9122	592.3	no	exact
	n4737-14	G3	10.33	0.9117	595.7	no	exact
	n4737-28	G4	9.903	0.9083	659.1	no	exact

Related citations made in Stab, M., et al. (2015) *Modes of rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar*. Tectonics.

- Barberi, F., G. Ferrara, R. Santacroce, and J. Varet (1975), Structural evolution of the Afar triple junction, in *Afar Depression of Ethiopia*, vol. 1, pp. 38–54, Schweizerbart, Stuttgart, Germany.
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Density Measurements Guidance

In this lesson, students calculate the density of granite and basalt using their own measurements of mass and volume. The average density of granite is $2.6\text{--}2.7\text{ g/cm}^3$, and the average density of basalt is $2.9\text{--}3.0\text{ g/cm}^3$. Because these values are relatively similar, it is important for students' measurements to be accurate to ensure that they will conclude that basalt, which makes up oceanic crust, is more dense than granite, which makes up continental crust.

Mass measurements using an electronic scale should be straightforward. Ensure that the scale reads zero before the rock is placed on the platform and that students record masses to at least the nearest tenth of a gram.

Volume measurements are the more likely source of error. Because the rocks are irregularly shaped solid objects, students will use water displacement to find the total volume of a rock sample. How this happens in your classroom depends on the equipment available to you.

Large Graduated Cylinder

If you have access to graduated cylinders that are wide enough to accommodate the rock samples and have gradation intervals small enough to measure single milliliters, students can observe displacement of water directly in the graduated cylinder. In this case, they will observe the increase in water level once the rock is added to the graduated cylinder.

- Students need to use the *difference* between the initial and final graduated cylinder readings.
- A common student error is to use the total volume of water + rock together. Make sure students are using the *volume of the rock only*, either by subtracting the initial water volume from the final reading or by observing the rise in water level.
- A beaker is generally not appropriate for this approach, because students will need to estimate volume rather than obtaining a precise measurement.

Displacement Can

If you have access to displacement cans, these will allow students to easily displace the correct volume of water for measurement in a graduated cylinder.

Beaker as Displacement Can Substitute

You can repurpose a normal glass beaker to function like a displacement can. The beaker must be large enough for the rock samples to be fully submerged without getting stuck.

- Make sure the initial water level in the beaker is high enough so that the rock can be fully submerged.
- Lubricate the beaker pour spout with petroleum jelly to help the water flow out easily.
- This works best if a graduated cylinder is held diagonally against the beaker pour spout to catch all the overflow water.
- Alternatively, you can place the beaker in a clean, dry plastic bin to catch the overflow. In this case, students need to be mindful of transferring all the overflow water from the bin to a graduated cylinder without spilling any or leaving residual water in the bin. A volume error of 1–2 mL can lead to errors in density calculations that will cause students to draw the wrong conclusion about which type of crust is denser.

Other Containers

As long as a container is large enough to hold the rock samples and can allow water to spill out into a bin, students can use it to displace water equal to the volume of the rock. An important consideration is whether the container will promote the retention of water due to surface tension. Be sure to test potential materials setups ahead of time.

- Plastic cups with a rounded lip generally do not let water spill out easily.
- Containers with vertical sides work better than containers that widen at the top.
- Glass typically works better than plastic. You can use petroleum jelly around the rim to reduce the effects of surface tension.

Additional Considerations

The way in which students place the rock into the water can affect how much water is displaced. This is not important when using a graduated cylinder that can contain the rock, because water is not spilling out of the container. In any methods that rely on spillage of the displaced water, it's important for students to be careful to displace only the amount of water equal to the volume of the rock itself.

- Introducing the rock too slowly and gently makes it more likely that the water will form a “bubble” held together by surface tension, rather than spilling out of the container.
- Sometimes small bubbles attach themselves to the rock; a small tap on the container can help get rid of these bubbles.
- Dropping the rock from a height makes it more likely that extra water will splash out of the container.
- Students may accidentally put their fingers in the water, thereby displacing extra water beyond the volume of the rock.

Watch <https://youtu.be/L14LJB9RhNo?si=OKkILWyhXoijhWR6P> for additional guidance on how to measure the density of the rocks for this investigation.

Lesson 10: Answer Key 1

Investigating Plate Interactions Key

Building toward: 10.A Use a computer model that simulates the movement of tectonic plates to produce data to serve as the basis for evidence that can support an explanation of how plate interactions at plate boundaries shape a planet's surface features. (SEP: 2.6; CCC: 4.3; DCI: ESS2.B.3)

	3D Elements Addressed in This Assessment	Q2	Q3	Q4	Q5
SEPs	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.	x	x		
CCCs	Systems and system models. Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions—including energy, matter, and information flows—within and between systems at different scales.				x
DCIs	ESS2.B.3. Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust. (HS-ESS2-1)		x	x	

	Investigation 1 - Convergent boundary	Investigation 2 - Divergent boundary
1. Which specific plates on the map interact at this kind of boundary?	Examples of plates interacting at this boundary: - Eurasian plate and Indian plate - Nazca plate - South American plate - Northern part of the Pacific plate - northwest of the North American plate	Examples of plates interacting at this boundary: - South American plate and African plate - North American plate and Eurasian plate - Australian Indian plate and Antarctic plate
2. What surface changes did you observe as a result of this interaction?	Formation of mountains on the less dense plate High volcanic activity Earthquakes with different degrees of magnitude Earthquakes occurring at multiple depths (very deep and sometimes shallow as well) Islands being formed close to, but not at, the plate boundary	High volcanic activity There are a lot of earthquakes with different degrees of magnitude. Most, if not all, earthquakes happen at a depth of 0-30 km.

3. Use the cross sections to describe the way both plates are moving at this plate boundary over time . Specify the more dense and less dense plate.	One of the plates slides down the other plate. Over time, it will start moving downward. The oceanic plate is more dense than a continental plate.	There is a bulge at the boundary, where the magma is coming toward the surface. Over time, the plates will move away from that bulge.
4. In the simulation, we need to define the density of the plates we are investigating. What role, if any, could the density of the plates play in their motion or interactions?	The more dense plate moves underneath the less dense plate. This only happens with oceanic plates. When two continental plates converge, they crumple together. We know that less dense material rises. Maybe magma rises toward the surface because it is less dense.	Density does not seem to play a role here. Both plates just move away from each other.
5. What do the cross sections tell us about the relationship between the movement of the plates and the observed changes in the crust?	As the densest plate slides down, the magma that flows from it is sometimes released through volcanoes in the less dense plate. Over time, the magma will accumulate on the crust, growing in elevation. The crumpling of two continental plates results in mountains. As the plates move toward each other, earthquakes and volcanic eruptions occur.	If two continental crusts are diverging, the land splits apart, and all the surface features, like mountains, move away from each other. As the plates move away from each other, there are volcanic eruptions and earthquakes on the plate boundary.

Lesson 10: Answer Key 2

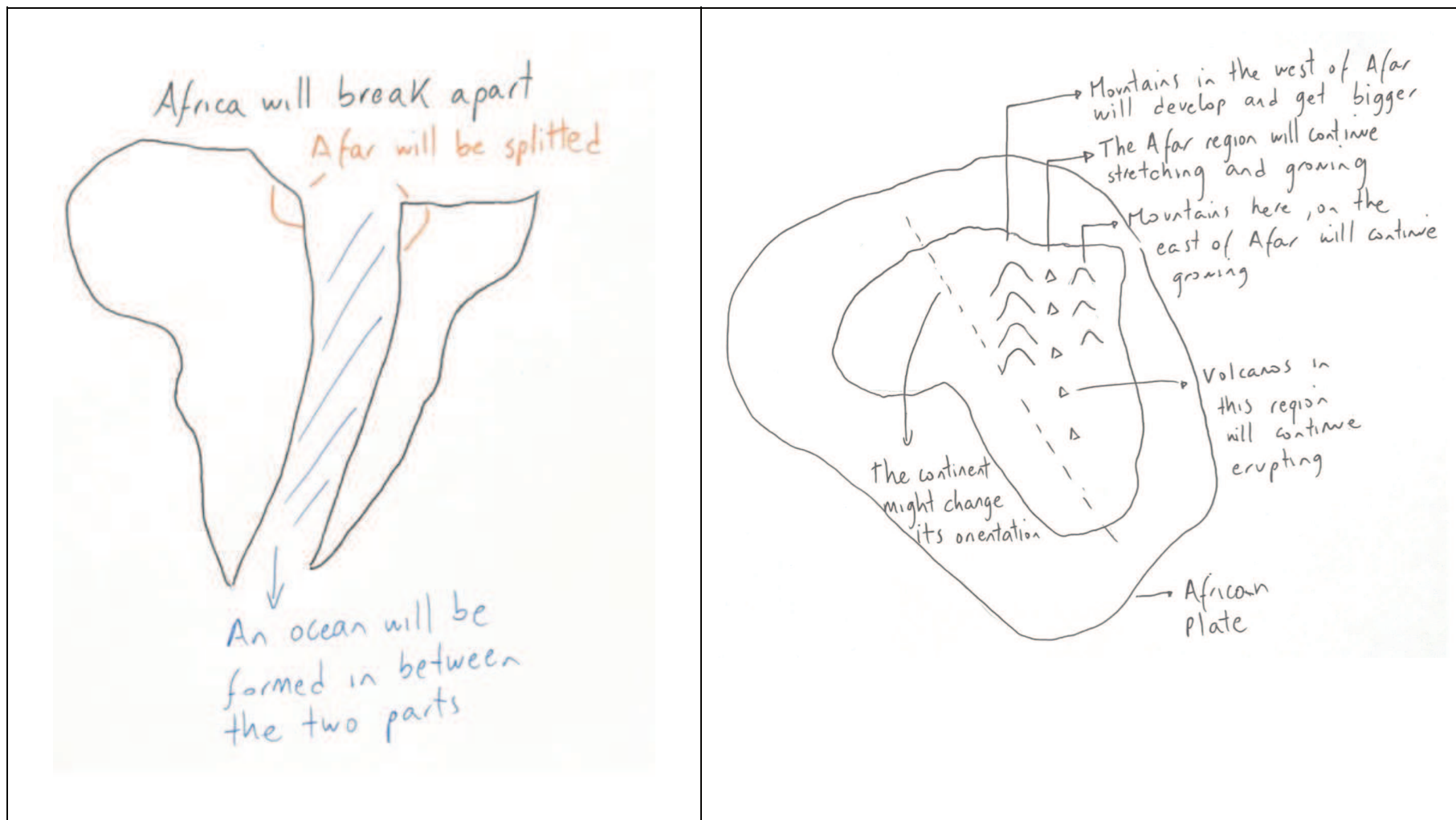
Predicting the Future of Africa and Afar Key

Building toward: 10.C Construct and revise an explanation about the future of Afar and Africa based on valid and reliable evidence obtained from a variety of sources and the assumption that plate tectonics is the unifying theory that explains the past and current movements of the rocks at Earth's surface. (SEP: 6.2; CCC: 4.4; DCI: ESS2.B.2, ESS2.B.3)

3D Elements Addressed in this Assessment		Q1	Q2	Q3
SEPs	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.	x	x	
CCCs	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.	x	x	x
DCIs	ESS2.B.1. 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. (ESS2.B Grade 8 GBE) (secondary to HS-ESS1-5)		x	
	ESS2.B.3. Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust. (HS-ESS2-1)		x	

1. Make a prediction about how the surface of East Africa will look in the future. Use drawings and/or words to explain your prediction.

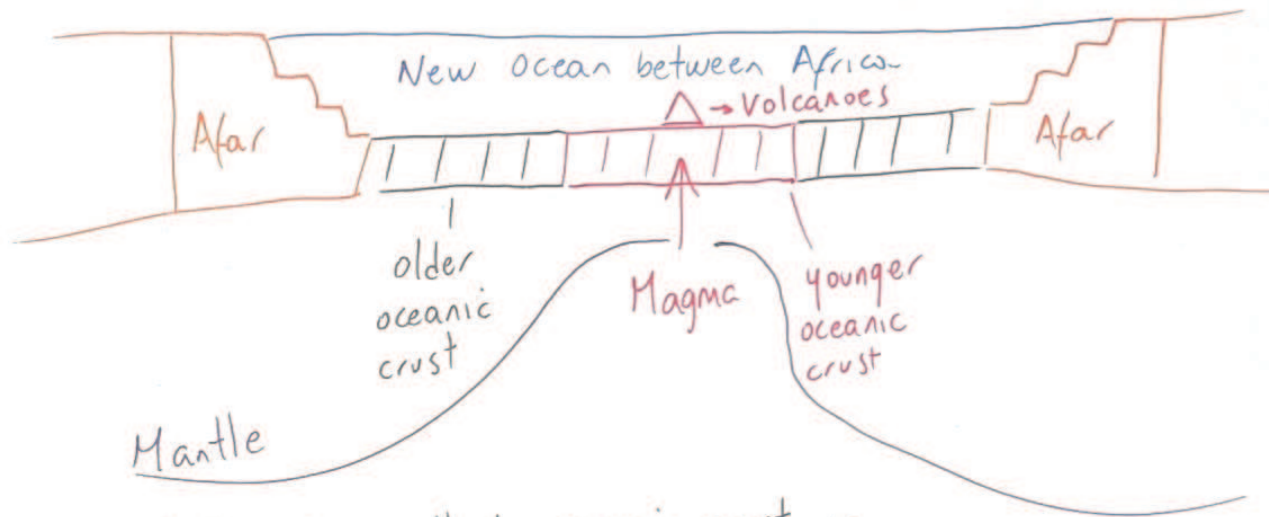
Sample prediction focused at a local level. It considers the rifting African plate to be its own system.	Sample prediction that takes into account the plates surrounding the African plate and how this can affect its future. This is one of many possible predictions. Students may predict the formation of mountains and a new ocean, for example.
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2. Use drawings and/or words to explain how the interactions between the plates and the mantle will cause the surface changes in Afar and Africa that you are predicting. Include any relevant source(s) of evidence from our investigations and your Progress Tracker to support your prediction.

Sample explanation for the local-level prediction

The local-level prediction relies heavily on the findings from the simulation, and it ignores the movement of other plates in relation to the African plate. It focuses on explaining the cause and effect of the rifting forming a

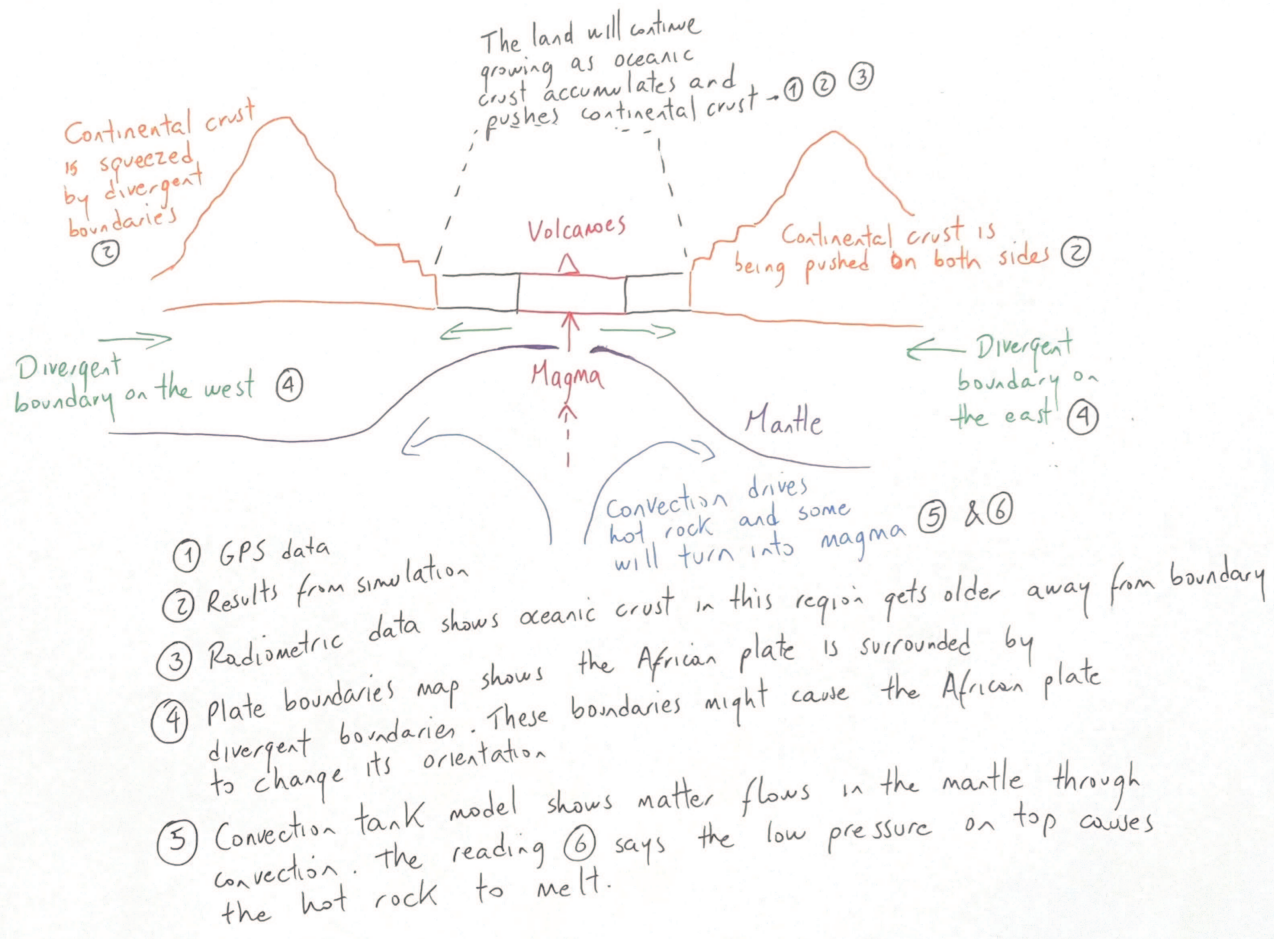


divergent boundary at the location of Afar. The explanation provided does not offer a full mechanistic explanation of why the newly formed plates will move away from each other.

The simulation shows that oceanic crust in a divergent boundary can separate continental crust and it will get covered by ocean water

The radiometric data shows younger rock toward Afar, and it gets older away from it.
There is oceanic crust and continental crust in Africa

Sample explanation for the large-scale level prediction



Notice that this large-scale level prediction is more complex, as it requires the support of additional evidence. This prediction is also more sophisticated, as it requires students going beyond the results from the simulation and considering other sources of information, such as the *Rate and Direction of Plate Movement* reference, to consider the motion of the African plate in relation to other plates. There is a great deal of uncertainty, so focus on the meaningful use of evidence to support the prediction of specific movement and geologic feature development.

3. A prediction about the future of a system usually includes the time it will take for the system to change in the ways described by the prediction.

3a. Approximately how long do you think it will take for the Afar region to look the way you are predicting? Why do you think so?

It will take several hundred million years. The GPS data show that plates move a few centimeters per year, so it will take a very long time to see significant changes. The radiometric data also show that rocks move over a scale of millions of years. The larger the distance scale involved, the longer the time it will take to see significant changes. A mid-ocean ridge would probably form before mountains are pushed up on the continental

crust, because mountain-building would require the land to move enough that it would collide with another plate.

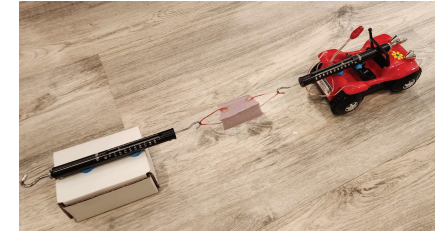
3b. What are the limitations and assumptions of the models of Earth and plate tectonics that we have been working with that could affect the accuracy of your prediction? How would these limitations or assumptions influence your prediction?

- Scientists use earthquakes to study Earth's interior, but they can't observe it directly, so we could be wrong about the dynamics of the mantle under Afar, especially over smaller distance scales.
- In our model, we were able to simulate changes taking place over long timescales. If this happens over millions of years, we can't observe it on Earth itself, so we don't know whether it is actually happening that way. It's all indirect evidence.
- We assume that Earth's mantle and crust at Afar will act the same way as the mantle and crust at other places on Earth, or at other times in Earth's history.
- Optional:
 - Our convection model showed a general pattern of motion, but it was based on observations of a small tank. Also, it was liquid and the mantle is solid, which may behave a bit differently, even if it can flow as well under higher temperatures.
 - Radiometric data provided a range of dates rather than a single date for the events at Afar, so there is some level of uncertainty of when these happened in the past.
 - Our GPS data are only from the years we've had that technology. Assuming that these rates would hold over many years, current plate motion is based on measurements taken over a relatively short timescale.
 - The interactions between plates can change over time, and we saw from the computer model that plates can break apart to form new plates, each with their own boundaries. So the boundaries and movement on the current map may not be what is happening millions of years from now.

Lesson 11 Teacher Reference

Demonstration Setup Instructions

The purpose of this demo is (1) to collect evidence that the forces on an object moving at a constant velocity are balanced and (2) to establish a way to measure friction. To do this, we use a constant velocity car with a spring scale attached that pulls a small block of foam (chosen to parallel the use of foam to represent tectonic plates in this unit), which in turn has a box with a spring scale dragging behind it.



PREPARING THE CARS. This demo will be conducted with 2 cars at different speeds in order to show that sliding friction is not dependent on speed. To make one car move more slowly than the other, you need to put a placeholder in the spot of one of its batteries.



Use foam or cardboard to create a block the same size as a C-cell battery, and wrap it in aluminum foil. Use a small screwdriver to open the battery compartment. Place 1 C battery and the foil-covered placeholder in the battery compartment, and resecure the battery cover with the screw. Place 2 batteries in the other car, and make note of which color car is the slower car and the faster car.

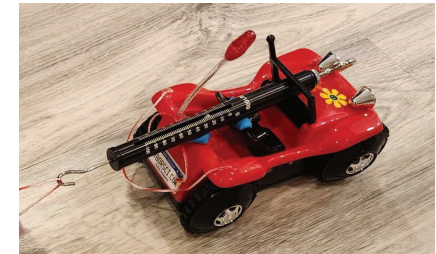


ZEROING THE SCALES. Review the Teacher Reference Zeroing Spring Scales Horizontally. It will help you determine whether you need to permanently modify the 1N spring scale so it can be zeroed in a horizontal orientation. It also outlines the steps to follow if you need to make that modification.

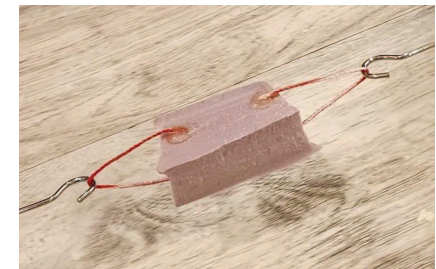
PREPARING THE SCALES. Use sticky tack to attach a 1N spring scale to each of the 2 cars, with the measuring hook facing backward. Be sure the scale is level. This can be accomplished by putting the end of the scale through the windshield of the car, as shown. (Note: the string loops attached to the back of the car in the image are not necessary for this demonstration.)



Use sticky tack to attach a 1N spring scale to the top of the empty cardboard box, as shown. These boxes are equal in height to the cars, so the scales should be at approximately equal heights. Another box may be substituted, as long as the heights of the scales are equal. Calibrate the scales using the screw knobs on the static end so the reading is zero while horizontal. There will be some wiggle around zero that may stick a little due to friction; this is OK. Get the scales as close as possible to zero to start.



PREPARING THE FOAM. Cut a small block of foam. This block should be light enough that it doesn't get weighed down or touch the ground while being dragged. We used a piece about 2 inches by 2 inches, but the exact size doesn't matter. Cut 2 short pieces of string, and hot glue the string to the foam block to create a loop on both ends of the block, as shown.



TESTING THE DEMONSTRATION. Hook up the parts of the system as seen at the top of this document. Start the test by turning on the slower car and letting it run across your classroom floor, dragging the foam and box with it. The scales should read the same amount. Test the demonstration with the faster car to make sure it still runs smoothly, and add mass as needed to make the procedure work with both cars. If the force shown on the scales is too low to read well, add mass to the box to increase the friction force. If the friction force is too high, the car will tilt back as it runs. If this happens, use sticky tack to attach something with mass to the front of the car. If the scales don't start at zero, start the system with a little slack so as not to begin with a measurement of static friction.

To see the demonstration in action, watch this video: https://youtu.be/Xg5_4pw3DOc.

Lesson 11 Teacher Reference

Zeroing Spring Scales Horizontally

Test to see whether you can zero the 1N spring scale by turning the screw and hook on the top of the scale while it is in a horizontal position. If you can do this, you should be able to adjust the edge of the measurement plunger, not just to ON, but even a bit above and below it.

If however, you can not get the edge of the measurement plunger to zero, the steps below outline what to do with one type of spring scale that was tested for this lesson. These steps are a one-time modification ensuring that future zeroing of the scale in a horizontal orientation can be done by simply turning the hook and nut assembly on the top. This modification ensures that the scale is ready to be used for the following lessons in the following units:

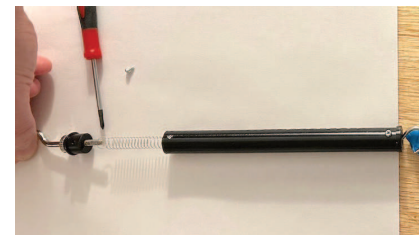
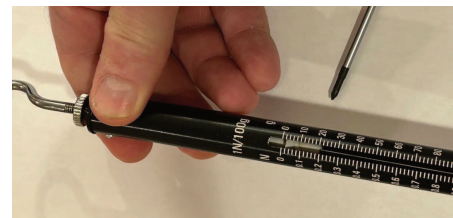
- Lesson 4 of *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*
- Lesson 11 of *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*

You need the following materials to make these modifications:

- tape
- small Phillips head screwdriver
- pliers

Remove the screw from the end of the spring scale closest to ON.

Tap 1 hook down and pull the other hook until about 1 inch of spring is extending from the case. Do not overextend the spring, as that will permanently deform it, compromising its future use as a force-measurement device.



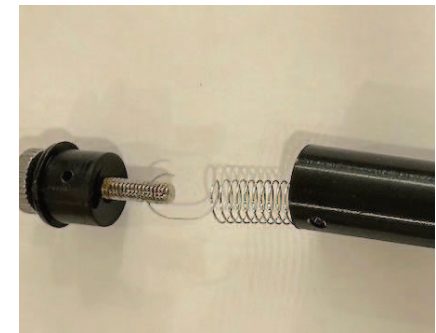
Isolate the circular ring on the end of the extended spring. This is the part of the spring that you will permanently deform. Doing so will help to offset the initial position of the plunger in the case, without compromising the spring constant of the coiled part of the spring.



Hold the bottom of the circular ring and pry the end of it upward. Continue bending it until it is permanently deformed into a J shape. The long end of the J should give the system an additional 3 mm of slack.



Use the pliers to permanently deform the end of the J shape back toward the coil to ensure that it will not slip out of the top screw/hook hole it is in.



Reassemble the scale. Set the top hook and cap back into the case, and reattach the set screw. With the scale reassembled, zero it. Do this by turning the screw and hook on the top of the scale while it is in a horizontal position.



Keep in mind that the system is now zeroed for horizontal force measurement, which is the extent of its use in HS OpenSciEd Physics units. If you want to use it for any vertical force measurement, you will need to re-zero it in a vertical orientation. You should be able to do that by simply turning the screw and hook on the top of the scale until it reads 0 newtons when you hold the scale vertically from the top hook. No additional disassembly should be needed.

Failed Midcontinent Rift Key

Performance expectation being assessed:

- HS-ESS2-1. Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features. (SEP 2.3; CCC: 7.2; DCI: ESS2.A.1, ESS2.B.2)

As well as the SEP, CCC, and DCIs associated with this PE, this assessment addresses one additional CCC and one additional DCI element, described below:

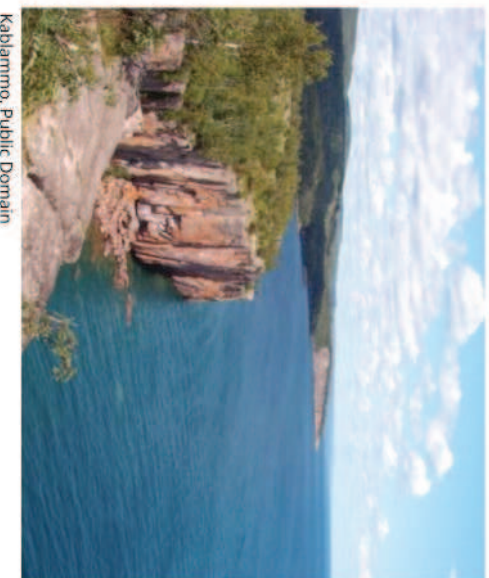
3D Elements Addressed in This Assessment							
	1a	1b	2	3	4	5	6
2.3 Developing and Using Models Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.	X	X			X		
ESS2.A.2 Earth Material and Systems. Evidence from deep probes and seismic waves reconstructs 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)		X	X	X	X		X
ESS2.B.2 Plate Tectonics and Large-Scale System Interactions. 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. (ESS2.B Grade 8 GBE) (HS-ESS2-1) (secondary to HS-ESS1-5)				X		X	X
ESS2.A.1 Earth Materials and Systems. Earth's systems, being dynamic and interacting, cause feedback effects that can increase or decrease the original changes. (HS-ESS2-1, HS-ESS2-2)					X		
5.4 Energy and Matter. Energy drives the cycling of matter within and between systems.		X	X	X	X		
7.2 Stability and Change. Change and rates of change can be quantified and modeled over very short or very long periods of time. Some system changes are irreversible.						X	X

Over millions and millions of years, tectonic plates can move apart, stretching the matter in Earth's crust between them. This causes deep cracks in Earth's crust where mantle material is able to rise to the surface. Where the land has been stretched, new oceans may form, breaking land that was once continuous into new, separate continents. This process is known as *rifting*.

Many scientists predict that rifting in the Afar region, evidenced by frequent volcanic and seismic activity, could someday result in a new ocean that will split the continent of Africa in two. But rifting can slow down over time, and even stop altogether, as shown by evidence from a history buried deep beneath the United States.

The Midcontinent Rift

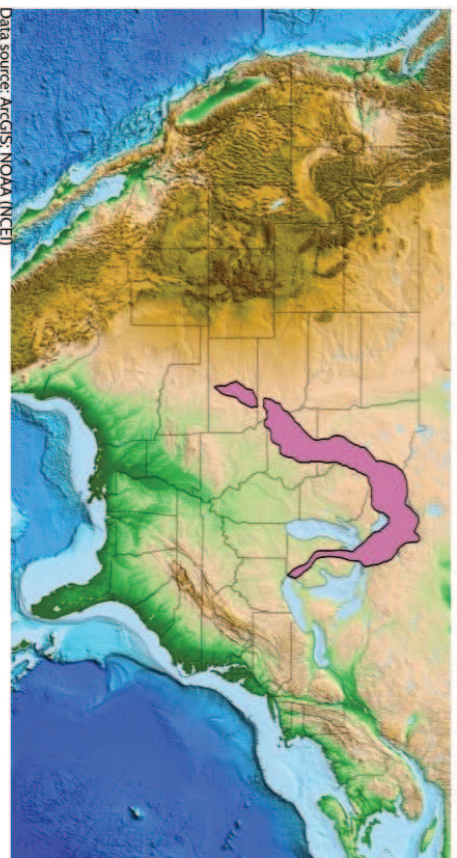
We don't usually think of the American Midwest as a place where there is a lot of volcanic or seismic activity. But over 1.1 billion years ago, evidence points to an active rift valley that stretched from what is now Ontario, Canada, to perhaps as far south as Oklahoma. Basalt seeped from cracks in Earth's crust as the land stretched over time, and frequent volcanic eruptions filled lakes of lava hundreds of feet deep. The weight of this dense rock caused the rift valley to sink farther, much like in the Afar region. Scientists call the 2,000 km (1,200 mi) long region of dense basalt that marks the location of this ancient valley the Midcontinent Rift.



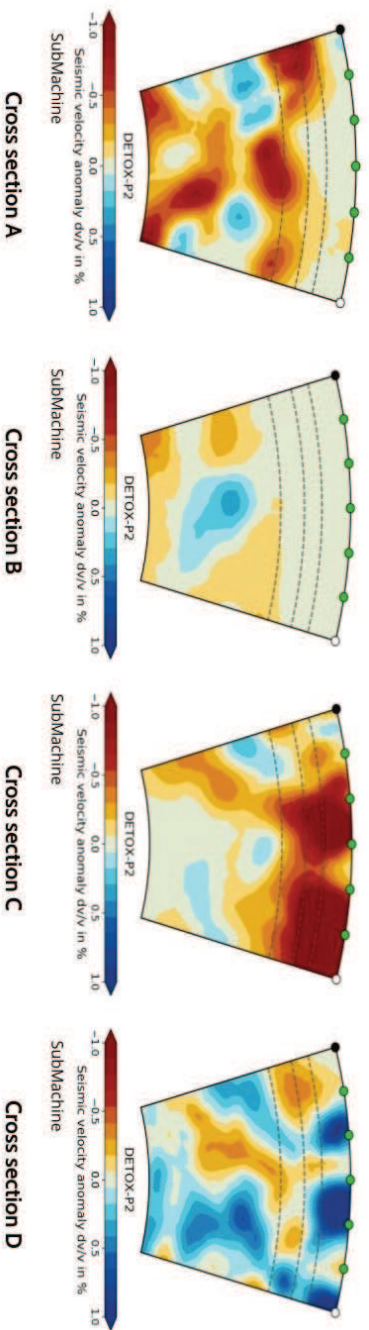
Kablammo, Public Domain

Most of the ancient Midcontinent Rift is buried beneath younger rock, but the basalt is visible on the shores of Lake Superior, Minnesota, exposed by more recent surface processes like glaciers and erosion. This photo shows part of the Midcontinent Rift that is exposed. The view is looking north toward Shovel Point along the shore of Lake Superior. This rock formed during the Keweenaw period, and due to the age of the rock that makes up the rift, it is sometimes called the Keweenaw Rift. The name Keweenaw probably derives from an Ojibway word that means "the crossing place" or "land crossing between two bodies of water."

This image created in ArcGIS shows the location of the Midcontinent Rift, cutting through Minnesota, Wisconsin, Michigan, Iowa, Nebraska, and Kansas. Some scientists also believe that the east side of the rift stretched down to Kentucky, Alabama, Tennessee, and possibly parts of Oklahoma.



Q1a: The four cross sections below model modern-day seismic velocity anomalies in Earth's mantle. Which cross section do you think is the most similar to what was happening in the mantle under the Midcontinent Rift 1.1 billion years ago?



The most accurate response is C. However, if a student chooses another option and gives a thoughtful and accurate reason for their choice, do not mark them down.

Q1b: Explain how the energy in the mantle cross section you chose would result in rifting at the surface, using your understanding of convection and unbalanced forces.

- Students with a foundational understanding may include 1 of the ideas below.
- Students with a linked understanding may cite several of the ideas below, but will not link them causally, or will link only 2 ideas.
- Students with a connected understanding will link 3 or more of the ideas below causally.
 - The mantle material that is hotter than its surroundings moves upward, because it is less dense.
 - The negative seismic velocity anomaly (red parcel) corresponds to a region of higher temperature.
 - Temperature differentials within the mantle cause convection (moving matter).
 - Moving matter from convection drags on plates with friction.
 - The dragging on the plates is a force, which causes unbalanced forces.
 - Unbalanced forces transfer energy.
 - Energy transfer (or unbalanced forces) causes the tectonic plates to stretch and move.

Q2: How do you think the mantle under this region might have changed over time? How would this change over time affect the transfer of energy from Earth's interior to the surface?

- When the rift was active, the parcel of mantle directly under the crust was exerting more upward force due to convection, driven by energy from the core.
- Over time, the mantle below this region became less anomalously hot compared to the surrounding mantle material.
 - We have evidence of this because we do not see rifting occurring there today.
- This would result in less convection upward, and less movement in the mantle at this location, resulting in less energy transfer to Earth's crust.
- That would reduce the amount of deformation of the rocks and movement of matter from the mantle up to the crust.
 - This would lead to no new rifting on the surface today.

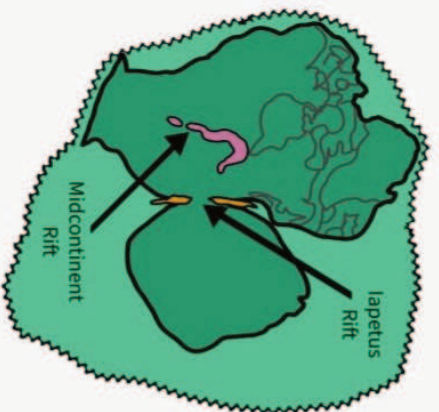
The Midcontinent Rift is a failed rift, meaning that over millions of years, the land stopped stretching and volcanic activity stopped. As a result, an ocean did **not** form in the center of North America.

Q3: What would have happened if this rift succeeded? Be as specific as possible, and use ideas about matter, energy, and forces.

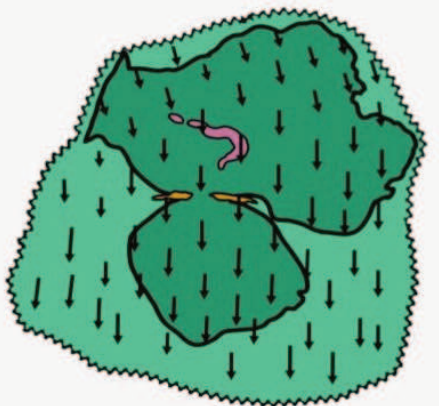
- Students with a foundational understanding may include the idea that there would be a new ocean, but will not address energy transfer, unbalanced forces, or matter effects.
- Students with a linked or connected understanding may cite several ideas similar to the ones below, and use a combination of matter, energy, and forces ideas to describe change.
 - The successful rifting would have resulted in a new ocean where the Midcontinent Rift is today.
 - Energy from the mantle would have caused unbalanced forces in the mantle and forced magma to the surface through the crust at the Midcontinent Rift.
 - The magma protruding at the surface would have created new seafloor.
 - The creation of new seafloor would have pushed the continental crust outward due to the force from ridge push.

Though North America is still in one piece to this day, the oldest rocks in the North American continent once made up the ancient continent of Laurentia. Laurentia is a past continent that has collided with and split apart from other continents over time to form the North America we see today. Over time, this large chunk of continental rock has moved as one piece since the Midcontinent Rift failed.

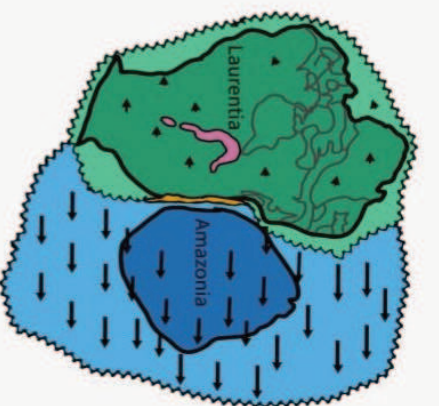
New research indicates that the Midcontinent Rift may have failed because a much larger rift had opened up near it, called the Iapetus Rift. The Iapetus Rift had started forming a new seafloor between the larger continents of Laurentia and Amazonia, creating the Iapetus Ocean.



This image shows the location of the Midcontinent Rift and the Iapetus Rift.



This image shows one large plate with two rifts, along with the plate movement. Far away to the right, this plate was connected to a subducting slab, which was pulling it to the right.



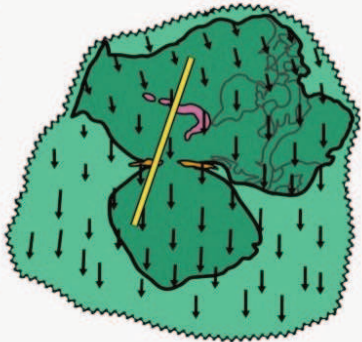
This image shows the two rifts after the original plate had torn apart into two plates and the Iapetus Ocean had formed between the continents of Laurentia and Amazonia.

As seen in the images, the motion changed after the plate separated into two plates. The net force on Laurentia, the smaller of the two plates, became closer to 0 (it was moving very slightly to the left). Amazonia continued to the right with a similar motion as before.

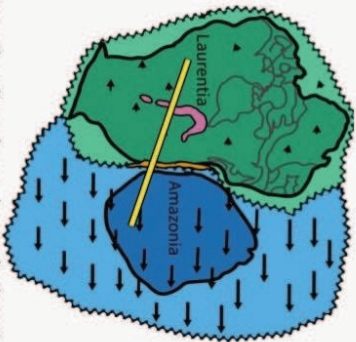
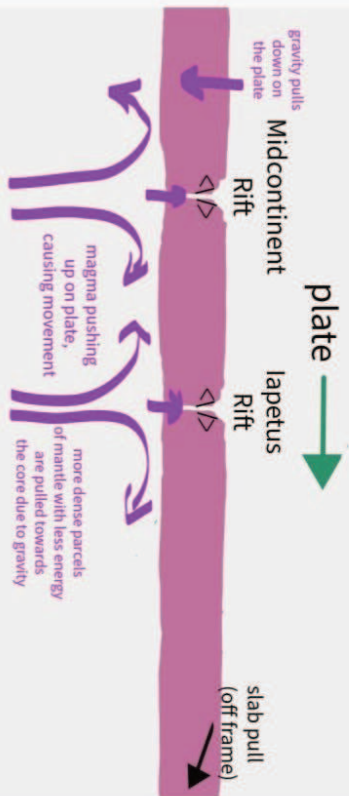
Q4: Use the cross section models below to explain how the forces acting on the mantle and crust systems both before and after the separation could have caused this change in motion. Show how the forces changed as the mass and size of the plates changed due to energy transfer. Make sure to use your understanding of friction, gravity, and the forces from the mantle in your explanation. Remember that slab pull is happening to the right of the plate(s).

Use any combination of words, drawings, and/or annotations on the models.

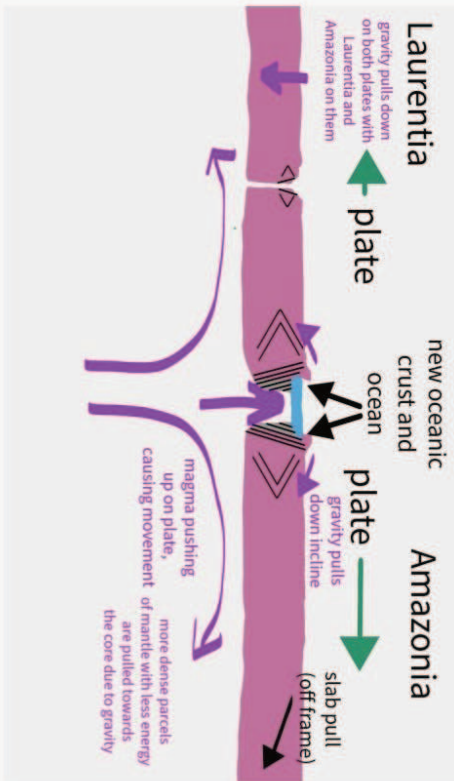
The next page shows examples of what a student with a linked understanding might draw.



The yellow line above shows the location of the cross section of the crust below, before the plate separated into two plates.



The yellow line above shows the location of the cross section of the crust below, after the plate separated into two plates.



Look for the following explanation to be present in words or images within the models:

	Foundational Pieces	Linked Understanding	Organized Understanding
3D Elements	Look for: Students illustrate the forces from the mantle, gravity acting on the crust, friction, and ridge push in both time periods. (SEP: 2.3)	Look for: Students illustrate the forces from the mantle causing ridge push and gravity acting on the crust, as well as their magnitude changes from one time period to the next. (SEP: 2.3) Students who demonstrate a linked understanding should also include at least 1 of the following: - Students show the relationship between ridge push and forces from the mantle, slab pull, and plate movement. (SEP: 2.3) - Students make connections between the process of thermal convection and the friction between the mantle and plate, causing a change in net force across time periods, showing change in plate movement over time. (DCI: ESS2.A.2, ESS2.B.2)	Look for: Students illustrate the forces from the mantle causing ridge push and gravity acting on the crust, as well as their magnitude changes from one time period to the next. (SEP: 2.3) Students further develop a model of forces acting on the plate due to the transfer of energy from mantle convection to explain how changes to plate size can cause rifting to fail and change plate motion (decreasing the original change between the interacting systems). Students who demonstrate an organized understanding should show the following: - The relationship between ridge push, slab pull, gravity, and the interaction of the mantle and plate systems, causing movement of plates over time. (SEP: 2.3; DCI: ESS2.A.2, ESS2.B.2) - Model the transfer of energy from the mantle, causing the movement of material at ridges and thermal convection, which causes plate movement. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, ESS2.B.2)
Example	In cross section 1: Arrows are shown coming up from the mantle to the crust where the rifts are shown. The arrows showing gravity are directed down, toward the center of Earth. Friction arrows are pointed in the opposite direction of the plate movement. In cross section 2: Arrows are shown coming up from the mantle to the crust only at the Iapetus Rift, and	In cross section 1: Arrows are shown coming up from the mantle to the crust where the rifts are shown, and are roughly of the same magnitude on each rift. The arrows showing gravity are directed down, toward the center of Earth. Larger friction arrows are pointed in the opposite direction of the plate movement, and are	In cross section 1: Arrows are shown coming up from the mantle to the crust where the rifts are shown, and are roughly of the same magnitude on each rift. The arrows showing gravity are directed down, toward the center of Earth. Larger friction arrows are pointed in the opposite direction of the plate movement, and are roughly the size of the plate movement arrow. A drawing of convection of the mantle due to differences in energy (high-velocity anomalies) has been attempted to show

	arrows show gravity is directed down. Arrows showing friction are in the opposite direction of plate movement for both new plates.	roughly the size of the plate movement arrow. A drawing of convection of the mantle has been attempted to show the relationship between plate movement and mantle movement, as well as friction. Students may draw a variety of convection cycles here, because there is a conflict between the forces from the mantle and plate movement at this time. This is consistent with current scientific literature as well.	the relationship between energy, plate movement, and mantle movement, as well as friction. Students may draw a variety of convection cycles transferring energy to the crust, because there is a conflict between the forces from the mantle and plate movement at this time. This is consistent with current scientific literature as well.
		In cross section 2: Large arrows are shown coming up from the mantle to the crust only at the Iapetus Rift, and arrows show gravity is directed down. Arrows showing friction are in the opposite direction of plate movement for both new plates. The Laurentian friction arrow is small, roughly the size of the plate movement arrow. The friction arrow for Amazonia is roughly the size of the arrow before plate separation in cross section 1. A drawing of convection of the mantle has been attempted to show the relationship between plate movement and mantle movement, as well as friction. Mantle movement is now shown moving outward from the ridge.	In cross section 2: Large arrows are shown coming up from the mantle to the crust only at the Iapetus Rift, and arrows show gravity is directed down. Arrows showing friction are in the opposite direction of plate movement for both new plates. The Laurentian friction arrow is small, roughly the size of the plate movement arrow. The friction arrow for Amazonia is roughly the size of the arrow before plate separation in cross section 1. A drawing of convection of the mantle has been attempted to show the relationship between plate movement and energy from the mantle driving convection under the crust, as well as friction in the opposite direction of plate movement. Mantle movement is now shown moving outward from the ridge due to the parcels of mantle with a higher energy than the rest of the surrounding mantle.
Feedback	<i>Linking:</i> Ask students to consider what the mantle might be doing to cause this change in motion of the plates, and how the motion of the mantle might affect the forces on the crust. Also ask students to consider whether all forces are of the same magnitude, or whether they are different.	<i>Organizing:</i> Encourage students to think about how the cross section in Question 1 might help to explain the movement they are modeling at the rift, and how they could include energy within their explanation.	<i>Extending:</i> Challenge students by asking them to consider how the more dense basalt that is now located in abundance at the failed Midcontinent Rift would affect the forces in the area (specifically gravity).

Q5: What effect will the breakage of one plate into two plates have on:
A. the mass of each plate?

- The splitting of the plate would decrease the mass of each plate.
- B. the forces of friction and gravity on each plate?

- The friction and gravity on each plate would be reduced due to the decreased plate size.
- Laurentia's net force would be closer to 0, making the plate movement slow down.
- The force of slab pull that was causing the original plate to move to the west would keep operating on Amazonia, but not Laurentia.

C. Use the ideas above to explain how the breakage of a very massive plate into two smaller plates could have stopped the Midcontinent Rift from tearing over time.

Q6: The process of rifting has many components, listed below:

- volcanic activity
- earthquakes
- formation of new plate material (basalt)
- mantle convection
- plate movement
- breaking of plate material

Based on your knowledge of changes to Earth's systems, do you think this process of the rift failing happened over a long period of time or a short period of time? Use the class Scale Chart poster to explain the spatial and temporal scales over which the events would occur, as well as any connections between those changes.

- Rifting is caused by mantle convection that occurs over a large period of time.
- Mantle convection is caused by particle movement, radioactive decay, and bonds breaking, which all occur over a much smaller period of time.
- The formation of new plate material occurs very slowly over a large period of time, as well as the convection currents and the movements of parcels in the mantle.
- The breaking of plate material, although felt suddenly during earthquakes, actually occurs over a large period of time.
- The formation of oceans takes millions of years because they only form at millimeters' pace each year.
- This means that the process of the rift failing must have occurred over a long period of time.
- Finally, the plates' relocation to their current positions has taken billions of years.

	Foundational Understanding	Linked Understanding	Organized Understanding
Suggestions for instruction	If the majority of the class demonstrates a foundational understanding, go back to the models made in Lessons 10-12. Ask students to identify the parts of the mantle and crust systems and how forces are causing changes in movement, as well as where the energy for this change in movement is located. Consider working through an example, such as Iceland, as a class.	If the majority of the class demonstrates a linked understanding, ask students to think back to the M-E-F triangle and identify what causes change in motion, and how forces, matter, and energy are related. Use questions from the M-E-F triangle to get students to think about how energy might be needed within the system models, and give them a chance to revise their models.	If the majority of the class demonstrates an organized understanding, share the Western and Central Africa Rift System with the class. Challenge students by asking them to draw a model of what could happen to Afar if one of these zones also begins to separate, like what is seen in Afar, or how the rifting in Afar might affect the rifting in Western and Central Africa.