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

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

This Lesson



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

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

BUILDING TOWARD NGSS

What students will do

HS-PS1-8, HS-ESS1-5, HS-ESS2-1, HS-ESS2-3 4.A Evaluate the merits and limitations of different models using a crosscutting lens (stability and change, thinking across scales, and/or cause and effect) for understanding and explaining different phenomena (earthquakes) and mechanisms (elastic deformation, cracking/breaking). (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2)



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

What students will figure out

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

Lesson 4 • Learning Plan Snapshot

Part	Duration	Summary	Slide	Materials
1	4 min	NAVIGATE Review questions from Lesson 3 and create a list of phenomenon categories that these questions can help answer. Reflect on this lesson's focal Community Agreement.	A-B	selected questions generated by students at the end of Lesson 3 (on this lesson's slide A), Community Agreements poster
2	10 min	DISCUSS MODEL 1 Use a video and its captions to evaluate how two foam panels can simulate the plate interactions that produce earthquakes.	C-E	Evaluating Models, https://www.youtube.com/watch?v=uVM 4t2QXtLo, Scale Chart poster, M-E-F poster, M-E-F expansion panels
3	6 min	IDENTIFY ADVANTAGES AND LIMITATIONS OF MODEL 1 Individually record advantages and limitations of the foam model on the handout. Identify points in the foam panels where slips originate or breaks occur, and discuss why it is happening there.	F-G	<i>Evaluating Models</i> , Scale Chart poster, M- E-F poster, M-E-F expansion panels
4	8 min	MAKE SENSE OF MATTER CHANGES AND RECALL PRIOR PARTICLE-LEVEL MODELS OF MATTER Recall prior experiences with simulating and visualizing particles and particle-level interactions. Identify the force interactions between similarly and oppositely charged particles (protons and electrons) that make up atoms.	H-L	Evaluating Models, M-E-F poster, M-E-F expansion panels
5	6 min	DISCUSS MODEL 2 Use a video and its captions to evaluate how two inverter magnets simulate force interactions between bonded atoms.	Μ	Evaluating Models, https://youtu.be/K3m2x6Vtj4I
6	3 min	IDENTIFY ADVANTAGES AND LIMITATIONS OF MODEL 2 Individually record advantages and limitations of the inverter magnet model.	Ν	<i>Evaluating Models</i> , Scale Chart poster, M- E-F poster, M-E-F expansion panels
7	3 min	BRAINSTORM FEATURES OF A SIMULATION Brainstorm what parts and interactions we would want in a particle-level simulation, and what we would want to be able to change, visualize, and measure in it.	0	Evaluating Models

8	5 min		INTRODUCE THE SIMULATION AND PLAN INVESTIGATIONS Watch the orientation video for the simulation. Complete Part 1 of the investigations handout in small groups.	P-Q	Particle Investigations, Evaluating Models, https://youtu.be/D8QZMCO5_oc
					End of day 1
9	15 min	Y	NAVIGATE: USE THE SIMULATION TO CARRY OUT A SERIES OF INVESTIGATIONS In small groups, carry out a four-part investigation using a computer simulation of deformation and breaking.	R	Particle Investigations, computer with access to https://openscied- static.s3.amazonaws.com/HTML+Files/Ap ply+and+Remove+External+Force+on+a+S olid.html
10	3 min		PREPARE FOR A SCIENTISTS CIRCLE Share and compare findings in partners.	S	Particle Investigations
11	13 min		UPDATE THE M-E-F POSTER Gather in a Scientists Circle. Use a demonstration to discuss changes in the system from a matter, energy, and forces perspective. Add to the M-E-F poster.	T- AA	Particle Investigations, M-E-F poster, M-E- F expansion panels, Scale Chart poster, 3x5 sticky notes, clear tape, chart paper markers, Breaking Foam Panels
12	12 min	ľ	ASSIGN THE ELECTRONIC EXIT TICKET Apply what we have figured out so far to an Electronic Exit Ticket about a new phenomenon: volcanic eruptions.	BB	copy of https://docs.google.com/forms/d/1bxE9h zdU7elsXuZvGC7jA6uEGDAKPDjVanSW eNr1vR8/copy made before class
13	2 min		NAVIGATE Conclude that we can not fully explain what is happening at Afar and need more information/data.	сс	
					End of day 2

Lesson 4 • Materials List

	per student	per group	per class
Breaking Foam Panels materials			 2 double V-notched foam pieces (3" x 12" x ½")
Lesson materials	 Evaluating Models Particle Investigations science notebook 	 computer with access to https://openscied- static.s3.amazonaws.com/HTML+File s/Apply+and+Remove+External+Forc e+on+a+Solid.html 	 selected questions generated by students at the end of Lesson 3 (on this lesson's slide A) Community Agreements poster https://www.youtube.com/watch?v= uVM4t2QXtLo Scale Chart poster M-E-F poster M-E-F expansion panels https://youtu.be/K3m2x6Vtj4I https://youtu.be/D8QZMCO5_oc 3x5 sticky notes clear tape chart paper markers copy of https://docs.google.com/forms/d/1bx E9hzdU7elsXuZvGC7jA6uEGDAKPDj VanSWeNr1vR8/copy made before class

Materials preparation (30 min minutes)

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

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

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

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

Make copies of the handouts for this lesson:

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

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

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

Before class, make a copy of the Electronic Exit Ticket found at the following link: https://docs.google.com/forms/d/1bxE9hzdU7eIsXuZvGC7jA6uEGDAKPDjVanSWeNr1vR8/copy . Share the link to the **copy** with students, **not** the link provided here; if you share the original link, that will create a new copy for each student, and you will not have access to their responses. See the reference *How to Create Electronic Exit Tickets*.

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

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

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

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

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

Breaking Foam Panels

• **Group size:** Whole class.



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

Lesson 4 • Where We Are Going and NOT Going

Where We Are Going

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

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

- ESS2.B.2: Plate Tectonics and Large-Scale System Interactions. Plate tectonics is the unifying theory that explains the past and current movements of the rocks at Earth's surface and provides a framework for understanding its geologic history.-Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust.
- **PS2.B.3: Types of Interactions.** Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields.
- PS3.B.2: Conservation of Energy and Energy Transfer. Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems. (HS-PS3-1, HS-PS3-4)
- **PS3.A.4: Definitions of Energy.** These relationships are better understood at the microscopic scale, at which all of the different manifestations of energy can be modeled as a combination of energy associated with the motion of particles and energy associated with the configuration (relative position of the particles). In some cases the relative position energy can be thought of as stored in fields (which mediate interactions between particles). This last concept includes radiation, a phenomenon in which energy stored in fields moves across space.

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

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

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

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

Where We Are NOT Going

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

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

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

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

LEARNING PLAN for LESSON 4

1 · NAVIGATE

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

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

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

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

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

- earthquakes
- cracking
- elastic behavior of all matter

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

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

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

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

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

* ATTENDING TO EQUITY

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

2 · DISCUSS MODEL 1

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

* SUPPORTING STUDENTS IN ENGAGING IN DEVELOPING AND USING MODELS

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

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

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

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

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

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

- Consider whether we would see motion at a smaller scale if we were to zoom into any part of the matter. Imagine you can observe in a zoomed-in location along the plate boundary as they do this again, and the magnitude of the external force on plate B slowly increases.
 - 1:06 What changes would you expect to see along the plate boundary as the magnitude of the forces on each plate increases?
 - While this prompt is displayed, consider restating the question as: What would you see happening to the matter at these locations?
- Consider why these particular pieces of foam would have cracked and broken off from the larger piece of material they were attached to.
 - 2:05 What, if anything, was different about the matter at the locations where the matter broke off versus where it did not? What, if anything, was different about the forces acting on the matter at those locations?

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

3 · IDENTIFY ADVANTAGES AND LIMITATIONS OF MODEL 1

MATERIALS: Evaluating Models, Scale Chart poster, M-E-F poster, M-E-F expansion panels

Evaluate Model 1. Present slide F. Have students reflect on the slide's first prompt:

• First take a moment to consider how Model 1 helps us explain how/why any of our listed phenomena occur.

Give them 3 minutes to record their response to the second prompt on *Evaluating Models*:

• Then evaluate the model's advantages and limitations for helping explain these phenomena through the particular lens you selected.

Transition to the next slide by saying, We should always try to evaluate the advantages and limitations of any model in terms of what phenomena it can explain. Let's discuss a few of those related to earthquakes.

Focus on points in matter where slips or breaks occur. Display slide G. Read the text at the top:

• Plates can suddenly slip along where they are in contact with each other. The video claimed that this is the cause of many earthquakes along plate boundaries.

Discuss the slide's two questions as a class, as shown in the table below. Use the follow-up questions to foreground the role of scale in considering matter changes in the system.

Suggested prompts	Sample student responses	Follow-up questions
What must be happening to the matter at points of contact between the plates right before this occurs?	It is elastically deforming. It is getting compressed or bent at those points.	Why would such changes be hard to detect in any solids interacting in this way unless we changed scales to zoom in and/or to slow down time?
Why, in most cases, would breaking, fracturing, or cracking tend to occur at points along the edge of the plate, instead of farther back, away from the edge?	There are stronger (higher-magnitude) forces on the matter along the plate edge than in the middle. There are small pieces of matter in contact along the plate edge, but larger amounts of matter farther away from the edge.	Why would differences in the amount of matter along the plates' points of contact affect where the matter breaks?

In students' responses to the follow-up questions, listen for the following ideas:

- It is hard to detect changes in solids, because the amount of elastic deformation is relatively small compared to the amount of force for most solids.
- Smaller pieces are more affected by forces than larger pieces, because they have less matter.
- There are fewer particles in that part of the matter.

4 · MAKE SENSE OF MATTER CHANGES AND RECALL PRIOR PARTICLE-LEVEL MODELS OF MATTER

MATERIALS: *Evaluating Models*, M-E-F poster, M-E-F expansion panels

Recall prior models of particles. Say, As we are now considering the changes happening in smaller parts of the plate, let's see what thinking about even smaller scales can help us understand about this system. Present **slide H**. Elicit 1-2 ideas in response to the prompt:

• How did thinking about the particles in the system help us better explain a phenomenon in our prior unit?

Listen for students to recall their experiences from OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit) with electrons moving through wires to help explain energy transfer through a circuit.

Update the M-E-F poster. Say, Paying attention to changes at the particle level helped us understand phenomena better in the past, so let's add a question to our M-E-F poster to remind us of that going forward.



Review types of particles. Present slide I. Read the text at the top, and elicit 1-2 ideas with the prompt:

- Particles is a general name for the smallest pieces of matter represented in a model we develop or use.
- What names have we used to refer to those particles in our prior modeling work in science class?

Listen for students to mention atoms, molecules, electrons, and protons.

ADDITIONALIf students mention things like grains of sand or rock, ask them to identify the more fundamental particlesGUIDANCEmaking up those materials. Encourage them to recall their prior Chemistry units and to consider particles that
are not visible to the unaided eye and have distinct properties and interactions.

Consider particle-level interactions. Display slide J. Have students turn and talk for a minute about the prompt:

- What is happening at the particle level within a solid that helps explain either of these behaviors of matter? (You pick.)
 - All solids elastically deform up to a point.
 - Pieces of a solid can break off when the matter reaches its elastic limit.

Compare models of bonds. Say, In Chemistry, you probably would have used the term "bonds" to describe what holds atoms or molecules in a solid together. Present **slide K**. Read all of the slide aloud:

- Bonds between atoms or molecules are often used to help explain some of the properties of matter. What does your own model suggest about what the bonds between these particles in a solid are like?
 - They are like strings.
 - They are like springs.
 - They are like rigid sticks.
 - They are like _____.

Explain that the blank option is included because these models are all analogies, which are useful in some ways but limited in others, and they may think a different model would be a more useful analogy. Give students a few moments to think on their own about which of the listed options is closest to their own model of the bonds in a solid. Then poll the class about these options with a show of hands.

After the poll, validate that scientists represent bonds in many ways, such as those on the slide, and these representations help explain some properties of matter but not all. Say, *If you asked scientists whether bonds are actually solid physical structures, like a string, spring, or stick, they'd say they are not, and that bonds are actually stable states that emerge from the electric forces between the charged particles making up atoms and molecules.*

Recall charge interactions. Present slide L. Read the text on the top:

• Smaller particles make up atoms. Some have a charge.

Discuss the prompts as a class to review how charged particles interact, as shown in the table below.

Suggested prompt		Sample student response
Which of these particle	s would repel each other?	Particles with the same charge repel each other.
		Electrons (negatively charged particles) push each other away.
		Two protons (positively charged particles) repel each other.
Which of these particle	s would attract each other?	Particles with different charges attract each other.
		Electrons and protons would be attracted.
ADDITIONALSlides K-L are designed to help students quickly recall their prior models for these particles and theirGUIDANCEinteractions. If they have taken OpenSciEd Chemistry, they have developed and used several models that could apply here. Eliciting these ideas supports making sense of the behavior of the magnets in the next model.		uickly recall their prior models for these particles and their Chemistry, they have developed and used several models that orts making sense of the behavior of the magnets in the next

5 · DISCUSS MODEL 2

MATERIALS: Evaluating Models, https://youtu.be/K3m2x6Vtj4I

Introduce Model 2. Say, The second model we're going to evaluate uses magnets to simulate the interactions between the nucleus of an atom and the electrons that produce bonds between atoms in a solid. As with Model 1, we'll use a video to orient to Model 2 and discuss what is happening through any lens that you choose.

Present slide M. Open https://youtu.be/K3m2x6Vtj4I and display it to the class. Turn the captions on. This video shows particle-level interactions, using magnets of different sizes to represent the nucleus and electrons of an atom. It includes the following prompts:

- What relationships do you notice between the distance between the magnets and the forces acting on them?
- Predict what you think the net force will be on these parts as we bring them together.
- What does this tell us about the magnitude of the repulsive versus attractive forces acting on the magnets at this point in the system?

Pause the video when each prompt is displayed, and have students turn and talk about it before discussing it as a class. Rewind and replay any section that you think supports this discussion.

6 · IDENTIFY ADVANTAGES AND LIMITATIONS OF MODEL 2

MATERIALS: *Evaluating Models*, Scale Chart poster, M-E-F poster, M-E-F expansion panels

Evaluate Model 2. Present slide N. Give students a moment to consider how Model 2 helps us explain how/why any of our listed phenomena occur. Then cue them to record the model's advantages (merits) and limitations on their handout, as well as the lens they are using to evaluate it.

7 · BRAINSTORM FEATURES OF A SIMULATION

MATERIALS: Evaluating Models

Brainstorm about a simulation. Say, To prepare to use a third model, which is a particle-level computer simulation, let's specify what we think it should have or do, based on our model evaluation work so far. Present **slide O**. Discuss the prompts as a class, as shown in the table below.

Suggested prompt	Sample student response
What parts and interactions would we need/want in a particle-level simulation to make progress on our questions?	We need atoms or molecules that can move when forces are acting on them.
	Bonds between particles.
What characteristics of the matter could affect some of these	Its size (dimensions).
interactions?	The type of material.
	Temperature.
What would we want to be able to visualize or measure in this simulation?	A measure of the amount of energy transferred.

I would like to see a representation of the forces.

Particle movement.

Say, Let's compare the features we specified to the simulation I have for us, and consider how we could use it to design investigations to help answer some of our questions.

8 · INTRODUCE THE SIMULATION AND PLAN INVESTIGATIONS

MATERIALS: Particle Investigations, science notebook, Evaluating Models, https://youtu.be/D8QZMCO5_oc

Orient to the simulation. Present **slide P**. Play the video https://youtu.be/D8QZMCO5_oc to introduce the simulation's assumptions, representations, and variables. Distribute the *Particle Investigations* handout.

ALTERNATE Extension opportunity: For those who are interested, the simulation has an information tab that describes the model's rules further, as well as a code tab that lets students inspect, modify, and recompile the code for the model.

No attempt is made to explain the simulation's underlying code, which emulates the effect of electric forces between particles by using an equation that calculates the combined effect of repulsive forces (e.g., between positive nuclei) and attractive forces (between nuclei and shared electrons). The code uses a twelfth-order potential energy equation known as the Lennard-Jones potential (LJ potential) to derive the net force versus distance relationships. Understanding this relationship is not a target DCI for high school.

Prepare for the investigation. Present slide Q. Assign students to groups of 2-3. Read the task instructions aloud:

- Decide which independent variable each person will investigate.
- Record this on Part 1 of your handout.

Have students store *Particle Investigations* in their science notebooks. Collect *Evaluating Models* before the end of the class period.

ASSESSMENT What to look for/listen for:

OPPORTUNITY	 Use evidence generated by the model to discuss the mechanism(s) the model helps explain in terms of matter changes and/or M-E-F interactions. (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2) Use a crosscutting lens (<i>stability and change, thinking across scales, and/or cause and effect</i>) to discuss the advantages and limitations of the model to further explain or test plate changes, breaking, and elastic deformation. (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2)
	See the <i>Evaluating Models Key</i> for sample responses.
	What to do: If students need additional practice, return the <i>Evaluating Models</i> handout toward the end of the next class period, and tell them to use the row for Model 3 to evaluate the avantages (merits) and limitations of the simulation we used.
	Building toward: 4.A Evaluate the merits and limitations of different models using a crosscutting lens (<i>stability and change, thinking across scales,</i> or <i>cause and effect</i>) for understanding and explaining different phenomena (earthquakes) and mechanisms (elastic deformation, cracking/breaking). (SEP: 2.1; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS2.B.3, ESS2.B.2)

End of day 1

9 · NAVIGATE: USE THE SIMULATION TO CARRY OUT A SERIES OF INVESTIGATIONS

MATERIALS: science notebook, *Particle Investigations*, computer with access to https://openscied-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html

Carry out investigations. Present slide R. Distribute a computer with access to https://openscied-

static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html to each group. Instruct them to take out the investigation plans they previously wrote on their *Particle Investigations* handouts and follow the instructions on the slide:

- Review your investigation plan.
- Carry out Investigations 1-4 and record your results.

Give them 14 minutes to complete the investigations and document the results. *

***** ATTENDING TO EQUITY

Universal Design for Learning: Provide multiple means of representing these findings. In Investigation 1, students can record both qualitative and quantitative data. They can also use tables or graphs. If they record only quantitative data, encourage

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What to look for/listen for: See the Particle Investigations Key. It includes a brief explanation of the goal of each investigation (1-4) and what to look for in student responses.

What to do: Encourage students to consider how their findings provide additional insight into how/why different phenomena happen that we have been trying to explain (earthquakes, elastic deformation of solid matter, and cracks/breaking).

Building toward: 4.B.1 Use a computational model to explore stability and change and cause-and-effect relationships between the magnitude of external forces acting on a solid, the changes in matter given its mass (number of particles), and the changes in energy in the system across different scales. (SEP: 2.3; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS3.B.2, PS2.B.3, ESS2.B.2)

10 · PREPARE FOR A SCIENTISTS CIRCLE

MATERIALS: Particle Investigations

ASSESSMENT

OPPORTUNITY

Share results with a partner. Present slide S. Ask students to share with a partner how the changes in their independent variable affected the outcomes in the simulation. It is OK if they only get to discuss their results from Investigation 1; this is enough to prepare them to share all their findings in the Scientists Circle.

11 · UPDATE THE M-E-F POSTER

MATERIALS: Breaking Foam Panels, Particle Investigations, M-E-F poster, M-E-F expansion panels, Scale Chart poster, 3x5 sticky notes, clear tape, chart paper markers

Facilitate a Consensus Discussion in a Scientists Circle. Display slide T. Have students bring their Particle Investigations handout to a Scientists Circle. Tell them explicitly, As in all Consensus Discussions, my role is to give everyone time to consider each proposed idea and weigh in on those ideas. Today we'll consider additions to our M-E-F poster. I'll need everyone to weigh in on those before we add anything to it. *

SCIENTISTS Having students sit in a circle facing one another is a key structure in building a sense of shared mission and a community of learners working together. This is also a good opportunity to have them briefly recap the CIRCLE logistics for forming a Scientists Circle. Challenging the class to see how smoothly and quickly this transition

***** STRATEGIES FOR THIS CONSENSUS DISCUSSION

As this is early in the unit, it is helpful to be explicit now about your role in a Consensus Discussion, so when you say "consensus" in future lessons and units. students will

3 min

them to write a conclusion summarizing their findings. If they include only qualitative data, encourage them to support their ideas with a couple of data points. For Investigations 2-4, which are brief, encourage students to record several observations at the very least.

Adjust the simulation speed using the setting located at the top. Some students with disabilities might benefit from using a lower speed to more easily track changes in the system.



can be achieved in each subsequent gathering can refine its timing. After another round or two of attending to this goal, it becomes something that can take fewer than 30 seconds to carry out.

Discuss macroscopic changes. Use the foam panel with a narrow middle section for a demonstration to establish the relationship between changes in external forces applied to a system and macroscopic changes in its matter. This supports considering differences in particle-level forces at different parts of the system. Say, *Let's use some of the M-E-F prompts and our ideas from all three models to see how particle-level thinking can help us better explain the changes in matter that we've observed.*

Hold up a double V-notched foam piece (3" x 12" x ½"). Compress it with your hands from both ends until it is in a slightly bowed shape, before it starts cracking. Ask, *What changes do we see in this matter right now?* Listen for the following observations:



- The foam is bending.
- The foam is changing shape.

Discuss how forces acting on the system affect the matter. Say, We saw in the simulation that paying attention to changes in particles helped us explain changes in shape. Let's consider what's happening at the particle level here.

Present **slide U**. Use the prompts to elicit ideas about the demonstrated changes in the foam:

- Consider whether forces acting on particles are balanced or unbalanced in the following conditions:
 - 1. No external forces are acting on the foam.
 - 2. Forces start bending the foam.
 - 3. Forces stop bending the foam, but keep it bent.
 - 4. Forces continue bending the foam, and cracks appear.
 - 5. The foam breaks into two pieces.
- What is happening to the particles along this sequence?

The class discussion may play out as shown in the table below.

Suggested prompt

Sample student response

recognize the goal of the work and your role in it.

Encourage student-to-student talk with a focus on representing how all their group's ideas compare to the ideas others have shared. Emphasize first restating what others said, before adding to it or saying whether there is agreement. Students can also use head nods or hand signals to show they had a similar idea.

Similarly to how we have developed the M-E-F poster so far in this unit, use student ideas to incrementally add annotations to it after class-wide agreement is established for a related set of ideas or ways of thinking/questioning.

✤ SUPPORTING STUDENTS IN DEVELOPING AND USING ENERGY AND MATTER

One purpose of the prompts in the M-E-F poster is to assist students in making sense of changes in energy within a system. By being prompted to observe macroscopic changes in matter and in the net force acting on a system, they begin to identify how interactions among the system's components help explain the changes in matter and energy, both macroscopically and at the particle level.

***** SUPPORTING STUDENTS IN

What is happening at the particle level as I change the shape of this form?	The particles move.	DEVELOPING AND USING ENERG MATTER
iouni.	The distance between particles increases and/or decreases.	You may want to ask for additional
As the shape of the foam changes, are the forces on its particles balanced or unbalanced?	Unbalanced.	of phenomena from students' prior Chemistry that involved explaining
When I stop pushing but hold the foam bended, are the forces on its	Balanced.	particles and/or energy stored in fie Examples they may cite:
What will happen if I continue bending the foam?	It will break.	 In OpenSciEd Unit C.1: How can the flow of energy on Earth to p vulnerable coastal communitie
	It will crack.	<i>Ice Unit</i>): The phenomenon w melting polar ice caps and se
When cracks start to form, what will happen to the forces on the particles along where the cracks form?	The forces will be unbalanced because particles will start moving.	composition. The particles we
	The bonds will break.	air, and their motion was rela
So in both cases, breaking and elastic deformation, the motion changes happening at the particle level are due to unbalanced forces on the particles?	Yes.	 In OpenSciEd Unit C.2: What co lightning and why are some plo than others when it strikes?

Discuss particle-level changes in the system. Present slide V. Lead students to summarize the role of unbalanced forces with the prompt:

What causes all changes in motion, whether the motion is at the particle level or macroscopic? ٠

They should say that unbalanced forces cause all changes in motion. Point out that we have seen unbalanced forces cause several types of changes: motion, shape change, and breaking. Suggest we use this insight to simplify the entire set of changes listed under the "Matter" section on the M-E-F poster, as these are all changes in motion.

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examples r work in energy of elds.

- ın we slow protect es? (Polar vas ea level pheric ere land. and ated to system.
- auses aces safer (Electrostatics Unit): The phenomenon was lightning. The particles were displaced electrons in the air, clouds, ground, and metal, and the positive nuclei left behind. The fields were electric fields between places where excess charges accumulated.
- In OpenSciEd Unit C.5: Which fuels • should we design our next generation vehicles to use? (Fuels Unit): The design problem was related to alternate fuels for energy. The particles were atoms and shared electrons in bonds within



molecules (for combustion reactions or batteries) or protons and neutrons (for fission reactions). The fields were electric for the former, and fields from strong nuclear forces for the latter.

Emphasize that we will continue to use this idea as a way of explaining all changes we observe in matter. *

Discuss how the amount of matter affects the forces acting on it. Present slide W. Continue the discussion with the prompts, as shown in the table below.

Suggested prompt	Sample student response
Where do we think the foam will break?	It will break in the narrow middle section.
How do the number of particles across this section compare to the rest of the sample?	There are fewer particles here.
Why would this lead to a higher magnitude of internal force per particle in this section, compared to other parts of the matter?	(Accept all answers.)

Introduce a term used to describe forces on particles. Say, When scientists consider the average amount of force per particle, they sometimes refer to this as "pressure." Ask for another example of hearing the term pressure referring to this sort of force. Students who completed

OpenSciEd Unit C.5: Which fuels should we design our next generation vehicles to use? (Fuels Unit) may provide examples of force on a piston surface due to particle collisions in a combustion engine.

ADDITIONAL GUIDANCE	Supporting emergent multilingual learners: If students use words like <i>stress</i> or <i>strain</i> to refer to what was happening in the simulation outcomes, it may be helpful to reinforce that scientists sometimes describe matter changes in this way. Help all students use a common understanding, and increase the <i>relevance</i> of these words at this point, by mapping the use of the words to (1) everyday language and to (2) the M-E-F ideas.
	Start by asking for an example of seeing someone use a strainer in food preparation to separate something. Reference the "Matter change" corner of the M-E-F poster, and say that the scientific measure of <i>strain</i> has a similar meaning, as it is a measure of how much the matter in a solid separates. Specifically, it is the ratio of the amount of deformation to the original length of the sample.
	Then note that "pressure" or "stress" is used in everyday language about people's feelings. Ask for examples of external things that can cause those feelings. Reference the "Matter force" corner of the M-E-F model, and say that the scientific measure of <i>pressure</i> or <i>stress</i> is similar, as it is a measure of the internal forces within a section of a solid, often in response to external forces. Specifically, it is also a ratioeither the ratio of force to area (of matter) or force per particle.
	Keep in mind that these terms are not needed in future lessons, so they do not need to be entered in students' Personal Glossaries.

Present **slide X**. Slowly bend the foam to its breaking point, asking students to pay attention to what they see happening. The foam will snap, and pieces may fly off. Turn the broken faces of the foam toward the class and point along it when you ask the questions shown in the table below.

Suggested prompt	Sample student response
What kept the matter from breaking apart along where it cracked before we reached the elastic limit?	The bonds between the neighboring particles.

What types of forces between protons and electrons produce those bonds?	Electric.	
Do those same types of forces help explain why all solids, including the plates, could elastically deform up to a point?	Yes.	
ADDITIONAL The next equals of minutes for smarth of energy this line. This is necessary to help up and (or at		

ADDITIONALThe next couple of minutes foreground two aspects of energy thinking. This is necessary to help upend (or atGUIDANCEleast call into question) prior ways students may have encountered for conceptualizing or referring to
potential energy. Keep the discussion focused on the distance between particles and changes in their motion
to make sense of energy transferred and energy stored in and out of the system.

Identify the role of fields. Say, We have argued that electrons and protons produce electric fields. So, because all atoms have these particles, we can say that all matter produces fields. In a solid, these electric fields produce forces that act on neighboring particles in ways that explain all sorts of macroscopic behavior. Update the M-E-F poster.



ALTERNATE	You might want to invite students to suggest updates to the M-E-F poster to reflect the ideas developed	
ACTIVITY	during this discussion. Ask questions such as:	
	 What components and interactions connect "Forces" and "Energy"? 	

• How are fields related to matter, energy, and forces?

Say, Let's see how this idea of fields can also be used to help explain how energy is transferred and stored in the system.

ADDITIONAL	You may want to emphasize the limitations of using the term potential energy to describe the energy stored in
GUIDANCE	a system, especially if students are already familiar with it. You can say something like: Scientists sometimes
	refer to the energy stored in systems like this as "potential energy." But this term can be problematic, because it
	doesn't help in tracking the energy or identifying what part of the system it's stored in. The phrase "potential energy"
	also doesn't have any explanatory power, because it's often isolated from thinking about unbalanced forceswhich
	we've discovered is the mechanism behind all energy transfer.

Connect to prior discussions. Continue by saying, When the foam is being held in this stable bent shape, there's no measurable energy increase in the system, like increased kinetic energy or temperature. So, we need to find a way to describe exactly where the energy is being stored; otherwise, we won't be able to account for conservation of energy--something that we know should occur in every process. When changes in the distance between objects or between particles acting on each other through fields affect the amount of energy stored in the system, scientists say the energy is being transferred into or out of, or stored in, the fields.

Discuss matter and energy relationships. Present **slide Y**. Continue the discussion with the prompts, as shown in the table below. Encourage students to refer to their *Particle Investigations* as needed.

Suggested prompt	Sample student response
What was the relationship between changes in the distance between particles and changes in the energy stored in the electric field(s) in the simulation?	Greater changes in distance result in greater amounts of energy being stored in the electric fields.
Can we store unlimited amounts of energy in those electric fields, or was there a limit?	There was a limit. When the material breaks, we can't store more energy in it.

Use our new ideas to explain earthquakes. Present slide Z. Discuss the prompts, as shown below.

Suggested prompt	Sample student response
How does the scale of a plate, and the number of particles that make up its matter, affect the amount of energy that can be stored in the electric fields between the particles before part of the plate reaches an elastic limit?	Plates have a lot of mass, which means they have a lot of particles, so they have more electric fields between particles that can store energy.
We know the motion of the plates is relatively slow. What does that tell us about why there are periods of apparent stability between earthquakes in any given region?	It takes a long time for the amount of energy stored in the system to build up. It takes a long time for the system to be deformed enough (again) to reach another elastic limit.

Revise the posters. Present **slide AA**. Emphasize that we can now say that what happens at a very small scale--the particle level--can explain changes in the plates at a much larger scale, including earthquakes and cracks. Part of the explanation is related to the amount of elastic deformation in the system, which steadily increases over time.



As you update the M-E-F poster, ask how we knew whether electricity was transferring energy through the system for the electricitypowered devices in *Electricity Unit*. Students should say heat, light, and maybe sound coming from those devices. Validate these responses.



Summarize the relationship between particle-level changes and energy stored in matter. Point out that we are considering how energy is stored in systems in a new way, related to elastic deformation. Note that this involves thinking about the motion of particles in matter and the energy stored in the fields based on their relative positions in space.

Emphasize that in our prior unit, we also thought about electricity in terms of particle motion and fields transferring energy, though we didn't focus on how fields can store energy. Ask students to recall what particles we studied in that system, and what types of fields transferred energy from the generator through space to the wires. They should say electrons in wires, and electric and magnetic fields.

Summarize how to account for energy changes in a system. Point out that it is not only elastic deformation and electricity that can be broken down into a combination of one or two things that describe where energy is in the system and how it is transferred. We can also think in this way about the kinetic energy of objects (generators, magnets, plates) or particles (electrons, atoms, molecules) and the energy in fields (electric, magnetic).

Challenge students to keep this lens in mind going forward--we can, if needed, account for all changes in energy as a combination of changes in kinetic energy and changes in energy stored in fields, even if the everyday name we give to the transfer of that energy is "sound" or "heat".

Use these ideas to update the M-E-F poster.



Emphasize that we just applied our M-E-F thinking to two Earth science phenomena, and going forward, we should recognize that we can now explain any Earth science phenomenon from a particle-level perspective. Point to the Scale Chart poster and its sticky note for volcanic eruption, and forecast that we will apply our thinking to this phenomenon in the upcoming Electronic Exit Ticket.

12 · ASSIGN THE ELECTRONIC EXIT TICKET

MATERIALS: copy of https://docs.google.com/forms/d/1bxE9hzdU7elsXuZvGC7jA6uEGDAKPDjVanSWeNr1vR8/copy made before class

Assign the Electronic Exit Ticket. Before class, make a copy of

 $\lfloor \leq$ https://docs.google.com/forms/d/1bxE9hzdU7eIsXuZvGC7jA6uEGDAKPDjVanSWeNr1vR8/copy . Share the link to the copy with students (do not share the original link, as that will create a new copy for each student, and you will not have access to their responses). Present slide BB. Give them 10-12 minutes to complete the Electronic Exit Ticket individually.

ASSESSMENT OPPORTUNITY	What to look for/listen for in the moment: Use the L4 EET Key to assess student work.
	What to do: The Electronic Exit Ticket addresses 3D elements associated with a lesson-level performance expectation (LLPE) for Lesson 4. This assessment is designed to make it easy to gather information about where students are still struggling to put the pieces together.
	Building toward: 4.B.2 Use a computational model to explore stability and change and cause-and-effect relationships between the magnitude of external forces acting on a solid, the changes in matter given its mass (number of particles), and the changes in energy in the system across different scales. (SEP: 2.3; CCC: 2.2, 3.2, 7.1; DCI: PS3.A.4, PS3.B.2, PS2.B.3, ESS2.B.2)

13 · NAVIGATE

MATERIALS: None

Navigate into Lesson 5. Present slide CC. Ask students to raise their hand (yes or no) in response to the prompt:

• Can we fully explain what is happening at Afar, or do we need more information/data?

Establish agreement that because the Afar events didn't happen at a plate boundary, something must be going on there that is different from what we think is happening for most earthquakes, or for the volcanic eruption in the Electronic Exit Ticket, which did occur near a plate boundary. We need some additional data/information to figure out the case sites that appear to be exceptions.

ALTERNATE ACTIVITY

Extension opportunity: You can assign home learning if you want to provide students with additional practice in engaging with *developing and using models*. Present **slide DD**, and suggest they identify the simulation's advantages and limitations by filling in the last row of the *Evaluating Models* handout.

The second prompt encourages students to add new meanings to their Personal Glossaries. Use it if you think some students might benefit from this.

Additional Lesson 4 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN ELA	CCSS.ELA-LITERACY.SL.11-12.1 Initiate and participate effectively in a range of collaborative discussions (one- on-one, in groups, and teacher-led) with diverse partners on grades 11-12 topics, texts, and issues, building on others' ideas and expressing their own clearly and persuasively.
	Four discussions are integrated into this lesson: two with different pairings of students for video analysis on day 1, one in small groups to compare investigation findings, and one whole-class Consensus Discussion on day 2. These provide multiple opportunities to engage in this speaking and listening standard. This lesson's focal Community Agreement further foregrounds the importance of student contributions that are recognized and valued by their peers; the last question on the Electronic Exit Ticket has students reflect on this as well.
