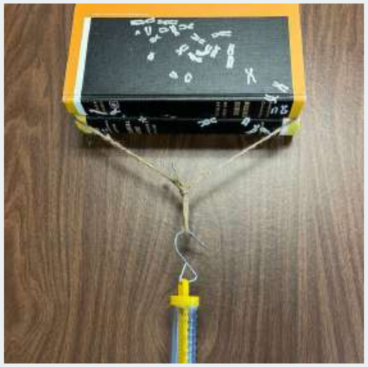
Lesson 11: How might forces between the mantle and plates affect plate motion?

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 *Friction Investigation*, 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 *Friction Investigation*. 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 *Friction Investigation*, 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 *Friction Investigation* 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 *Friction Investigation* and plate motion. Revise initial predictive models.	V-X	initial predictive model from day 1, *Rate and Direction of Plate Movement* from Lesson 10, Plate Interactions Consensus Model poster, M-E-F poster
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 • *Rate and Direction of Plate Movement* 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=miufUs3GPyJvIViO
- Friction Investigation Demonstration (part 2): https://youtu.be/idYX7kkRqbs?si=q4I9SKus4gvEkrU3 .

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.

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.

✱ 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.

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 platesis 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	Sample student response
What physical properties of the plates could cause differences in the forces acting on them?	Their density. Their thickness. Their mass/size. The type/shape of rock (texture). The other plates surrounding that plate. Their speed.

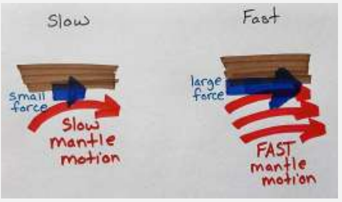
ADDITIONAL GUIDANCE	Though speed is not a physical property of a plate, students may still bring this up, as it has affected plate movement in prior lessons. The next investigation includes a demonstration showing that speed does not affect the force of kinetic friction.

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
What do our models have in common?	We are using arrows to represent forces. The size of the arrow represents the magnitude of the force. Some of us have included convection.
What are the differences between our models?	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

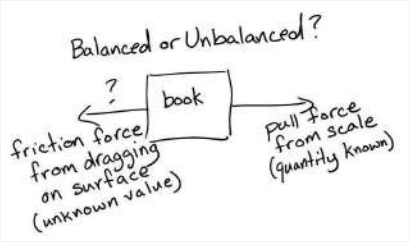
Problematize quantifying/measuring friction. Say, *To understand how friction might affect plate motion, we need to investigate what variables affect how friction interacts with moving plates. To do this, it would be useful to have a way to quantify or measure friction. How have we measured forces in 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?*

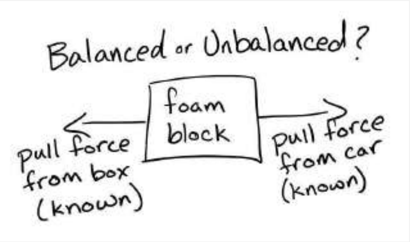


Start a free-body diagram on the board, depicting a book being dragged by a spring scale as shown on the slide. Ask what forces should be included and how they should be represented. Refer to the M-E-F poster's questions about system stability, and ask whether the forces should be balanced or unbalanced 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.

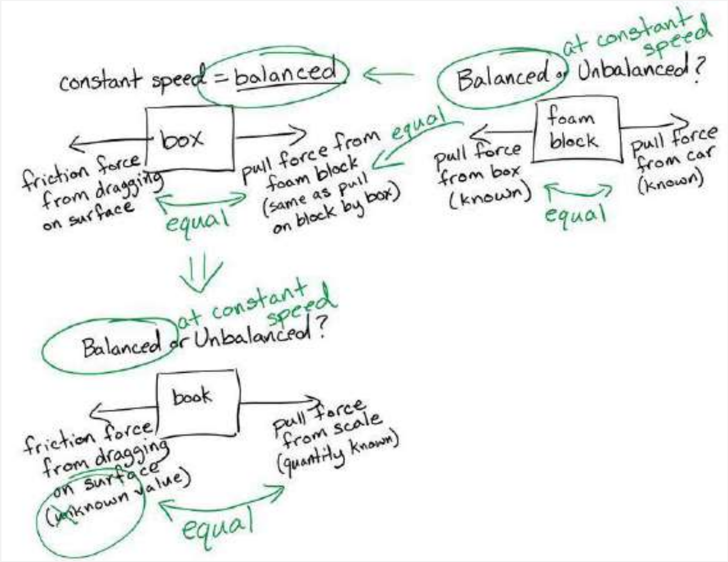


Present **slide L**. Point out the photo example of equal force readings, and pose the slide's questions:

- *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
What characteristics of an object might increase or decrease the force of friction acting on it?	Its size. Its material. The material of the surface. Its mass. Its shape.
Do we think these characteristics could also affect the force of friction acting on the plates? Why or why not?	Yes--maybe the more surface area there is, the more friction is acting on a plate.

✱ 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.

> 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).

ADDITIONAL GUIDANCE	If you are having trouble visualizing the lab, watch these videos: https://youtu.be/9w-ORd14Ucs?si=miufUs3GPyJvIViO 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
How could we alter our book/block-spring scale system to change one of these variables?	Add more books next to each other to increase the surface area.	*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?*

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
Where do we think plates are experiencing friction?	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.
How could we use our results from our Friction Investigation to help explain the plate motion that we have observed?	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.

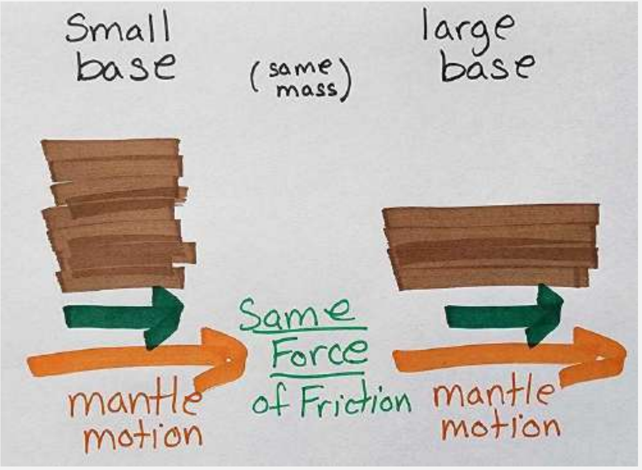
Point to the M-E-F poster and help students see how forces might be related to motion. For example, you can perform a simple demonstration of dragging a stack of books to show how different forces (pulling force and friction force) affect the motion. Suggest that we keep this relationship in mind, and forecast that a later unit will explore the relationship between forces and motion in more detail.

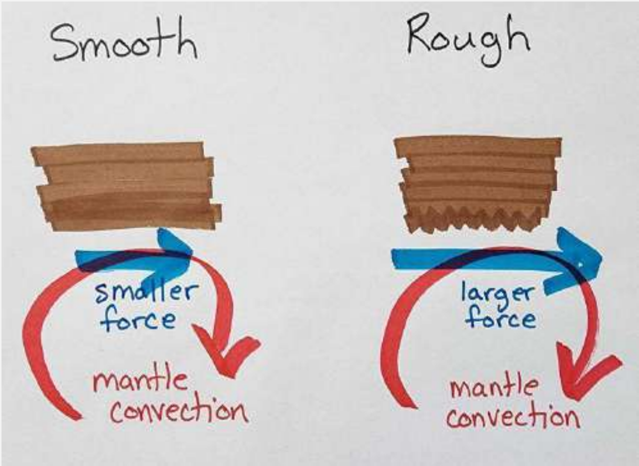
ADDITIONAL GUIDANCE	If students struggle to come up with ideas to answer this prompt, return to the Plate Interactions Consensus Model poster and highlight other directions that the plates are moving, like plates sliding down into the mantle or the oceanic crust moving upward at a divergent boundary. Students should suggest that some plates move upward. Follow up by asking, *Which force have we explored before that can cause up-and-down movement?* They should suggest gravity.

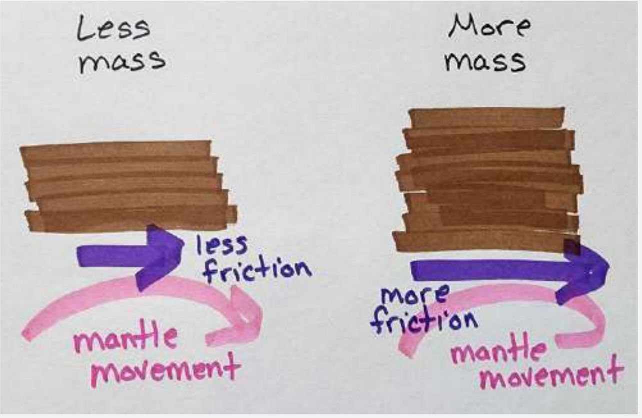
Revise predictive models into explanatory models. Present **slide X**. Return students' predictive models from day 1. Guide the class in the next task with the slide's prompt:

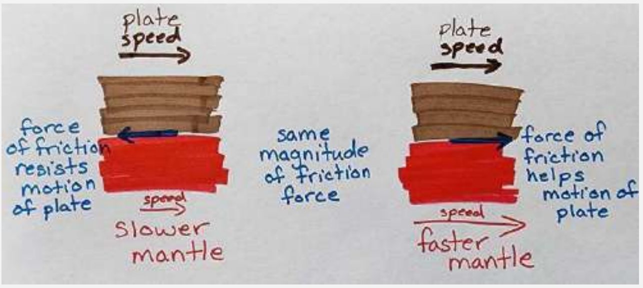
- *Use your initial predictive models and your findings from the Friction Investigation to model the relationship between friction and mass, surface area, or texture.*

Example student models are shown below.









ASSESSMENT	**What to look for/listen for in the moment:** Models should include:

OPPORTUNITY	• 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.