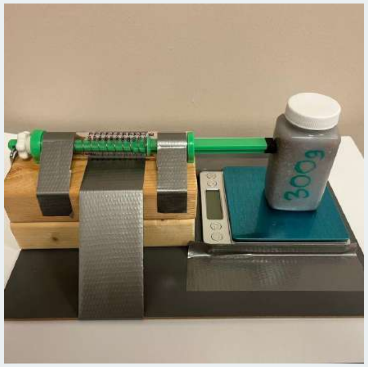
Lesson 12: How do forces act on objects, such as the plates, when they are on inclines?

Previous Lesson *We created initial models of how we thought forces acted on plates. We considered the properties of plates that might influence how forces act on them. We investigated the properties that we thought could affect the friction forces between an object and the surface it slides over. We connected our conclusions to plate properties and motion. We wondered how other forces could be acting on plates.*

This Lesson

Investigation, Putting Pieces Together

2 days



We model forces acting on plates and wonder how gravity can pull plates to cause changes in motion. We investigate forces on an object placed on an incline and model how the force of gravity can be split into two vector components to make sense of how gravity pulls down inclines. We connect this to plate motion and update our Plate Interactions Consensus Model poster from Lesson 10 and our Progress Trackers.

Next Lesson *We will revisit our Scale Chart poster to add processes and update connections. We will revisit our Driving Question Board. We will engage in a transfer task to explain why the Midcontinent Rift did not tear apart.*

BUILDING TOWARD NGSS

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

What students will do

12.A Use mathematical models to illustrate the force interactions (including gravity) between a plate and other systems to explain stability and change of plate motion that is too large and too slow to observe directly. (SEP: 2.3, 5.2; CCC: 3.2; DCI: ESS2.A.2)

What students will figure out

- The force of gravity can be broken into components that pull parallel and perpendicular to an incline, and as the incline gets steeper, the component of gravity parallel to the incline increases.
- The force of gravity on an object is directly proportional to the mass of the object.
- The force of gravity contributes to changes in plate motion through processes called slab pull and ridge push.

Lesson 12 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	2 min		**NAVIGATE** Reorient to the forces we identified as acting on plates, and identify gravity as the force to investigate next.	A	Plate Interactions Consensus Model poster, Forces and Variables poster
2	15 min		**MODEL GRAVITY** Review what we know about the force of gravity. Construct free-body diagrams of plates on various inclines, orient to a simplified system for investigation, and develop consensus for the free-body diagram of the simplified case.	B-G	plastic bottle, funnel, water or sand, small whiteboard, books or blocks, painter's tape, Model of Movement in the Mantle poster from Lesson 6 (optional), chart paper, chart paper markers
3	10 min		**DEVELOP A MATHEMATICAL MODEL FOR GRAVITY** Develop an equation for the force of gravity acting on an object of a given mass in grams.	H-I	push-pull spring scale (5N)
4	8 min		**PLAN AN INVESTIGATION ABOUT GRAVITY** Orient to the investigation setup, and use it to discuss the forces and variables that can affect an object on an inclined plane.	J-K	plastic bottle, funnel, water or sand, digital scale (3 kg max weight), push-pull spring scale (5N), protractor, small whiteboard, books or blocks, painter's tape
5	8 min		**CARRY OUT AN INVESTIGATION ABOUT GRAVITY** Measure forces on an object parallel and perpendicular to the incline it is on for multiple angles, observing what happens to the forces as the angle changes.	L	Measuring Forces on Inclines Investigation
6	2 min		**NAVIGATE** Record initial noticings about the data for the forces acting on an object on an incline.	M	
					End of day 1
7	2 min		**NAVIGATE** Revisit initial noticings about the data for the forces acting on an object on an incline.	N	
8	13 min		**REPRESENT FORCE DATA WITH COMPONENTS**	O-R	*Measuring Forces on Inclines Investigation*

			Review force vector components from Lesson 2. Draw free-body diagrams for the lab data and calculate the force of gravity using the indirectly measured components.		
9	12 min		**MAKE SENSE OF DATA AND CONNECT TO PLATE MOTION** Make sense of how the forces change with the angle, and connect this to mass. Consider what would happen if the forces become unbalanced. Connect lab findings to plate motion on the handout.	S-W	*Measuring Forces on Inclines Investigation*
10	7 min		**DEFINE FORCE PHENOMENA AT PLATE BOUNDARIES** Discuss forces within the context of divergent and convergent plate boundaries. Add to Personal Glossaries.	X-Z	
11	11 min		**ADD TO THE PLATE INTERACTIONS CONSENSUS MODEL** Update the Plate Interactions Consensus Model poster with friction and gravity ideas. Update Progress Trackers.	AA-CC	Progress Tracker, Plate Interactions Consensus Model poster, chart paper markers

End of day 2

Lesson 12 • Materials List

	per student	per group	per class
Measuring Forces on Inclines Investigation materials	• *Measuring Forces on Inclines Investigation*	• plastic bottle • funnel • water or sand • digital scale (3 kg max weight) • push-pull spring scale (5N) • protractor • small whiteboard • books or blocks • painter's tape	
Lesson materials	• science notebook • *Measuring Forces on Inclines Investigation* • Progress Tracker	• push-pull spring scale (5N)	• Plate Interactions Consensus Model poster • Forces and Variables poster • plastic bottle • funnel • water or sand • small whiteboard • books or blocks • painter's tape • Model of Movement in the Mantle poster from Lesson 6 (optional) • chart paper • chart paper markers • digital scale (3 kg max weight) • push-pull spring scale (5N) • protractor

Materials preparation (60 minutes)

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

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

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

Make 1 copy of the *Measuring Forces on Inclines Investigation* handout for each student.

Make sure that all students can easily see the Plate Interactions Consensus Model poster from Lesson 10 and the Forces and Variables poster from Lesson 11.

Day 1: *Measuring Forces on Inclines Investigation*

- **Group size:** 3-4 students.
- **Setup:**
    - Fill the plastic bottles with water or sand using a funnel so each bottle has a different mass between 300 and 500 grams. The different masses between groups set up a richer discussion about mass at the end. Prepare 1 bottle for each group plus 1 for demonstration.
    - Prepare a scale platform for each group with a small whiteboard or other small board, digital scale (3 kg max weight), and push-pull spring scale (5N). Using painter's tape, carefully tape the digital scale to the whiteboard on the edges so the scale plate is still free to move. Tape blocks, boxes, or books to the whiteboard next to the digital scale to create a platform for the spring scale to be level with about the middle of the bottle while it is on the digital scale. Tape the spring scale to the blocks with the plunger hanging over the digital scale. Test the setup as described in the *Measuring Forces on Inclines Investigation* handout to make sure the scales are free to work properly. See the example in the lesson image and the image within this lesson.
    - Provide each group with a protractor.
- **Notes for during the lab:** Look for students to follow the steps described in the handout when they collect their data. If they do not remove the bottle from the scale and tare it before the next reading, the reliability of their data will be compromised.
- **Storage:** Digital scales must be stored level and without weight on top of them. Storing them on their sides or with things on top of them may cause them to stop working or be less accurate.

Lesson 12 • Where We Are Going and NOT Going

Where We Are Going

In this lesson, we target the following disciplinary core idea (DCI):

- **ESS2.A.2: Earth Materials and Systems.** Evidence from ~~deep probes and seismic waves, reconstructions of historical changes in Earth's surface and its magnetic field, and~~ an understanding of physical ~~and chemical~~ processes lead to a model of Earth with ~~a hot but solid inner core, a liquid outer core,~~ a solid mantle and crust. Motions of the mantle and its plates occur primarily through ~~thermal convection, which involves the cycling of matter due to the outward flow of energy from Earth's interior and~~ gravitational movement of denser materials toward the interior. (HS-ESS2-3)

For this DCI, we investigate how gravity acts on objects on an incline to discuss what causes slab pull and ridge push at plate boundaries and how this can affect plate motion. This builds on the mechanisms for plate motion developed in Lesson 6 (convection) and Lesson 11 (friction with the mantle). Although the DCI describes plate motion as primarily caused by convection, in recent years scientists have come to accept that gravity through slab pull is the main driver of plate motion on Earth.

The SEP and CCC coverage of this lesson builds on extensive development across the unit:

- In Lesson 1, students begin their engagement with SEP 2.3 ("Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system") with the development of an initial predictive model based on observations of the anchor phenomena. In Lesson 6, they use data from a mantle tank video to develop a model for thermal convection within Earth's mantle. This model is then used in combination with tomography data in Lesson 7 to explain surface features. In Lesson 10, students pull together all the pieces so far into an overarching explanatory model that combines concepts from across the unit. In Lesson 11, they create predictive models about how friction is involved in plate motion and then revise these models based on data from their investigation.
- In this lesson, students add the final piece of the force of gravity and update their model from Lesson 10 with friction and gravity. This updated model will then be used for the assessment in Lesson 13. The use of this SEP element in this unit differs from its development in *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*, in which models were primarily energy transfer models. In this unit, students use and develop a variety of models, including free-body diagrams, particle-level representations of matter, and illustrated explanatory system models.
- Students engage throughout this unit with CCC 3.2: "Some systems can only be studied indirectly as they are too small, too large, too fast, or too slow to observe directly." Development of the Scale Chart poster helps them to track processes at both large and small spatial and temporal scales. In this lesson, students use an investigation of small objects on inclines to make sense of much larger, slower processes of changes in plate motion due to the force of gravity.

Students encounter and/or co-construct ideas around several terms during this lesson, and may decide to add the following words to their Personal Glossaries: *slab pull* and *ridge push*. **Do not** ask students to define or keep track of any words until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

For the DCI above, we do not specifically talk about deep probes and seismic waves, reconstructions of historical changes in Earth's surface and magnetic field, chemical processes, nor convection moving mantle material. These topics were discussed in previous lessons and built into the Plate Interactions Consensus Model developed in Lesson 10, to which the physical processes of gravitational forces are added in this lesson.

LEARNING PLAN for LESSON 12

1 · NAVIGATE

2 min

MATERIALS: Plate Interactions Consensus Model poster, Forces and Variables poster

Revisit the Lesson 11 exit ticket. Make sure everyone can easily see the Plate Interactions Consensus Model poster and the Forces and Variables poster. Present **slide A**. Say, *Last time, we investigated the role of friction on an object's motion, and we found that some plate variables affect the force of friction acting on a plate. But we think other forces are involved. Let's consider what we should investigate next.*

Give the class a moment to review their exit tickets from the end of Lesson 11. Ask a few students to share out. Listen for suggestions that we should investigate the force of gravity. If gravity is not mentioned, point to the Plate Interactions Consensus Model poster to focus students' attention to the motion of plates sliding down inclines into the mantle.

2 · MODEL GRAVITY

15 min

MATERIALS: science notebook, plastic bottle, funnel, water or sand, small whiteboard, books or blocks, painter's tape, Model of Movement in the Mantle poster from Lesson 6 (optional), chart paper, chart paper markers

Review the vector nature of gravitational forces. Present **slide B**. Use the prompt to elicit student ideas, as shown below.

Suggested prompt	Sample student response
What do we know about how the force of gravity acts on objects?	Gravity pulls down (inward toward Earth's center). Gravity acts on everything that has mass. Gravity is why things fall.

Use student ideas to review that forces, including gravity, are vectors that have both magnitude and direction, and that if an object is stable (stationary or moving at a constant velocity), the forces on it are balanced.

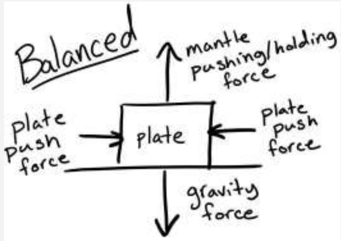
✱ ATTENDING TO EQUITY

Universal Design for Learning: The *representations* used by students in free-body diagrams do not need to match any specific convention. What is important is to have a shared understanding of what each piece means. Allow students agency over these representations, and do not try to force them into any specific convention without an expressed need that the students understand.

If students do not mention gravity, quickly ask them to recall the forces used in Lesson 6 to explain the movement of other systems, such as the mantle and mantle tank. Display the Lesson 6 Model of Movement in the Mantle poster and ask what forces in the mantle tank might also be affecting the stable plate. Guide students to determine that gravity would be present in both models.

Model forces on a stable plate. Present **slide C**. Say, *Let's model the force of gravity acting on Earth's plates, starting with a very simplified case.* Use the slide's prompts to guide students to draw a free-body diagram:

- *Consider the simplified, stable plate system of a plate squeezed between two plates, all sitting on top of the mantle.*
    - *Draw a free-body diagram of the forces on the middle plate.* ✱
    - *If the plate motion is not changing, what do we know about the forces?*



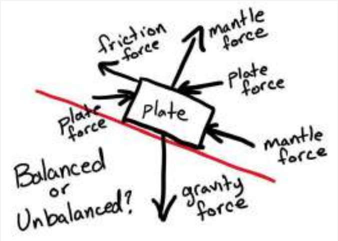
Give students 1-2 minutes to draw the free-body diagram in their notebooks. Have a couple of volunteers draw their diagrams on the board. Use these to come to an agreement on the diagram through a quick class discussion of similarities and differences. Be sure to establish that the forces are balanced, both vertically and horizontally. An example of this diagram is shown to the right.

Problematize the simplified model. Say, *These free-body diagrams show a super-simplified scenario, but they're a good baseline for us to work from. Let's use them to expand to the more complex plate scenarios that motivated us to think about gravity in the first place.*

Present **slide D**. Have students work with a partner to draw a free-body diagram for a plate at a divergent boundary, and to consider whether the forces are balanced or unbalanced.

Ask a few pairs to draw their diagrams on the board. Facilitate discussion around these examples to highlight the complexity of the scenario and the unknowns, such as whether there is friction, what direction it points, and whether the forces are balanced. Do not try to build a correct or consensus model here; the purpose is to highlight complexity and unknowns.

Present **slide E**. Repeat the process for a convergent boundary. The force diagrams for these are likely to get very messy, and students are likely to have many questions or disagreements on details. An example of a proposed free-body diagram is shown to the right.



In the discussion about balanced versus unbalanced forces, highlight the need to know more about how the plates are or are not changing motion. Listen for students to reason about the temporal and spatial scale of the changes and what would tell us whether the forces are balanced.

Present **slide F**. Read the prompt aloud:

- *What do we think are the differences in the forces acting on the plate at points A and B?*

Mention that point A is an early convergent boundary and point B is a convergent boundary with significant overlap and subduction. Listen for students to offer ideas about gravity pulling on B differently because there is more of an incline.

ASSESSMENT OPPORTUNITY	**What to look for/listen for in the moment:** Students to talk about: • Using their free-body diagram models to support their claims or explanations about plates. (SEP: 2.3, 5.2; DCI: ESS2.A.2) • The force of gravity pulling on plate systems and affecting plate motion. (SEP: 2.3; DCI: ESS2.A.2) • That we cannot directly measure the force of gravity on plates or their motion because they are too large and too slow. (CCC: 3.2; DCI: ESS2.A.2) • How the mantle and plates interact and how this changes based on how they are configured at plate boundaries (e.g., how tilted the plate is on the mantle). (SEP: 2.3; DCI: ESS2.A.2) **What to do:** This formative assessment is followed by an individual written assessment near the end of the lesson. If students struggle with the connection between gravity and plate motion, support sensemaking about these ideas throughout the rest of the lesson. Use probing questions to elicit student thinking about the forces in the simplified setup, and how this connects to the plates. **Building toward: 12.A.1** Use mathematical models to illustrate the force interactions (including gravity) between a plate and other systems to explain stability and change of plate motion that is too large and too slow to observe directly. (SEP: 2.3, 5.2; CCC: 3.2; DCI: ESS2.A.2)

Define a simplified model for plates on inclines. Say, *Our models and thinking about these boundaries seem to confirm that we need to know more about gravity, especially how it behaves with inclines. Our models also highlight the complexity and unobservable temporal and spatial scales of the plates. To investigate how gravity acts on inclines, we need to use a simplified model.*

Present **slide G**. Display one of the bottles for the lab on a small whiteboard with a book or block in place of the spring scale, as shown on the slide and to the right. Explain that, because the surfaces of the bottle and whiteboard are both very smooth, we can ignore friction for this system. Ask students to individually follow the prompts on the slide:

- *Draw a free-body diagram for the bottle.*
- *If the bottle stays sitting there, are the forces balanced or unbalanced?*
- *What would happen if the incline were increased?*

Use student input to create a consensus on what this free-body diagram should look like (an example is shown to the right) and whether the forces are balanced. Create this model in a way that can be kept to reference during the next class, because students may want to revisit it during the *Midcontinent Rift Transfer Task*. If wall space is short, consider making this model on a whiteboard with dry erase markers. Listen for students to say that the forces might become unbalanced or change in some way if the incline is increased.

ADDITIONAL GUIDANCE	A major concept further developed across this unit is that of balanced and unbalanced forces. In this lesson, the concept of balanced forces being equal strengths and opposite directions is important. However, note that these are **not** Newton's third law force pairs, as these forces are acting on the same object. If students use language such as "action/reaction" or bring up Newton's third law, emphasize that those concepts are related to interaction forces between two objects as opposed to multiple balanced forces on the same object.

3 · DEVELOP A MATHEMATICAL MODEL FOR GRAVITY

10 min

MATERIALS: push-pull spring scale (5N)

Discuss how to measure forces. Present **slide H**. Say, *OK, we want to investigate the role of gravity acting on plates, but we know we can't investigate plates directly. Similarly to our Friction Investigation in the last lesson, we'll need to use a simpler object in the classroom.* Pose the slide's questions to the class, as shown in the table below.

Suggested prompt	Sample student response
What tools have we used to measure forces in the past?	A spring scale. A digital scale.
How could we use these tools to measure how much gravitational force is acting on an object?	We can hang the object on a spring scale and read the force. We put the object on a digital scale and it tells us how much it weighs.
How could we use them on the incline?	We could place the scale below the bottle on the incline.

If it is not brought up, talk about how, if you hang something from a spring scale, the scale reads the amount of force it pulls up with, which must be balanced with the force of gravity, therefore telling us the magnitude of the gravitational force. If necessary, draw a free-body diagram to illustrate.

If students do not mention a digital scale, or if they mention something like a bathroom scale, bring out a digital scale and show that when you press on it (gently), the number changes, so it seems to be measuring force too, but it is giving a readout in grams/kilograms.

Develop a mathematical model for gravity. Present **slide I**. Distribute spring scales to every pair/group of students, or use the image on the slide to elicit noticing and wonderings. Give students a minute to look at the spring scale before inviting them to share.

Students should recall from Lesson 2 that a spring scale gives readings in both grams and newtons. Ask them to now consider the relationship between grams and newtons on the scales. Expect them to notice that for any measurement, newtons are about 100 times larger than grams.

Ask what the unit grams is typically used to measure; listen for students to say mass. Say, *Mass and the force of gravity are related. We won't be investigating why this relationship exists until the Meteors Unit, but we can figure out the mathematical relationship between mass and gravity with the spring scales, using grams as a proxy measurement for the force of gravity.*

ADDITIONAL GUIDANCE	In previous lessons, students worked with spring scales and should have noticed that these use grams and newtons as units. When considering the relationship between these, they may notice that it is not exactly 100 grams = 1 newton. This is OK, but for the sake of the investigation, guide them into using the approximated value (alternatively, you could use 102 grams = 1 newton, which is more precise). Note that we are not converting to kilograms or taking the reciprocal to get to 10 N/kg. Although this is the traditional form, it is not necessary for establishing the proportionality of mass and the force of gravity, and could introduce confusion.

Then ask, *What do we mean that newtons are 100 times larger than grams? Can you give me a few examples*? After a few volunteers share, continue by asking, *Can we use this to write out a ratio that we can use to convert from grams to newtons?* Write the examples on the board as mathematical equations. For example:
5N x 100 = 500 g
10N x 100 = 1000 g
1N x 100 = 100 g

Say, *Let's use our findings to write a mathematical model for the force of gravity based on mass. We can start by substituting variables for the values we read according to the units.* Ask what variable the newtons should become, and write "Force of Gravity" on the board. Then write the "x

100 =" and ask what variable the grams should become, adding "mass" to the end of the equation when prompted by students. This should look like "Force of Gravity x 100 = Mass".

Continue, *Now let's figure out what the units of this 100 are*. Look for students to rearrange the equation to get 100 on its own; guide them to show that the units of 100 are g/N.

Say, *Because we're developing a model for the force of gravity, we should solve for that. How should we rearrange the equation to solve for the force of gravity?* When prompted by students, divide both sides of the original equation by 100 and rewrite the equation as "Force of Gravity = Mass/(100g/N)".

Reason about proportionality. Ask what would happen to the force of gravity on an object if its mass doubled, tripled, and so forth. Then introduce the term "directly proportional" to describe the relationship between the force of gravity on an object and the object's mass.

Say, *We can measure many types of forces with the spring scales, but the mass markings on them assume that we're using a force of gravity measurement to find mass by hanging the object from a single scale. The markings don't read the mass of objects when using them for something like the friction forces we measured.*

Continue, *Similarly, the digital scale assumes we're measuring mass by placing an object on it on a level surface. But really, it's measuring the force that it has to push back with to balance the gravity pulling down on the object. Therefore, even though the digital scale reads grams, we can use it to gather force data.*

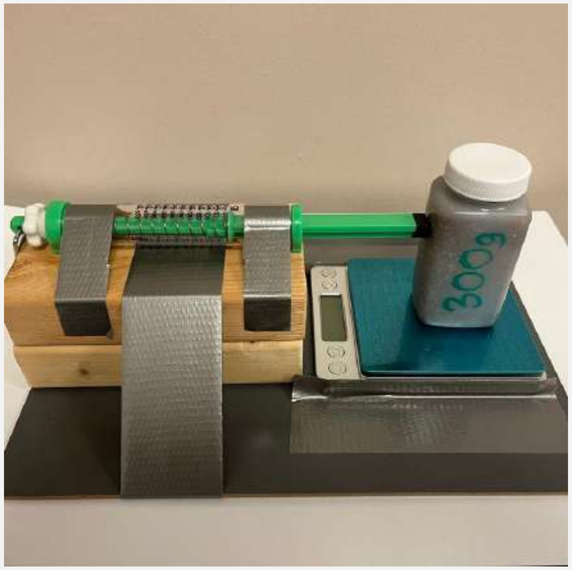
ADDITIONAL GUIDANCE	Some students might be confused about the force of gravity being different on different objects, due to seeing things such as a feather and hammer being dropped on the moon. Affirm and keep track of questions, reassuring them that the phenomenon of how things fall will be addressed in the *Meteors Unit*. Then, to help them understand the relationship for how much the force of gravity pulls, talk about how it is the amount of force per amount of mass that is constant: every 100 g of mass is pulled on by 1 newton of gravitational force. One way to help clarify this is to use "force of gravity" language as opposed to simply saying "gravity". Students have not yet developed an understanding of the concept of acceleration, so it is best not to complicate things by discussing acceleration due to gravity; instead, concentrate on "gravitational field strength" or force of gravity per unit mass. Acceleration will be covered in the *Vehicle Collisions Unit*.

4 · PLAN AN INVESTIGATION ABOUT GRAVITY

8 min

MATERIALS: plastic bottle, funnel, water or sand, digital scale (3 kg max weight), push-pull spring scale (5N), protractor, small whiteboard, books or blocks, painter's tape

Orient to the lab setup. Present **slide J**. Introduce the setup, which is similar to the one shown in the image above. Show students how to use a protractor to measure the angles they will use. Use the slide's prompts to elicit ideas, as shown in the table below.



Suggested prompt	Sample student response
What force is the digital scale measuring?	The force the surface exerts on the object.
What force is the spring scale measuring?	How much force is on the bottle.
We said forces are vectors, and vectors have a magnitude and direction. What is the direction of each force?	The force the surface exerts on the object is perpendicular to the surface. The force down the incline acting on the bottle is parallel to the surface.
When are the forces acting on the bottle balanced?	When the object is not moving.

When the force pulling down the incline is equal to the force of the spring scale pushing up the incline.

When the force that the digital scale exerts on the bottle is equal to the force pulling the bottle into the incline (how much the incline is getting in the way).

Consider additional variables. Present **slide K**. Ask the question:

- *Besides inclination (a.k.a. tilt angle), are there any other variables that could affect the forces we read with our scales?*

Listen for students to suggest the mass of the bottle. Say, *Because the mass was also a plate variable that we thought was connected to forces, we could investigate the role of mass as well. I have bottles between 300 and 500 grams. Your group needs to choose which mass to work with, and then compare your results with groups who investigated the other mass.*

ADDITIONAL GUIDANCE

If students wonder why we have the digital scale measuring the force perpendicular to the incline, point out that when the incline is flat, it reads the force of gravity, and when the incline is 90 degrees, the spring scale measures the force of gravity. Use this to motivate looking at both values as the angle changes.

5 · CARRY OUT AN INVESTIGATION ABOUT GRAVITY

8 min

MATERIALS: Measuring Forces on Inclines Investigation

Carry out an investigation of gravity. Present **slide L.** Distribute the *Measuring Forces on Inclines Investigation* handout to each student. Orient them to the table in Section 1 where they will record their data. ✱ This is a very short investigation, with only 5 data points to collect. Sample data for a 500-g bottle is shown below:

Angle	Force on Spring Scale (N)	Mass on Digital Scale (g)	Force calculated from Digital Scale (N)
0	0	500	5
30	2.5	433	4.33

✱ **ATTENDING TO EQUITY**

Students with physical disabilities may have a hard time holding the platform at a steady, specific angle while also reading the scales. For students who struggle with this task, provide additional books or blocks for them to set the platform at an angle. They may need an extra book to keep the platform from sliding as well.

45	3.5	354	3.54
60	4.3	250	2.5
Choose your own angle:	(mass/100)*sin(θ)	mass*cos(θ)	[mass*cos(θ)]/100

6 · NAVIGATE

2 min

MATERIALS: None

Record noticings. Present **slide M**. Orient students to Section 2 of the *Measuring Forces on Inclines Investigation*, and have them record their noticings from their data collection so far.

End of day 1

7 · NAVIGATE

2 min

MATERIALS: None

Revisit noticings so far. Present **slide N**. Reorient the class to Section 2 of the *Measuring Forces on Inclines Investigation*, and to the investigation question at the top. Ask a student to remind the class what we were investigating and why. Allow others to suggest additional details or ideas. Be sure that the discussion talks about not only the bottle and gravity on an incline, but also the forces on plates that we are modeling.

Give students a moment to review their noticings from their data collection in the last class.

8 · REPRESENT FORCE DATA WITH COMPONENTS

13 min

MATERIALS: *Measuring Forces on Inclines Investigation*

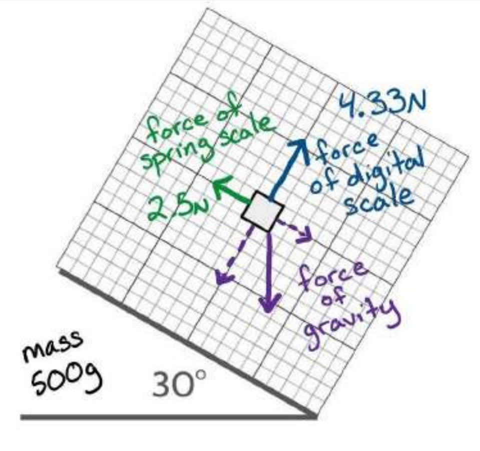
Review force components. Revisit the free-body diagram for the bottle, either by displaying the version from day 1 or by recreating it. Relabel the forces as being applied by the digital and spring scales. Present **slide O**. Pose the question:

- *How have we dealt with forces at angles before?*

Listen for students to mention force components or ideas about splitting the force at an angle into pieces. If they do not, remind them about the foam and spring scales from Lesson 2 and how we drew the components of the forces that were at an angle. If needed, go through the Lesson 2 example again, drawing the dashed lines for the components of the angled force.

Turn back to the free-body diagram of the bottle and ask which force(s) we should break into components. If students say gravity, probe them to explain how. If they say the forces applied by the scales, point out that these are perpendicular, like the two that weren't split in Lesson 2. Say, *A convention that scientists came up with to make this process easier is to rotate the grids we use to consider the forces to align with the ramp. That way we only need to break the force of gravity into components.*

Represent data with force components. Present **slide P**. Ask students to use their data to draw free-body diagrams of the forces on the bottle for 30, 45, and 60 degrees. If they struggle to remember how to do this, draw the first one together using student data, or do an example with a bottle of a different mass. Give them a few minutes to complete their diagrams. An example diagram for a 500-g bottle at a 30-degree angle is shown.



Present **slide Q**. Have students turn and talk about their free-body diagrams using the prompts:

- *How do the forces of gravity at each angle compare?*
- *How do the components compare?*

Ask a few pairs to share out. Listen for them to say that the force of gravity doesn't change from angle to angle, but the components change. Take a moment to discuss why this is. Be sure to note that how much the force of gravity pulls isn't changing, because the mass of the bottle doesn't change, but changing the angle changes which scale has to push more to balance out that component of gravity.

Calculate the force of gravity using its components. Remind students that when we drew force components, we could also use the Pythagorean theorem to combine these to determine the whole force. Present **slide R**. Ask them to complete the slide's tasks on the *Measuring Forces on Inclines Investigation* handout:

- *Use the Pythagorean theorem to add the force components together to calculate the force of gravity that the two scales are balancing out.*
- *Compare these values to the force of gravity you measured/calculated at the beginning of the lab.*

9 · MAKE SENSE OF DATA AND CONNECT TO PLATE MOTION

12 min

MATERIALS: *Measuring Forces on Inclines Investigation*

Make sense of how the angle changes the forces. Present **slide S**. Pose the questions:

- *As the angle changes, what happens...*
    - *...to the force of gravity acting on the bottle?*
    - *...to the force on the bottle from the digital scale?*
    - *...to the force on the bottle from the spring scale?*

Listen for students to say that when the angle increases, the force of gravity stays the same, the digital scale force decreases, and the spring scale force increases.

Connect to mass. Present **slide T**. Ask students to turn and talk about the prompts:

- *What would happen to the component of gravity pulling down the ramp if the mass were doubled?*
- *What if the mass were decreased to half?*

Have a few pairs share out. Listen for them to say that doubling the mass would double the gravity, which would double both components of the force of gravity, and that halving mass would halve the components.

Present **slide U**. Take a moment to discuss how a plate could have more mass by being either thicker or more dense, using the first prompt:

- *How could one plate have more mass than another?*

Then, ask the second prompt:

- *How can plates at convergent boundaries still slide down inclines when they are sliding into the mantle?*

Guide students to make connections to the convection model from Lesson 6 through the density differences between the plates. Both plates are being pulled by gravity, but the bottom plate is denser and therefore is pulled down into the mantle.

Consider unbalanced forces. Say, *In the Measuring Forces on Inclines Investigation, the forces were always balanced, but we are trying to make sense of the plates and what they do when the forces are balanced and unbalanced.* Present **slide V**. Pose the questions on the slide:

- *What happened to the foam plates squished between the spring scales in Lesson 2 when we removed one of the spring scales?*
- *What would this look like on an incline/with plates?*

Listen for students to remember that when the spring scale was removed, the foam plates suddenly moved until they found a new resting position, and to propose that something similar would happen on an angle, likely with the bottle/plate starting to move down the incline.

Connect gravity to plate motion. Present **slide W**. Reorient students to the *Measuring Forces on Inclines Investigation* handout and have them complete Section 4. Encourage them to use free-body diagrams, drawings, and words to map the connections made in this lesson's investigation to the stability and change of the plates. Collect the handout to review students' responses.

ASSESSMENT OPPORTUNITY	**What to look for/listen for in the moment:** Look for student models and explanations to show (SEP: 2.3): ● The force of gravity pulls plates toward Earth's center/down, but a component of it also pulls things down inclines. (SEP: 2.3, 5.2; DCI: ESS2.A.2) ● Component forces are mathematically related to the force they make up according to the Pythagorean theorem. (SEP: 5.2) ● Relationships between the systems of the plates, mantle, and gravity can be balanced or unbalanced to keep plates stable or cause changes in plate motion. (SEP: 2.3; DCI: ESS2.A.2) ● Plate motion and changes in motion are too big and happen on timescales that cannot be directly observed, but forces on plates can be modeled at various scales. (CCC: 3.2; DCI: ESS2.A.2) **What to do:** If students struggle with these connections to plate motion, take some time to review (as a class or in groups) the connections using the Plate Interactions Consensus Model poster updated at the end of this lesson, before moving on to the assessment in Lesson 13. Students will use the updated model poster in that assessment, so it is important to address confusion beforehand. **Building toward: 12.A.2** Use mathematical models to illustrate the force interactions (including gravity) between a plate and other systems to explain stability and change of plate motion that is too large and too slow to observe directly. (SEP: 2.3, 5.2; CCC: 3.2; DCI: ESS2.A.2)

10 · DEFINE FORCE PHENOMENA AT PLATE BOUNDARIES

7 min

MATERIALS: science notebook

Consider divergent and convergent plate boundaries. Present **slide X**. Pose the questions on the slide, referring students to the two images showing the development of a divergent boundary:

- *How is an incline being formed at this divergent boundary?*
- *How is gravity acting on the plates at this boundary?*

Listen for students to say things such as the magma pushing up causes a type of incline that thins the plate/crust, and gravity pulls the plates away from each other as the magma creates new crust.

Present **slide Y**. Repeat the process for convergent boundaries. Listen for students to say things such as gravity is pulling the plate under the other and into the mantle, and it would pull more as it becomes more slanted. They may also mention something about density of the plates and that the plate going into the mantle must be denser.

Add entries to Personal Glossary. Present **slide Z**. Say, *Scientists have terms for how the force of gravity pulls down on plates. At a subduction zone of convergent boundaries, they call it "slab pull". At a divergent plate boundary, they call it "ridge push".* Give students time to add definitions to their Personal Glossaries, which may include *slab pull* and *ridge push*.

ALTERNATE ACTIVITY	**Extension opportunity:** There is the opportunity to discuss how, within the *Friction Investigation* of Lesson 11, increasing the mass is really increasing the pressing forces between the surfaces, and decreasing this force (without changing mass) would decrease friction. This can be connected to the digital scale reading in this lesson's *Measuring Forces on Inclines Investigation*, and how increasing the mass increases the perpendicular component of the force of gravity. To extend this conversation, you could also discuss how increasing the incline made the perpendicular component of gravity read by the digital scale decrease, and how this means that friction would decrease as the angle increased.

11 · ADD TO THE PLATE INTERACTIONS CONSENSUS MODEL

11 min

MATERIALS: science notebook, Progress Tracker, Plate Interactions Consensus Model poster, chart paper markers

Revisit and revise the consensus plate model. Present **slide AA**. Be sure that the Plate Interactions Consensus Model poster is visible to everyone. Ask students to individually review the model for a couple of minutes, and consider what should be added from the friction and gravity investigations. Present **slide BB**. Say, *Let's bring our ideas together and add to or revise our consensus model.* Ask students to share and discuss their ideas for changes to the model, and update the poster.

Update the Progress Tracker. Present **slide CC**. Direct students to turn to their Progress Trackers and record what we figured out from investigating friction and gravity in Lessons 11 and 12. Give them the rest of the period to complete this update. Before they leave class, point out that we have learned a lot about the movement of plates. Suggest that next time, we can apply our ideas to explain a rift that occurred where the United States is located today!

Additional Lesson 12 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH	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 use the concept of vector components within the context of forces to solve for the force of gravity on an object from measured forces that balance with the components of gravity. **Geometry:** ● **CCSS.MATH.CONTENT.HSG.SRT.C.8** Use trigonometric ratios and the Pythagorean Theorem to solve right triangles in applied problems. Students use the Pythagorean theorem to identify the relationship between the components of gravitational force acting on an object on an incline. This builds on ideas developed at the end of grade 8, when they learned to apply the Pythagorean theorem to determine the unknown side lengths in right triangles in real-world and mathematical problems in two dimensions. Use mathematical and geometrical representations to support students' sensemaking of this relationship.