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 the 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	*GPS Plate Map*
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	*GPS Plate Map*, 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 *Investigations A and B* in small groups.	P-Q	https://youtu.be/YwxIfBUDgqQ, 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**	T	1" grid chart paper, chart paper markers

			Create free-body diagrams for *Investigations A and B*. Learn about negative forces and net force.		
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	*Investigations A&B*, *GPS Plate Map*
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	*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
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	*Investigations C&D*, 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 *Progress Tracker*, 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	• *GPS Plate Map*		• 3 pre-prepared interlocking foam pieces • 3x3 sticky note • colored marker (red) • copy paper
Investigations A and B materials	• *Investigations A&B* • science notebook	• 4 push-pull spring scales (5 N) • 8 sticky tack tabs • 1 foam rectangle • ruler	
Investigations C and D materials	• *Investigations C&D*	• 4 push-pull spring scales (5 N) • 8 sticky tack tabs • 1 foam rectangle • ruler	
Lesson materials	• science notebook • *GPS Plate Map* • *Investigations A&B* • *Investigations C&D* • 3 copies of *Progress Tracker* • 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) • *Free-Body Placemat* • 1 clear sandwich bag containing 12 cutouts from *Free-Body Manipulatives* • 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/YwxIfBUDgqQ • 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).

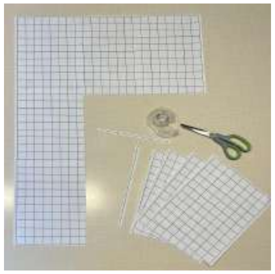
Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

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.

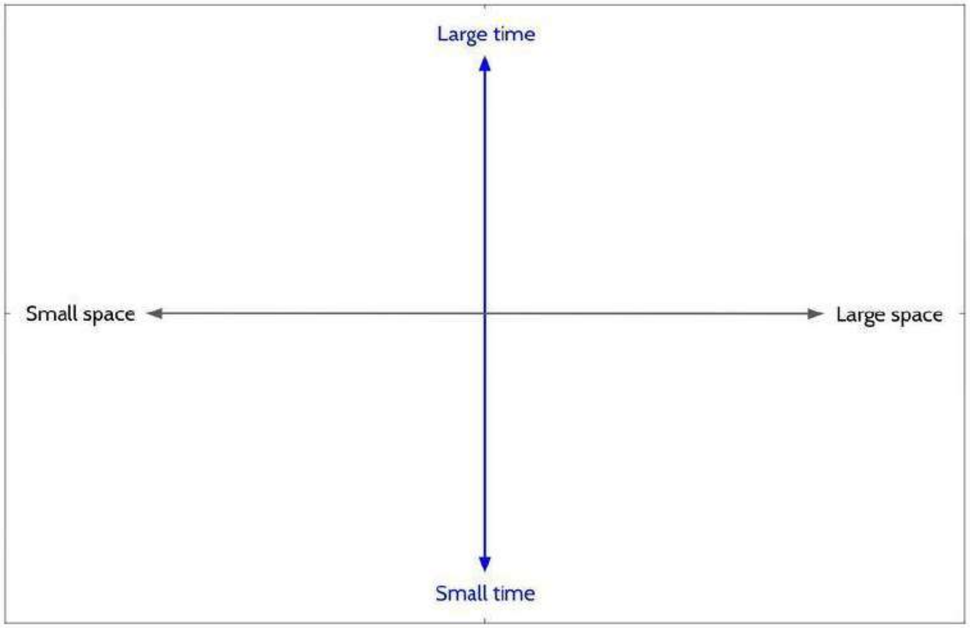
Print 1 copy of the *Free-Body Placemat* for each pair of students in your largest class. Place each copy in a sheet protector if available.

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.

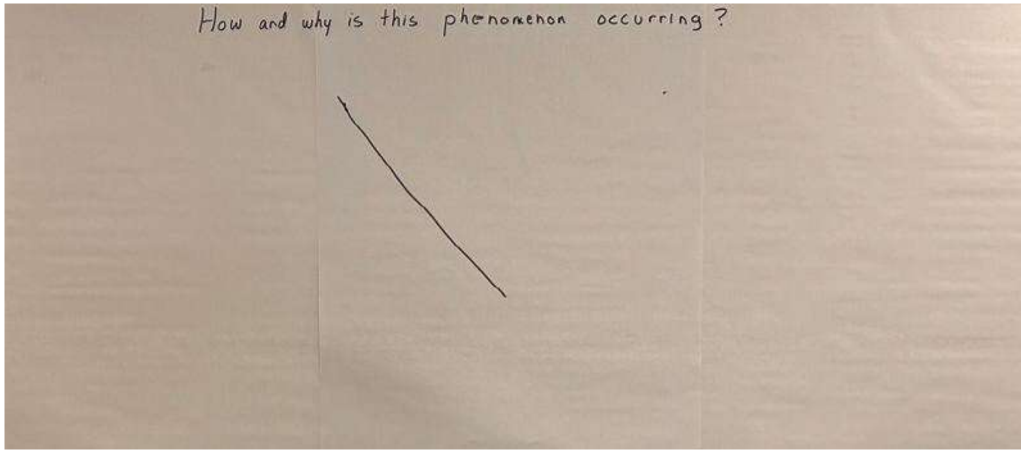
Use scissors to cut out the 12 *Free-Body Manipulatives* pieces printed on cardstock for each pair of students in your largest class. If you are printing these, print 1 copy for your own use. Place each set into a clear sandwich bag for distribution, collection, and reuse across classes. Preparing the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

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.

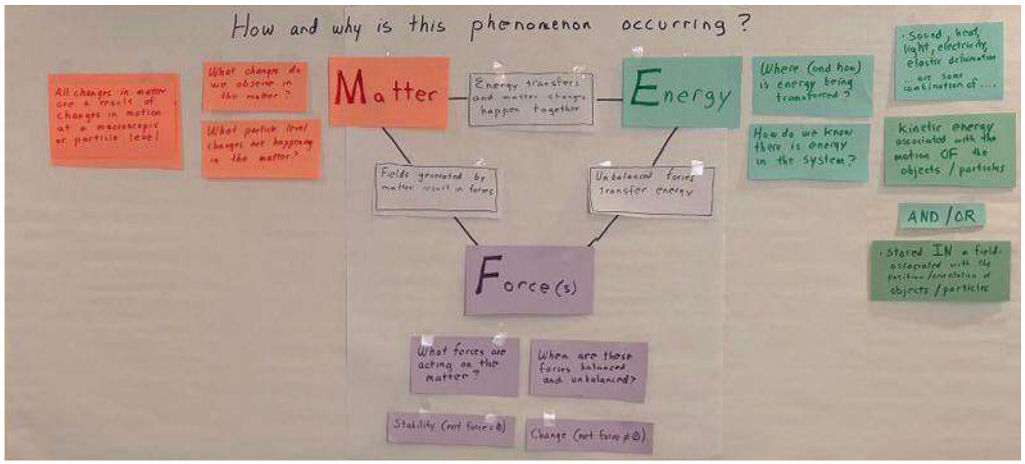


Connect 3 pieces of chart paper . Write “How and why is this phenomenon occurring?” across the top, having the title span the three pieces of chart paper. This will serve as the M-E-F poster. To see how this develops over time, see *Developing the M-E-F poster*, located in Lesson 3, where lines are added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

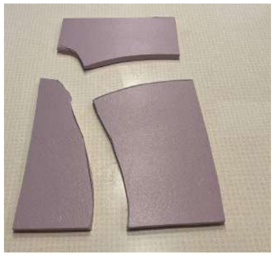
- Scale calibration and alignment procedure: https://youtu.be/YwxIfBUDgqQ
- Removing or adding one force to a stable spring-scale system: https://youtu.be/LR1Ui-IVsO4

- Slow motion removal of a force from a stable 4 spring-scale system: https://youtu.be/vmmZPt1ZI-A

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 quantitive 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
What could be causing the land to move or crack?	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.
Does land only move and crack during an earthquake, or could it happen when or where there is no perceptible shaking?	(Accept all answers.)
What measurements or data would you want to analyze to see whether any of these things are happening before an earthquake occurs?	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
What do the arrows represent?	How fast plates are moving. The direction plates are moving.
Why are some arrows longer than others?	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.

Problematize 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 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

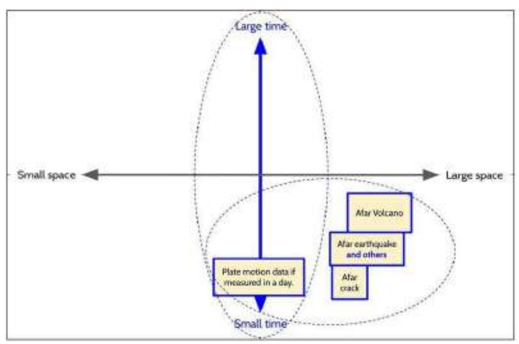
7 min

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.

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.	

✱ 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.

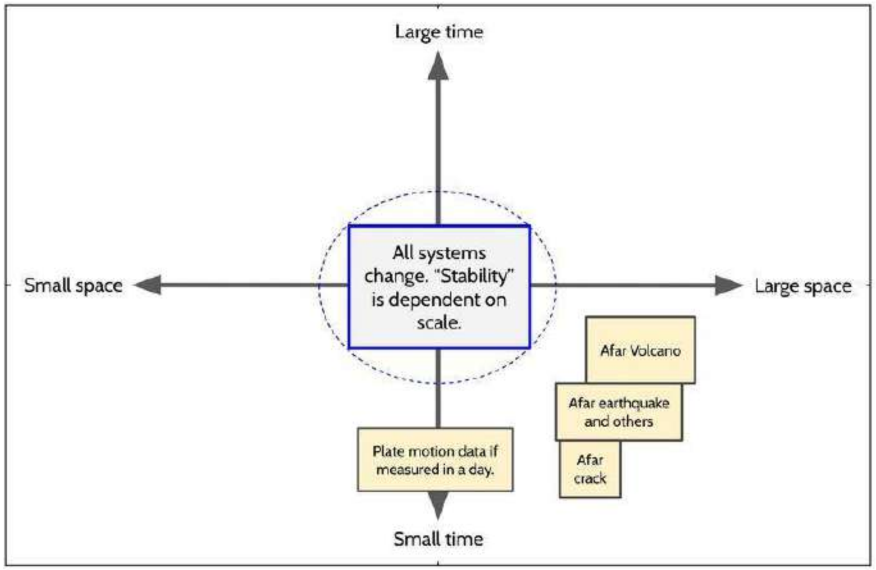
Other phenomena were added to the Afar earthquake and moved downward to reflect occurrence over a relatively short period. Space can vary for hypocenter or distance felt, or plate movement at a boundary. The timescale is likely between the Afar volcano and the Afar crack.	

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
Under what conditions is it stable?	If nobody or nothing moves it.
What if we changed the temperature in the room?	It might get warmer, but it would remain stable.
What if we changed the temperature and looked at the particle scale?	The particles would speed up as the temperature increases.
What if we left the object here for hundreds of years? Would it still be stable?	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.

"All systems change. 'Stability' is dependent on scale" was added to the center of the chart.	

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.

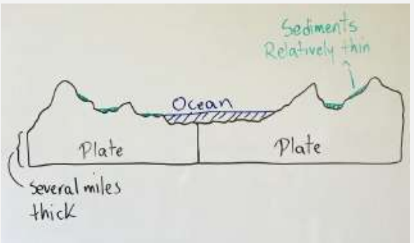
Suggested prompt	Sample student response
How big across are the plates?	Hundreds or thousands of miles across. Huge--sometimes they have continents and an ocean on them.
What material(s) are plates made of?	Rock/stone.
In some places, plate material is buried below layers of sediment, but in other places, it is not. What are some places where you have seen plate material exposed at the surface?	I 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:

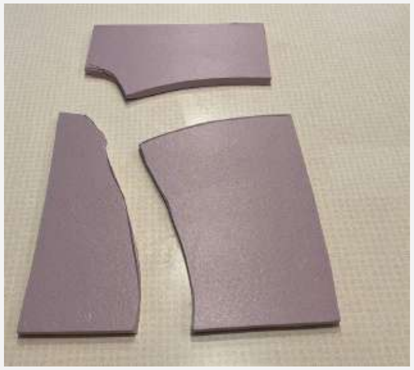
- *Changing scales is an important tool that scientists and engineers use in every science discipline to help develop explanations for why phenomena occur.*
- *Understanding why a system appears "stable" at one scale, for example, may require analyzing it at a different scale where changes are more evident.*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

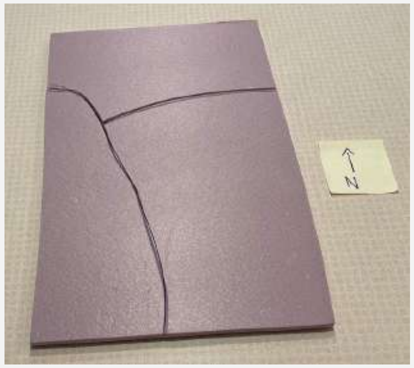
Orient to the apparent stability of the Caribbean plate. Use the slide to identify where the Caribbean plate is. Note that it appears to be stable, and that the Nazca and South American plates appear to be moving in opposite directions. Suggest that we re-create this type of motion using smaller-scale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

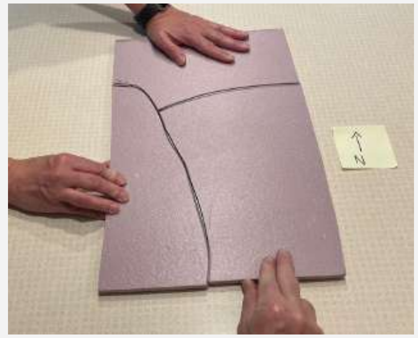
Explore plate motion with a physical model. Have students gather around a table with the prepared foam pieces. Suggest we use these to represent the Caribbean, Nazca, and South American plates, bearing in mind that the scale is of course much smaller and some of the differences in elevation or inclusion 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.

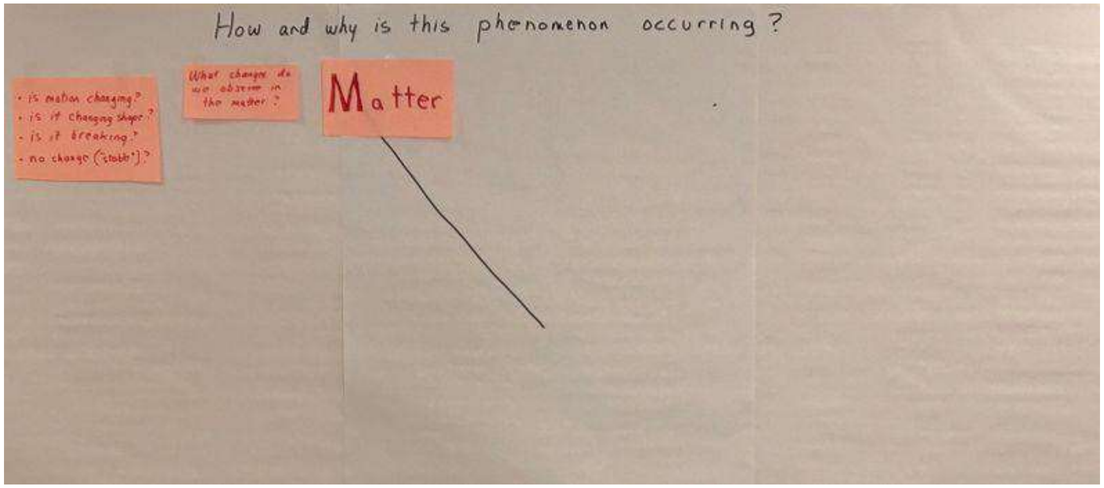
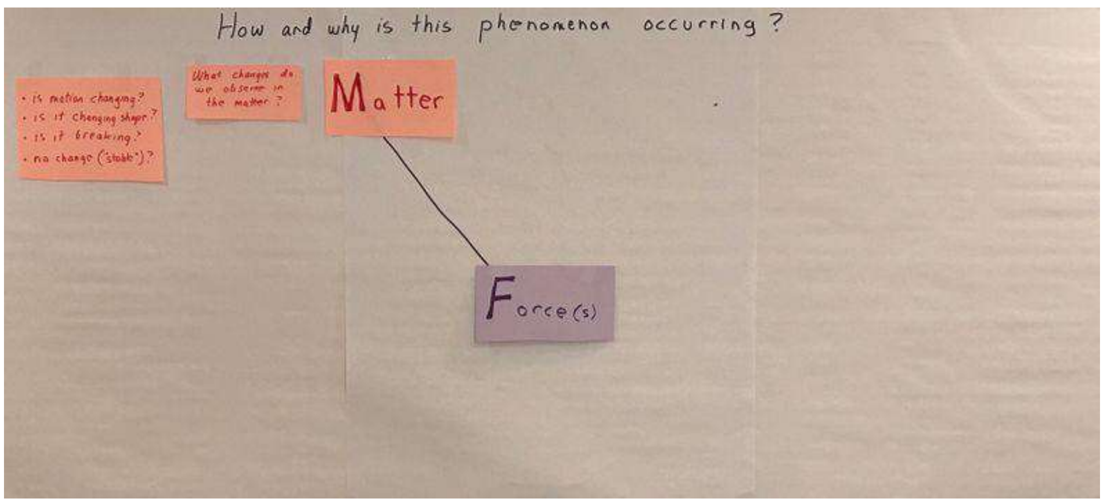
Follow up by asking, *Does this mean that whenever forces are acting on matter, it's going to change in one of these ways? Or is it possible that none of these things would happen?* Listen for the suggestion that there may be no change. Add this last possibility to the list of ideas:

- 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.

<table>
<tr>
<td>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.</td>
<td>
</td>
</tr>
<tr>
<td>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”.</td>
<td>
</td>
</tr>
</table>

ADDITIONAL 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*

GUIDANCE

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: Which fuels should we design our next generation vehicles to use? (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.

✱ 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

- 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.*

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/YwxIfBUDgqQ

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/YwxIfBUDgqQ 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/YwxIfBUDgqQ) 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.

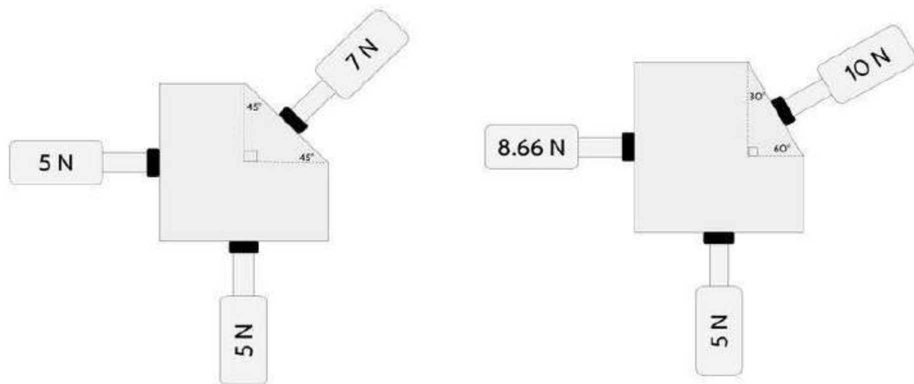
Present **slide Q**. Have groups follow the first prompt and raise their hands when they have agreed upon the conditions to test:

- *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

What to look for/listen for in the moment:

OPPORTUNITY	• 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.

✱ SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING

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)certainty in their results. ✱

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

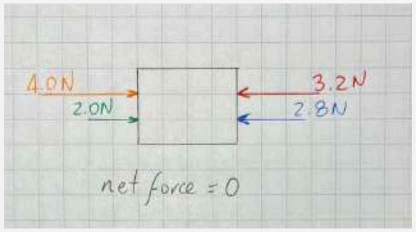
6 min

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. ✱

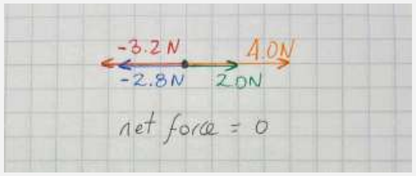


Explain that in a free-body diagram, each force is represented as a vector, and when vectors represent a quantity, we use an arrow to show its direction, scaling the arrow's length so it is proportional to the magnitude of the force.

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.

✱ 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.

- 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.

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)

✱ 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

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?*

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.*

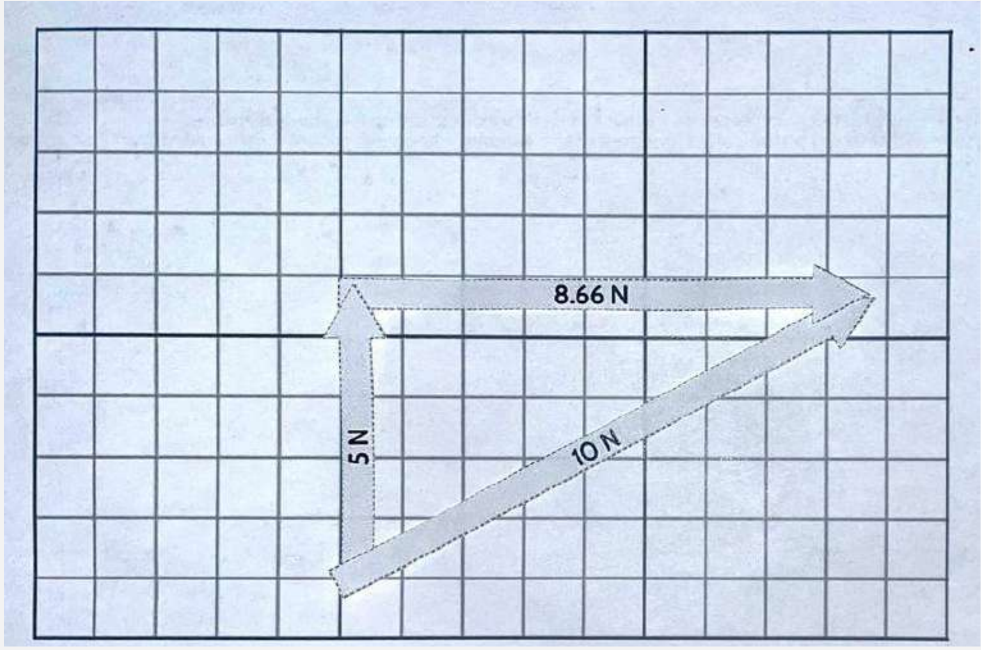
✱ SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

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.



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.

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

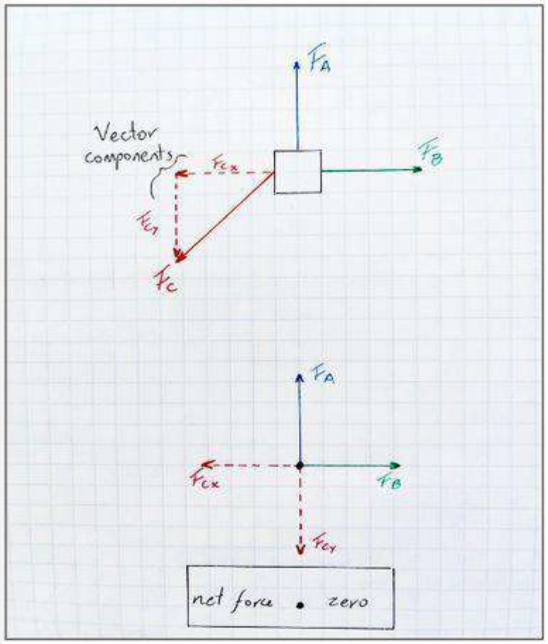
✱ SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

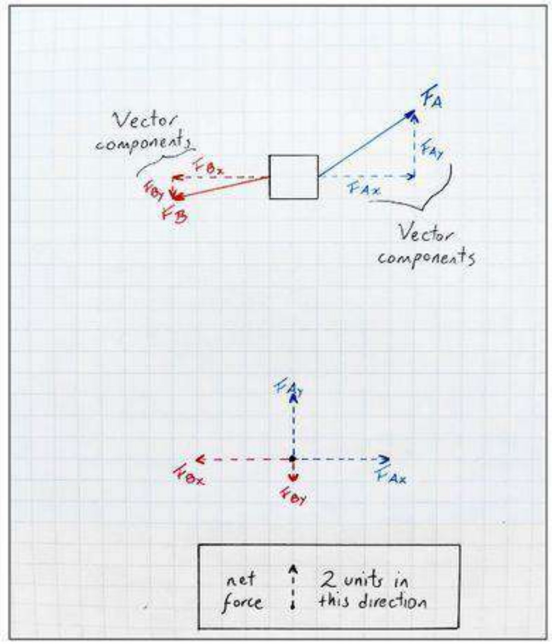
You may want to ask the math teacher(s) at your school how your students have used (or will use) the Pythagorean theorem this year. That theorem would have been developed in grade 8 in the CCMS (CCSS.MATH.CONTENT.8.G.7), but many applications and derivatives are explored in subsequent high school courses 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.

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.



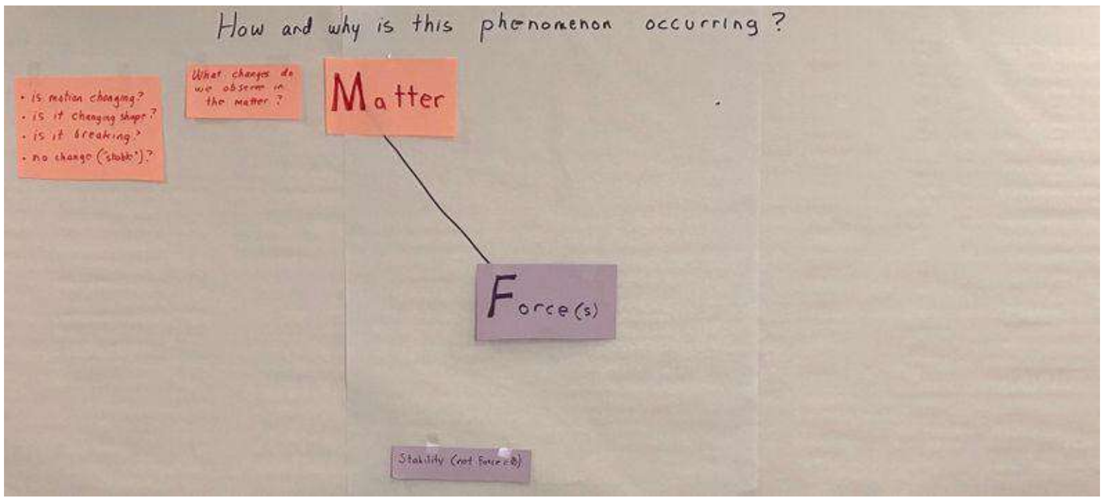


Connect to work in high school math. Note that in their math classes, students will continue to refine and develop mathematical tools that will enable them to do this analysis of any two-dimensional vector. ✱ Explain that for now, it is sufficient to simply recognize that there are ways to determine 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-IVsO4, 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.

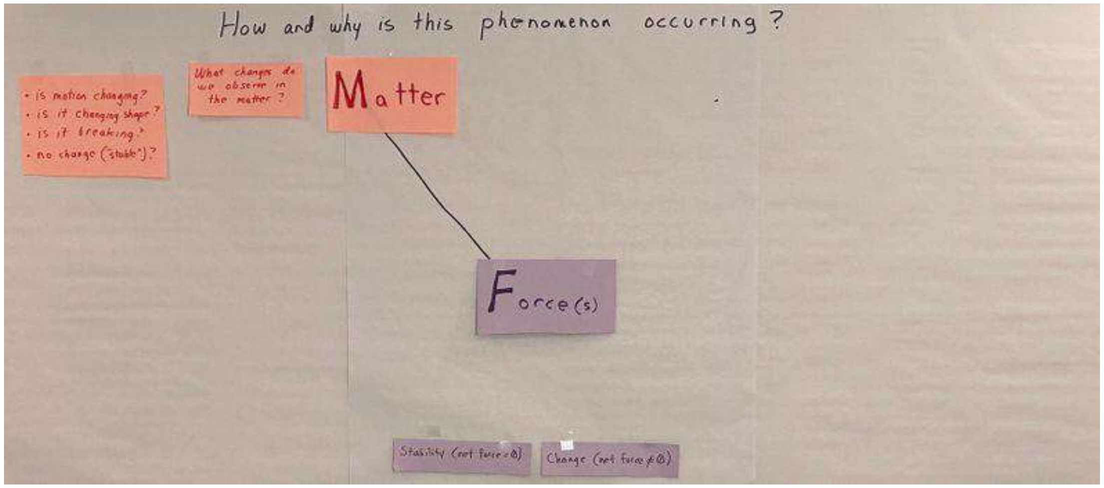
Display **slide DD**. Play https://youtu.be/LR1Ui-IVsO4 . If students sent you a slow-motion video from their investigation, you can show this as well, and ask them to describe the changes in motion they saw in the system.

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?*
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 ≠ 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:

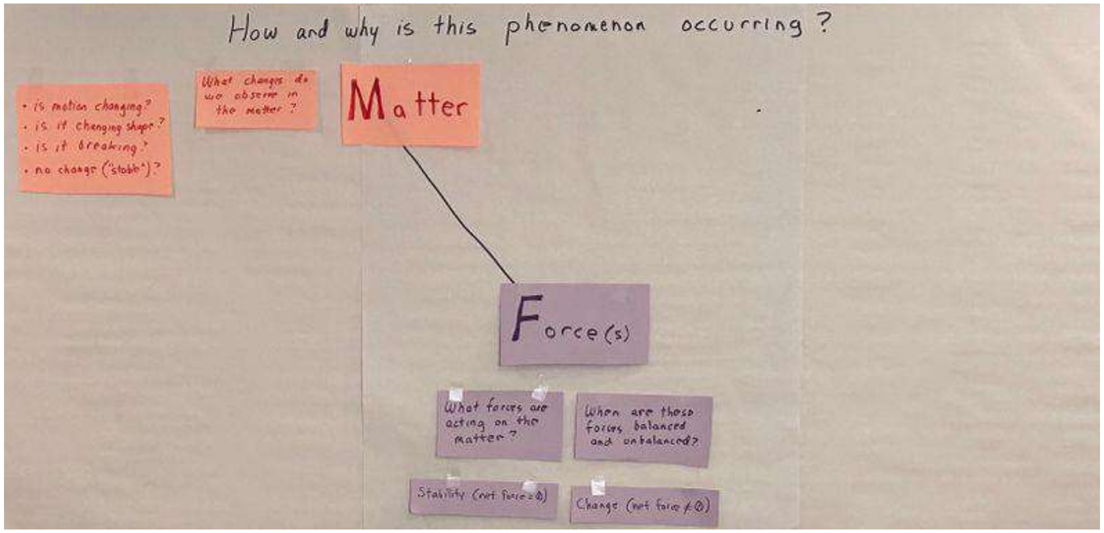
- Is the shape changing?
- Is the object moving?
- Is the change visible?
- What changes do we observe in the matter?
- What are the forces acting on the system?
- Are the forces acting on the matter balanced or unbalanced?

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_9qGMfkD1hqN7sARigc-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_9qGMfkD1hqN7sARigc-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
If we keep increasing the magnitude of these forces acting on a solid object, what do you predict would happen to it?	It could break. It could bend. It could crack.
What additional investigations does this suggest we need to do next time?	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.