Lesson 6: How is temperature related to the behavior of the matter in the mantle?

Previous Lesson *We analyzed seismic velocity anomalies to infer that Earth's interior is not entirely solid. We used a model of Earth's layers and a simulation to make sense of our observations. Then we zoomed in to a local scale to investigate the connection between mantle matter properties and surface features across the globe. Finally, we revised our model of Earth's layers to include a heterogeneous mantle and added to our Progress Trackers.*

This Lesson

Investigation

2 days

We look back at our tomography data and create a predictive model of the movement of the mantle. We analyze a video of a tank containing a mixture of liquid and plastic pellets simulating the matter in the mantle to figure out what happens to the matter when heat is added. We utilize the M-E-F triangle to create a model to explain the thermal convection in the mantle.

Next Lesson *We want to know where the heat comes from that drives mantle convection, so we will jigsaw a series of articles that answer this question from forces, matter, and energy perspectives. We will develop a cause-effect model to explain how radioactive decay results in heat in Earth's mantle.*

BUILDING TOWARD NGSS

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

What students will do

6.A Develop a model to explain the relationship between energy transfer and the motion of matter in a solid material via thermal convection and the motion of particles. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)

What students will figure out

- Increasing the temperature of matter in the mantle causes particles to move faster and farther apart, occupying a larger volume that results in a lower density.

- In different parts of the mantle, the relationship between the gravitational force and the pushing force from the matter beneath explains the cycling of matter in Earth's interior through convection.

Lesson 6 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	4 min		**NAVIGATE** Revisit the Lesson 5 exit ticket. Discuss the role of temperature in the mantle and its effect on matter changes.	A-B	exit ticket from Lesson 5
2	6 min		**DEVELOP EXPLANATORY MODELS OF THE MANTLE UNDER AFAR** Use the *Afar Mantle Model* handout to create an explanatory model of mantle movement using tomography data.	C-D	*Afar Mantle Model*
3	6 min		**INTRODUCE THE MANTLE TANK** Discuss how a tank filled with matter could serve as a scaled-down model of the mantle. Consider how it could be used to test our models of what is happening in the mantle under Afar.	E-I	
4	13 min		**ANALYZE VIDEO FROM THE MANTLE TANK** Analyze the video of the mantle tank investigation as a class.	J	*Mantle Tank Model*, https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOHtsy
5	6 min		**USE M-E-F PERSPECTIVES TO EXPLAIN THE MANTLE TANK** Create an explanatory model of the mantle tank using a matter, energy, and forces perspective.	K	*Mantle Tank Model*, M-E-F poster made in Lessons 2-4
6	10 min		**NAVIGATE AND COMPARE MANTLE TANK MODELS** Compare models of the mantle tank with a classmate who used the same M-E-F perspective, and then with a classmate who used a different perspective.	L-M	*Mantle Tank Model*
					End of day 1
7	5 min		**REFLECT ON OUR COMMUNITY AGREEMENTS** Reflect on the Community Agreements in a Scientists Circle.	N	Community Agreements poster
8	20 min		**DEVELOP A CONSENSUS MODEL ABOUT MOVEMENT IN THE MANTLE TANK** Meet in a Scientists Circle to discuss ideas about how temperature influences the structure of matter and the forces that cause convective motion.	O	*Mantle Tank Model*, M-E-F poster, Model of Movement in the Mantle poster, chart paper markers, Community Agreements poster

9	10 min	☑	**USE THE MANTLE TANK CONSENSUS MODEL TO TEST/REVISE AFAR MANTLE MODELS** Compare the parcel within the tomography data from Afar to the mantle tank. Use lava lamps to consider non-uniform convection and its manifestations in the mantle.	P-R	*Afar Mantle Model*, *Mantle Tank Model*, https://youtu.be/I2HLRgpIJsQ
10	5 min		**REVISIT THE DRIVING QUESTION BOARD** Revisit the Driving Question Board and add any new questions.	S	3x3 sticky notes, permanent marker
11	5 min		**UPDATE THE PROGRESS TRACKER** Add an entry to the Progress Tracker.	T	*Progress Tracker*

End of day 2

Lesson 6 • Materials List

	per student	per group	per class
Lesson materials	• science notebook • exit ticket from Lesson 5 • *Afar Mantle Model* • *Mantle Tank Model* • 3x3 sticky notes • permanent marker • *Progress Tracker*		• https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOHtsy • M-E-F poster made in Lessons 2-4 • Community Agreements poster • M-E-F poster • Model of Movement in the Mantle poster • chart paper markers • https://youtu.be/I2HLRgpIJsQ

Materials preparation (20 minutes)

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

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

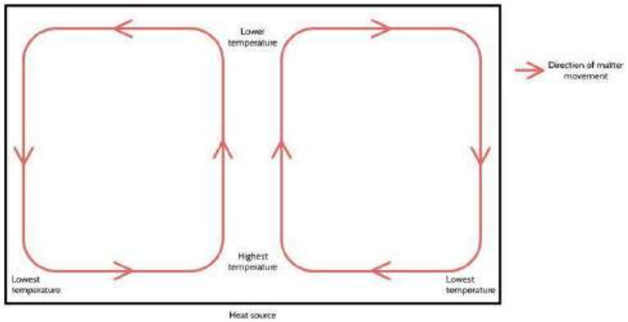
Three-hole-punch all handouts so they can be added to students' science notebooks.

Make copies of the handouts for this lesson:

- *Afar Mantle Model* - 1 per student
- *Mantle Tank Model*- 1 per student

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

- Model of Movement in the Mantle



Make sure the M-E-F poster developed in previous lessons is readily visible in the classroom.

Test the following links:

- Mantle Tank Investigation Video, https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOHtsy
- Optional particle simulation, http://bit.ly/heating-and-cooling
- Note: the Mantle Tank Investigation Video shows condition A and references a condition B, but there is no condition B in this lesson.

On day 2, if a clear, shared understanding of what happened in the tank does not easily develop, draw a base descriptive model on the board. This might look like the image on the upper right.

Another option to help students make sense of temperature in the tank after watching the video is to have them sketch what tomography data would look like for the tank. This might look like the image on the lower right.

Lesson 6 • Where We Are Going and NOT Going

Where We Are Going

This lesson works toward building the following disciplinary core idea:

- **ESS2A.1: Earth Materials and Systems.** ~~Evidence from deep probes and seismic waves, reconstructions of historical changes in Earth's surface and its magnetic field, and an understanding of physical and chemical processes lead to a model of Earth with a hot but solid inner core, a liquid outer core, a solid mantle and crust.~~ Motions of the mantle ~~and its plates~~ occur primarily through thermal convection, which involves the cycling of matter due to the outward flow of energy from Earth's interior and gravitational movement of denser materials toward the interior.

The lesson only addresses the last sentence of this element, as students figure out that the motions of the mantle are caused by convection in its matter. They model the movement of energy and matter in the mantle. They also begin to consider the forces involved in various sections of the mantle due to convection: both gravity and the pushing forces from beneath the matter.

If students have experienced *OpenSciEd Unit C.1: How can we slow the flow of energy on Earth to protect vulnerable coastal communities? (Polar Ice Unit)*, they may already have a basic understanding of density-driven convection currents in water, with warmer but more dense salt water present at the bottom of bays while less dense water from glaciers cycles via convection currents.

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

Where We Are NOT Going

In this lesson, the mechanism of convection is only developed as needed to continue building a conceptual model of what is happening in the mantle. This exploration and discussion will continue in Lesson 7 as students figure out more about how convection in the mantle affects interactions between the mantle and crust. They will not figure out the source of the heat that causes this convective motion until Lesson 7.

Though a lava lamp model is used to explain the non-uniform convection in the mantle, no attempt is made in this unit to explain differences in the type of matter within the mantle. This will be revisited in *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)* when students learn about Earth's history, the collision that created the moon, and the possible effects on the components of Earth's interior.

LEARNING PLAN for LESSON 6

1 · NAVIGATE

4 min

MATERIALS: science notebook, exit ticket from Lesson 5

Review the Lesson 5 exit ticket. Display **slide A**. Remind the class that at the end of Lesson 5, we were thinking about the mantle and how there are different temperatures of rock. We recognized that the mantle moved, and we were trying to explain how matter having different temperatures might affect the flow in Earth's interior. Finally, we had an exit ticket with the question on the slide:

- *What do we know about how flowing matter of different temperatures interacts that could explain how the mantle might change over time?*

Have students turn and talk about their exit tickets for 1-2 minutes, then ask a few to share out. Accept all ideas. Highlight ideas about heat rising and cold sinking, analogies to boiling water, and the introduction of words like *convection*. Validate these, but if they do not come up, simply move on.

Present **slide B**. Say, *Let's work on connecting these ideas to the mantle and our understanding of how it moves. We've been moving between scales to explain matter, energy, and forces. Let's start at the particle scale again, and build our explanation from there.* Pose the first two questions on the slide:

- *When flowing matter is heated, what changes at the particle level?*
- *How do these changes at the particle level affect what we observe about matter at the macro scale?*

Listen for suggestions that the particles move more (have higher kinetic energy) as the temperature rises. Students might also note that these particles apply more forces to particles around them because they are moving more.

Guide the class to remember that the velocity anomalies identified in Lesson 5 correlated to different temperatures in the mantle. Suggest that hereon, we refer to these areas of different temperatures as parcels of mantle material.

ADDITIONAL GUIDANCE	The term *parcels* was chosen because it is how students referred to sections of matter in convective cycles in middle school, such as when discussing the atmosphere in *OpenSciEd Unit 6.3: Why does a lot of hail, rain, or snow fall at some times and not others? (Storms Unit)*. Take a moment to ensure that students have an intuitive understanding of a parcel as a fixed quantity of something. This will be important when the class begins to discuss how temperature changes in the mantle cause density changes within the fixed quantity of matter in a parcel.

Ask students to consider what would be different between a parcel with a higher temperature versus a lower temperature. They should determine that the higher-temperature parcel would have particles with a higher average kinetic energy, and a parcel with a higher kinetic energy would be less dense than a parcel with a lower average kinetic energy. They may also have the idea that the matter in the parcels pushes on other matter in the mantle.

ADDITIONAL GUIDANCE	Students may need a refresher on what temperature is a measure of. If they do not remember from middle school that temperature is the average kinetic energy of a sample, consider pulling up a simulation that allows you to manipulate a sample's temperature in a particle-level view. Many such simulations exist; for example, http://bit.ly/heating-and-cooling utilized in *OpenSciEd Unit 6.2: How can containers keep stuff from warming up or cooling down? (Cup Design Unit)*. Oscillate between different temperatures and have students make observations about the particles' behavior. This simulation can also be used to consider differences in the density of mantle parcels.

Once students determine there would be a difference in the average kinetic energy and the density of these parcels, ask them to consider the slide's third question:

- *How might this affect how matter flows in Earth's mantle?*

Elicit responses. Remind the class that this would mean that parcels of different densities would be interacting within the mantle. Then ask how this interaction would affect the movement of these larger sections. Point to the image of parcels and have students consider how a more dense parcel and a less dense parcel might be moving relative to the others. Accept all responses.

ALTERNATE ACTIVITY	If students have not yet had the opportunity to make sense of the relationship between density and objects floating or sinking, consider conducting an experiment in which they can measure the mass and volume of objects, such as density cubes, to see that less dense objects float and more dense objects sink.

2 · DEVELOP EXPLANATORY MODELS OF THE MANTLE UNDER AFAR

6 min

MATERIALS: *Afar Mantle Model*

Create an explanatory model using tomography data. Project **slide C**. Say, *Last time, we looked at tomography data to give us an idea of how what was happening in the mantle affected the surface. Let's shift to consider what might cause the motion of the parcels of mantle material.*

Distribute the *Afar Mantle Model* handout. Ask students to use what we know about particles and samples of matter (such as parcels) at different temperatures, as well as the tomography data, to predict why and how the mantle is moving. Direct them to draw the motion directly on the data in the handout, and to use the circles to consider what we would see happening at the particle level.

As students work, take the opportunity to walk around the classroom and collect formative data about how students currently view the mantle's movement and the mechanisms for that movement.

ASSESSMENT OPPORTUNITY	**What to look for/listen for in the moment:**
	● Look for all models to predict the relationship between the particle nature of the parcels of different temperatures and their movement in the mantle. (SEP: 2.3; DCI: PS3.A.4)
	● Models should include particle-level interactions at various locations in the mantle system. (DCI: PS3.A.4)
	● Models should include changes in the matter related to the energy transferred in the mantle parcels. (CCC: 5.4)
	
	What to do:
	● At this point in the lesson, the model does not need to be accurate. It is meant for formative assessment purposes and can inform instruction at future steps in this lesson, including the consensus model at the beginning of day 2. Students also have one more chance to revisit this model at the end of day 1. Do not press for specific right answers at this point. Instead, use the following sections as guidelines for helping students consider a new perspective or idea.
	● If particle differences are missing or limited:
	    ● Direct students to consider what differences exist between particles of the same matter sample in the same state at two temperatures. Have them consider this movement and how it would affect the density of the sample.
	● If the movement of the sample and/or changes in matter due to energy transfer are missing or limited:
	    ● Direct students to consider how that density difference would affect movement if the samples were two vastly different densities, such as a more or less dense pool toy in water. Ask them to consider how this difference might affect the movement of parcels in the mantle, and how those blobs interact with blobs of different densities.
	● Some students may include Earth's core as an energy source. Though this is an important

component of the model of Earth's interior, it is not necessary to include at this time. By the end of the lesson, students will converge on the idea that thermal convection occurs in the mantle, but they will not have evidence of the mechanism. This will provide a segue into Lesson 7.

Building toward: 6.A.1 Develop a model to explain the relationship between energy transfer and the motion of matter in a solid material via thermal convection and the motion of particles. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)

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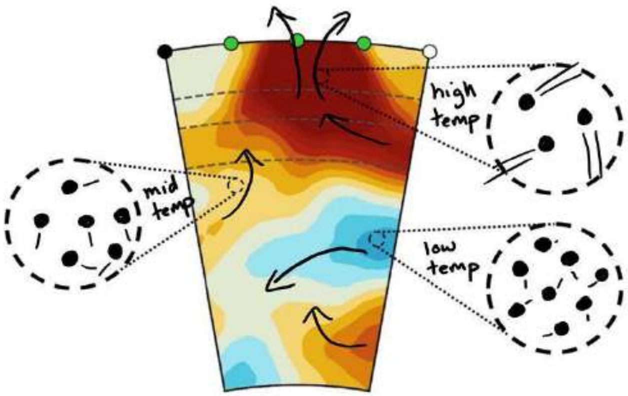
<td>

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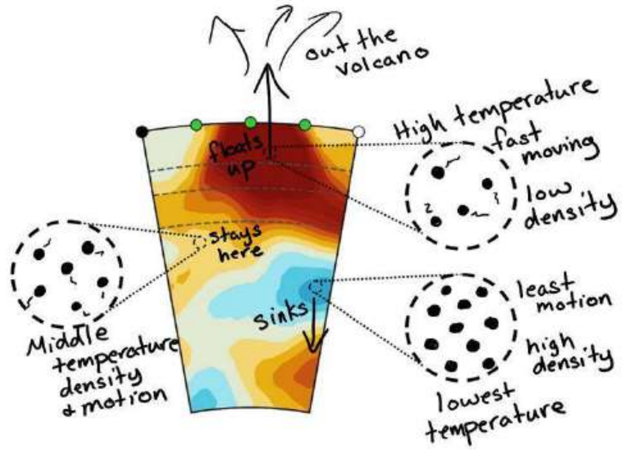
<td>

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<tr>
<td>Student who is thinking about kinetic energy differences between the parcels of mantle material and the flow of matter.</td>
<td>Student who is thinking about kinetic energy and density differences between the parcels of mantle material and how those might manifest on the surface.</td>
</tr>
</table>

Bring the class back together and have a few students share elements of their models. Accept all ideas. Say, *It seems we have a lot of ideas about what might be happening with the movement of these blobs in Afar. Thank you for sharing. Let's consider how we can test our models.*

Remind students that in our models, we are trying to show rock moving like a thick fluid. We know that this phenomenon takes millions of years, but we don't have millions of years to investigate it.

Recall ways to test predictions of events over different time scales. Project **slide D**. Say, *Is there a way we can investigate fluids moving at a rate we can observe in the classroom, to test our predictions?*

Allow students to respond, and accept all ideas. Have them hone in on the idea of changing the rate by asking the question on the slide:

- *What have we done in the past to increase or decrease the speed at which a phenomenon happens?*

Elicit a few ideas. Listen for students to suggest simulations, videos, or models of the same mantle substance, or using a faster-moving fluid.

3 · INTRODUCE THE MANTLE TANK

6 min

MATERIALS: None

Consider the usefulness of the mantle tank. Present **slide E**. Say, *I have a video of a model that was created to visualize how matter in the mantle moves when parcels of it have different temperatures. Let's consider how the model might be used to test our models.*

Present **slide F**. Ask students to turn and talk about the slide's list of tank elements and the prompt:

- *What purpose might each element of this model serve, and how can we use it to test our models?*

Have pairs share out. Listen for these ideas:

- comparisons of the tank's mixture of liquid and pellets with the rock mixture in the mantle, and specifically, that both are similar throughout and can flow
- mentions that the pellets might allow us to see the motion of the liquid
- ideas about heating parts of the tank to create temperature differences and then making observations

Use probing questions or suggestions to help students explore these ideas if they do not develop them on their own.

ADDITIONAL GUIDANCE

The plastic pellets are **not** meant to represent particles at the microscopic level. They are used as a way to visualize motion in the surrounding matter when energy is transferred into the system. If students propose the idea of the pellets representing the mantle at the particle level, be sure to discuss how the pellets behave in the liquid and how this is different from particle behavior. For example, the pellets:

- are not vibrating and bouncing off of each other
- stay consistently spaced in the liquid and do not visually show changes in density

✱ SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

In Lesson 4, students evaluated the merits and limitations of different models using three lenses: (1) *stability or change* over time or space, (2) *thinking across different scales*, and (3) *cause and effect* in M-E-F relationships. Encourage them to continue using these lenses to assess whether and how a model can help explain the phenomenon under investigation.

It might also help students to better understand the tank model if you propose that the pellets represent smaller parcels of matter in the mantle.

Discuss advantages and limitations of the tank. Present **slide G**. Read the prompt aloud:

- *What advantages and limitations does this model have for testing our models?* ✱

Listen for ideas such as:

- Because rocks move very slowly, maybe we can see changes in matter much faster with the liquid in the tank.
- It is very hard to study the mantle directly, so this will give us evidence of how matter responds to temperature.
- The mantle is made of rock, but this is liquid, so maybe the conclusions we draw from this tank would not apply to the mantle.
- The tank is very small compared to the mantle. Maybe a large-scale system does not behave in the same way as a small system like the tank.
- The tank has walls, but the mantle under Afar isn't blocked off from the rest of the mantle.
- The liquid might not visually show the temperature differences like we see with the tomography data.

Determine how to use the tank to test our models. Present **slide H**. Point out that although it has limitations, the tank still seems like a good representation. Pose the slide's question:

- *How can this mantle tank be used to test the reliability of our drawn models of the mantle under Afar?*

Listen for suggestions that the tank can serve as a representation of the mantle and that it should function like the mantle with a heat source at the core. The tank can be used to compare the movement of mantle parcels of different temperatures, to determine whether the movement is similar in the models we have created.

Discuss heating the tank. Say, *It seems like we can use this model to test at least some parts of our models by heating part of the tank, as long as we remember that all models have limitations.*

Present **slide I**. Explain that the image shows how the tank is heated by using pennies stacked on a hot plate and touching the bottom of the tank. Mention that the tank does not touch the hot plate directly, so the pennies transfer heat from the hot plate to the tank. Pose the question on the slide:

- *Why do the pennies only make contact with the middle of the tank?*

Listen for students to mention that the tomography data suggested that the temperature of the mantle varies between different spots, so we want to unevenly heat the liquid in this model.

Say, *Okay, now that we have an idea of what is represented in the tank and how it can be used to test our models, let's analyze a video taken of what happens in the tank over time.*

4 · ANALYZE VIDEO FROM THE MANTLE TANK

13 min

MATERIALS: *Mantle Tank Model*, science notebook, https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOHtsy

Describe the video observation task. Present **slide J**. Distribute the *Mantle Tank Model* handout to each student. Say, *On this handout, we'll keep track of how we make sense of the mantle tank. You can put your Afar model in your notebook. We'll come back to it when we check our models against what we learn.* Tell students to record noticings and wonderings on their handout while we watch the video.

Watch the mantle tank video. Project the video, https://youtu.be/VuEqdCyub5s?si=S3rZtUJEyKKOHtsy (about 3 minutes long). ✱ At the time stamps in the chart below, pause the video and use the prompts to elicit ideas.

Time stamp	What is happening in the video	Prompts to use with the class
0:07 - 0:09	A frontal view of the mantle tank setup is shown.	*Can someone remind us what the role of the pennies is?* *Why do you think the pennies were placed in this pattern?*
0:10 - 0:46	The video shows the mantle tank recorded from two angles: frontal view (right); side view (left). Each screen shows the tank and the temperature recorded, first from the front, then the side. All temperatures are equal.	*What do you notice about the temperature measured in the different locations?* *What changes do we see in the matter?*
0:50 - 1:03	The person turns the hot plate on.	*What do we think is going to happen to the temperature of the mantle tank?* *What do we think is going to happen to the matter as the temperature increases?*

✱ ATTENDING TO EQUITY

Universal Design for Learning: As a second option, consider separating the video into six shorter videos, according to the series of timestamps below, to help students *perceive* the movement in the mantle tank. Students who could benefit from seeing the video up close on their devices could start and stop each video along with the class, giving them increasing access to this task.

✱ ATTENDING TO EQUITY

Universal Design for Learning: When asking students to describe how matter moves in the mantle, encourage them to use their hands and arms to *represent* this motion. Visual, nonlinguistic supports such as this can increase students' ability to understand concepts, especially for new learners of the classroom's dominant language.

1:03 - 1:33	The hot plate is on, but there are no visible changes in the mantle tank.	*Do we expect to see changes immediately after we turn the hot plate on?*
1:40 - 2:02	The video is sped up 20 times faster, which allows observers to see changes in the matter more clearly. The plastic pellets move in a convective pattern.	*What scale changed?* *How is the matter moving in the mantle tank?*
2:10 - 2:53	The person remeasures the temperature. The highest temperature is found in the middle of the mantle tank, close to where the pennies are transferring the heat from the hot plate. The temperature is lower at the surface, and even lower at the sides, closer to the bottom.	*What is the temperature at different locations?* *Why is the temperature different at these locations?*

Collectively analyze the video. Ask students to share noticings and wonderings. If needed, rewatch parts of the video to establish consensus. Be sure that these main ideas are established: ✱

- The matter moves up in the middle of the tank, along the pennies.
- The matter moves down along the sides of the tank, away from the pennies.
- The motion is cyclical.
- The highest temperature is at the bottom, in the middle, near the pennies.
- The lowest temperature is at the bottom, near the sides, away from the pennies.
- The temperature at the top of the tank, above the pennies, is lower than the temperature down near the pennies.

5 · USE M-E-F PERSPECTIVES TO EXPLAIN THE MANTLE TANK

6 min

MATERIALS: *Mantle Tank Model*, M-E-F poster made in Lessons 2-4

Use an M-E-F perspective to explain the movement in the tank. Ensure that the M-E-F poster is visible in the classroom. Say, *Okay, now that we have an idea of how matter moves in the mantle tank, let's make explanatory models of what's happening in there, so we can use them to test our Afar models. We'll use the M-E-F triangle to help us make our models.*

Present **slide K**. Guide students in creating models on their handout with the slide's prompts:

- *Use the evidence we obtained from the mantle tank video to create a model to describe and explain why the matter in the tank is moving in the way we observed.*

- *Choose at least one of the following perspectives to develop in your model:*
    - *matter (particle-level interactions)*
    - *energy*
    - *forces*

Allow students 5 minutes to complete their models. It is OK if they use only one perspective in their explanation.

ADDITIONAL GUIDANCE	As students work, quickly take stock of which M-E-F perspectives they are using. If one of the three perspectives is underrepresented across the class, encourage students who finish early to consider this perspective as well.

ASSESSMENT OPPORTUNITY	**What to look for/listen for in the moment:** • Look for all models to reference the observed motion of matter and the temperature readings in the mantle tank video as evidence about energy transfer and matter changes. (SEP: 2.3) • Models using the matter perspective should include particle-level interactions at various locations in the mantle tank system. (DCI: PS3.A.4) • Models using the energy perspective should include changes in the matter related to the energy transferred into and out of the mantle tank system. (CCC: 5.4) • Models using the forces perspective should mention explicitly or illustrate the forces acting on matter at various locations in the mantle tank that could explain the convective motion of matter or energy transfer in the model. (DCI: ESS2.A.2; CCC: 5.4) **What to do:** • If students struggle with explaining the parts of the tank that changed, encourage them to look back at the observations they recorded from the video investigation. Some students who choose the matter perspective might focus on describing the observed motion in the matter. Encourage them to use particle-level interactions in their models. • Use the M-E-F poster to support students in using at least one of the perspectives to explain the movement of matter in the tank. Point them to the questions we should be asking ourselves about matter, energy, or forces when we try to explain a phenomenon from these perspectives. • Consider asking more focused questions, such as the following, to help students consider how matter, energy, and/or forces can be used to explain the movement of the items in the tank and the

corresponding blob movement in the mantle:

  - *What do we know about the average kinetic energy of each blob and the different sections of our tank? How is that energy transferring? How does that affect the movement of what we see in our tomography data, and the movement of liquid and beads in our tank?*
  - *What did we see the matter in the tank doing, and what changes at the particle level might explain that movement? How might the matter be similar or different in different parts of the tank, and why?*
  - *What forces do we know act on matter? How might that affect mantle parcels of different densities in our tomography data and our tank? What is pushing or pulling on this matter to make it move up and down in our tank?*
- For students who are ready to consider more than one perspective, ask them to consider how another perspective might also be explained within their model, and how that perspective might be stable or change over varying spatial and temporal scales.
- Once some students finish, encourage them to consider what forces might be acting on the matter, and how that might affect the movement.

Building toward: 6.A.2 Develop a model to explain the relationship between energy transfer and the motion of matter in a solid material via thermal convection and the motion of particles. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)

6 · NAVIGATE AND COMPARE MANTLE TANK MODELS

10 min

MATERIALS: *Mantle Tank Model*

Compare explanatory models of the movement in the tank. Present **slide L**. Review the directions:

- *Look for a person who used the same perspective that you did to explain the motion of matter in the mantle tank. Each person will have a minute to explain their model. After each partner has shared, look for:*
  - *similarities between models*
  - *differences between models*
  - *areas of uncertainty*
  - *areas of disagreement*

After a few minutes, present **slide M**. This time, have students look for a person who used a different perspective to explain the movement. Direct them to the new prompts on this slide:

- *how both models combined help to explain the movement of matter*
- *areas of uncertainty*
- *areas of disagreement*

Have students use their handouts to record the ideas for changes or new understandings that they developed from comparing models. These will be used in the next class.

Say, *Next time, we'll use our mantle tank models to develop a consensus model, and then use that to test our Afar mantle models.* Collect the *Mantle Tank Model* handouts for review before the next class.

ADDITIONAL GUIDANCE	Use your review of the *Mantle Tank Model* handouts to anticipate how students might want to represent things during the consensus model discussion. You may want to identify specific students to ask to share their representations. See the Key Ideas callout in day 2 for guidance on what to include in the consensus model.

End of day 1

7 · REFLECT ON OUR COMMUNITY AGREEMENTS

5 min

MATERIALS: Community Agreements poster

Take stock of our Community Agreements. Say, *Our next step is to develop a consensus model for the mantle tank that integrates the matter, energy, and forces perspectives. That will be a tricky conversation as we're working together to come to consensus. So, this is a good time to revisit our Community Agreements.*

Present **slide N**. Display the list of agreements either digitally or physically. Use the slide's prompt to start a brief discussion: ✱

- *Which of our Community Agreements will help us as we work together to develop a consensus model?*

Revisit the Community Agreement shoutouts from Lesson 4. Remind students that at the end of Lesson 4, they recorded one instance when someone else's contributions had helped them figure something out. Quickly share these shoutouts with the class, and suggest that we consider using the same strategies that were identified in them for our consensus modeling today.

✱ ATTENDING TO EQUITY

Building classroom culture: This lesson's two focal agreements are respect and moving our thinking forward. As students create a consensus model, it is important that they think about how to treat each other with respect while advancing our understanding. This is an opportunity to emphasize that building a consensus model does not always mean agreeing with each other's ideas; sometimes challenging each other's ideas helps us make progress in our thinking and identifies areas of consensus and uncertainty in a model.

It is important to remember that how we define respect can be culturally constructed, which is why we ask students to explicitly name what respect looks like/sounds like during the development of agreements in Lesson 1. Be aware of how the word "respect" can be used to reproduce gendered or racialized ideas (e.g., "bossy" versus "leader," or "angry" versus "passionate"), and steer students to the more detailed Lesson 1 agreements if necessary.

8 · DEVELOP A CONSENSUS MODEL ABOUT MOVEMENT IN THE MANTLE TANK

20 min

MATERIALS: *Mantle Tank Model*, M-E-F poster, Model of Movement in the Mantle poster, chart paper markers, Community Agreements poster

Convene a Scientists Circle. Make sure the M-E-F poster is visible to everyone. Say, *Let's try to capture what we've figured out about what's happening in the mantle that can help us explain what is happening at Afar.* Return students' *Mantle Tank Model* handouts.

Develop a consensus model for the motion of matter in the mantle tank. Display the prepared Model of Movement in the Mantle poster. Present **slide O**. Use the prompts to initiate a discussion:

- *What did we observe in the mantle tank?*
- *What do these observations tell us about matter, energy, or forces?*
- *How are things different in different parts of the tank?*

As consensus is reached about elements of the model, draw them on the poster or have students do this. Be sure to include a key so everyone knows what the representations mean. Listen for the ideas in the Key Ideas box below. To direct the discussion and model development as needed, use guiding questions for each M-E-F perspective, such as those proposed below:

Energy:

- *What evidence do we have from the video that tells us about energy?*
- *Where was energy transferred in/out of the system?*
- *Why do you think energy is being transferred in/out of the system there?*
- *How could we represent energy flow in our model?*

Matter:

- *What did we observe the matter in the tank doing?*
- *What evidence did we see that tells us the matter is changing at the particle level?*
- *What changes at the particle level explain the evidence we observed?*
- *Where in the tank did the matter have higher/lower amounts of energy/motion at the particle level?*
- *Where in the tank would the particles be closest together/farthest apart?*
- *How could we represent the energy/density of the matter in our model?*

Forces:

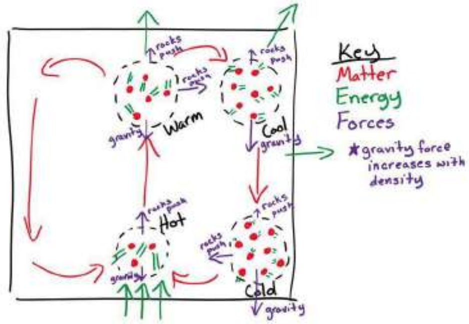
- *What forces act on sections of the matter as it moves around the tank?*
- *What can we infer about the gravitational force acting on sections of the matter, based on the particle-level differences we discussed?*
    - *We discussed that the matter's density changed. If you make something more dense by packing more matter into the same space, what happens to the force of gravity, or the weight?*
- *Where in the tank do we see evidence of balanced or unbalanced forces?*
    - *Where does the motion of the matter change?*
- *Can differences in the force of gravity explain the rising of the matter in the middle of the tank?*
    - *What else might be pushing on the matter to cause it to start moving up?*

ALTERNATE ACTIVITY	Depending on how comfortable your students are with developing consensus models, you may want to chunk this discussion into discrete perspectives. It is suggested that you start with energy, then matter, then forces. These discussions should still create a single holistic model.

KEY IDEAS	Although your students' consensus models are likely to look different from these examples, the following key ideas should be represented and explicitly discussed.

Listen for these ideas overall:

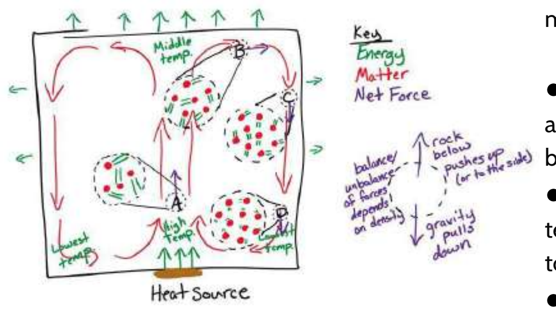
- Density changes in the matter, associated with changes in temperature, unbalance the net force on the matter in the tank in a way that causes it to cycle up and down.



Energy:

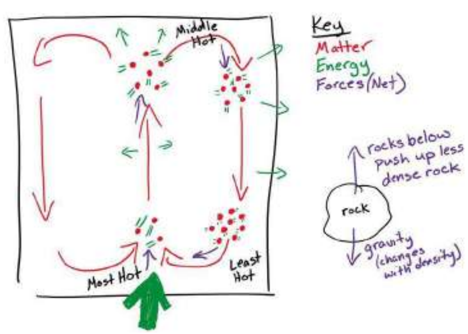
- Energy flows into the system from the pennies at the bottom of the tank, making this part of the tank have the highest temperature.
- Energy flows out of the matter to the surroundings as the matter moves around the tank.

Matter:



- High-energy matter moves up, low-energy matter moves down.
- The matter moves in a cyclical pattern up and away from the energy source and then back down around the slides of the tank.
- As the matter lowers (decreases) in temperature, the particles become closer together (move slower), changing density.
- As the matter rises (increases) in temperature, the particles become farther apart (move faster), changing density.

Forces:



- Forces that act on the matter in the tank include gravity pulling down and contact forces pushing in all directions from the matter around it.
- The denser matter is pulled down by a stronger force of gravity (because it has more matter).
- The denser matter pushes the less dense matter up, toward the top of the tank.
- The net force on a section of the matter changes as the temperature changes.

- The unbalanced net force on the matter changes the matter's motion.

Extension ideas that can be developed:

- There is a positive feedback loop driven by the movement of matter away from one location, creating less resistance in that direction for other matter to move into that space. (This helps explain the lateral motion.)

ADDITIONAL GUIDANCE	The force of the matter around an object in a fluid is often referred to as the *buoyant force*. We have deliberately chosen not to use this term. By focusing on the mechanism rather than the type of force, our goal is to help students develop an intuitive model of forces as pushes and pulls that sum to net forces; naming specific types of force comes later. But feel free to share this term with students after they have developed an intuitive understanding of why a higher-temperature parcel pushes on the matter above it. This is also an opportunity to draw on multilingual resources in your classroom. The word *buoyancy* in Spanish is *flotabilidad*, and in French it is *flottabilité*. If students in your class speak Spanish, French, or a related language, you can point out that these words sound like "floatability" and help to describe the buoyant force as the ability of a parcel to float, determined by its density.

Once the model is established, highlight any Community Agreement that was especially well used during the discussion. For example, thank the class for their participation and collaboration to move our thinking forward. Leave the consensus model up for the remainder of the lesson.

9 · USE THE MANTLE TANK CONSENSUS MODEL TO TEST/REVISE AFAR MANTLE MODELS

10 min

MATERIALS: science notebook, *Afar Mantle Model*, *Mantle Tank Model*, https://youtu.be/I2HLRgpIJsQ

Observe non-uniform convection in lava lamps. Have students return to their seats and take out their *Afar Mantle Model* and *Mantle Tank Model*. Present **slide P**. Pose the prompt:

- *What are the differences between what we saw in the mantle tank and the Afar tomography data?*

Ask students to compare their two handouts. Listen for them to notice that the hottest spot in the mantle data is at the top, and there doesn't seem to be a clear cycle. Say, *One difference I'm hearing is that the tomography doesn't show the same locations for temperatures as the tank did. I have another video that shows non-uniform examples of convection.*

Project the lava lamp video, https://youtu.be/I2HLRgpIJsQ . Have students share out their observations in real time as the video plays.

Present **slide Q**. Ask the class to consider the questions on the slide:

- *What similarities do we see between the lava lamp video and the mantle tank video?*
- *What differences do we see?*
- *How might these differences help explain the different mantle parcels we see in our tomography data?*

Have a quick discussion using those questions. Guide students to make the following determinations:

- Both the mantle tank and the lava lamps are heated from the bottom.
- Hot stuff moves up in blobs, parcels, or sections.
- The mantle tank motion is much more continuous and flowing than in the lava lamps.
- The hot stuff at the top of the lava lamps stays at the top longer than in the mantle tank.
    - This is like what we see in the Afar tomography data.
    - This is because it takes longer for that matter to lose enough energy to sink.

ADDITIONAL GUIDANCE	If questions arise regarding the types of fluids in the lava lamps, do not dismiss them. Ask students to add these questions to the DQB. Though they will not be addressed in this unit, questions about the differences in the type of matter that exists within the mantle will be answered in the future in *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)*.

ALTERNATE ACTIVITY	If you have access to a lava lamp, consider bringing it to the classroom for direct visual observations. Be sure to advise students not to touch the lamp, as it can get extremely hot. It is suggested that the class also watch the video, as it was selected for the variety of behaviors seen across several lamps. A non-contact thermometer can be used to make temperature observations of a lava lamp. Temperature patterns will vary based on the lamp and will not be as clear and consistent as the patterns in the mantle tank. This is because the rate of energy transfer into and out of the wax "lava" in a lamp is slower than energy transfer within the consistent fluid in the tank.

Test/revise Afar mantle models using mantle tank understanding. Present **slide R**. Tell students to use the newly formed consensus model to see whether their initial models explaining how and why the mantle is moving under Afar still hold. Refer to the slide's instructions:

- *Using our consensus model for the mantle tank, revise your model of the mantle movement under Afar on your handout.*
- *Make note of any lingering questions or uncertainties.*

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Look for revised models to include density differences in the particle-level modeling of the matter based on thermal energy tomography data and evidence from a mantle tank and lava lamps. (SEP: 2.3; DCI: ESS2.A.2, PS3.A.4)
- Models should include energy being transferred into and out of the system to heat/cool the matter of the mantle, causing motion in the mantle. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2)
- Models should reference balanced and unbalanced forces to explain the convective motion of matter in the mantle due to density differences. (SEP: 2.3; DCI: ESS2.A.2, PS3.A.4)

What to do:

- If students do not reference density or particle-level differences, direct them to look at the consensus model, consider the differences between mantle parcels, and consider how those differences might affect the sample's movement. If needed, direct them to look back at the optional simulation from day 1 to observe the differences in particle movement.
- If students do not show the transfer of energy through the system as shown in the convection model, direct them to look at the consensus model and consider what is occurring as one mantle parcel comes into contact with a parcel of lower kinetic energy. Tell them to think at the particle level to remember what happens as particles with higher energy come into contact with particles of lower energy. Then tell them to scale up to the size of the parcels and consider how the separate parcels might affect the movement of the entire section of mantle material.
- If students do not consider the effects of gravity on more and less dense sections of the mantle, ask them to consider what might be causing the more dense sections to be pulled down toward Earth's center. Have them consider how this might be different for different samples of different densities, and whether any pushing would occur between the parcels.

Building toward: 6.A.3 Develop a model to explain the relationship between energy transfer and the motion of matter in a solid material via thermal convection and the motion of particles. (SEP: 2.3; CCC: 5.4; DCI: ESS2.A.2, PS3.A.4)

10 · REVISIT THE DRIVING QUESTION BOARD

5 min

MATERIALS: 3x3 sticky notes, permanent marker

Revisit the DQB. Present **slide S**. Remind the class that at the end of the last lesson, we revisited the DQB and determined what questions we could answer, as well as what questions still need answers.

Ask the slide's first question, and have students look at the DQB to determine whether they can answer any more questions. Place a checkmark on the sticky notes with questions that have been answered, and move those to the side.

Ask the slide's second question. Distribute sticky notes and permanent markers, and tell students to add any new questions to the DQB. If questions do not emerge about where the energy/heat comes from that causes this cycle within the mantle, say: *It seems that we've figured out a lot about the movement of matter in the mantle. Did anyone draw what was causing it, or where this heat is coming from? Does anyone have ideas or questions about the energy source that could cause this movement?*

Allow students to respond. Point out that we have ideas about where the heat for this convection cycle might be coming from, and we have some questions about this as well. Say that the class should explore this topic next to determine where the energy is coming from for this cycle to occur.

11 · UPDATE THE PROGRESS TRACKER

5 min

MATERIALS: science notebook, *Progress Tracker*

Introduce the term *convection*. If the word has not yet been introduced, explain that the heating cycle we have been studying is called *convection*. If desired, give students a moment to add this or other terms to their Personal Glossaries.

Update the Progress Tracker. Display **slide T**. Say, *Now that we've developed our convection model, including what's happening from a matter, energy, and forces perspective, add an entry to your Progress Tracker that helps answer this lesson's question: "How is temperature related to the behavior of the matter in the mantle?"*

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING STABILITY AND CHANGE

Look for students to explain that the mantle's movement is predictable and also

Give students time to update their trackers. They may write something like, “The mantle is composed of heterogeneous samples of matter that have different energy levels. The parcels with a higher average kinetic energy are pushed to the top of the mantle by the more dense parcels underneath that have a lower average kinetic energy. This cycle will continue where the more-dense parcels of matter push up the less-dense mantle parcels of matter.”

Students should also mark the checkbox(es) in the tracker for any of the three lenses that we used throughout this lesson to help figure out these ideas, because each lens was utilized at least once. ✱

To close, remind the class that we have many unanswered questions left on our DQB, and our models don’t quite reflect the source of the energy. Say that we will investigate this further next time.

cyclical, based upon the changes that occur in the matter due to the sample’s increased or decreased energy. This change happens over a long period of time.

Additional Lesson 6 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA	**CCSS.ELA-LITERACY.SL.9-10.1** Initiate and participate effectively in a range of collaborative discussions (one-on-one, in groups, and teacher-led) with diverse partners on grades 9-10 topics, texts, and issues, building on others' ideas and expressing their own clearly and persuasively. Students discuss the convection in the mantle tank and Earth’s mantle, coming to consensus on thermal convection. They also revisit the Driving Question Board as a class and identify any questions they can now answer. Students also add any new questions that have come up.