the liquid and the room converge to a more uniform temperature (HS-PS3-4). With careful measurements, students should discover a slight difference between freshwater and water with sugar or salt added. The difference in bulk properties must relate to some sort of microscopic interaction between the salt and the water that students will investigate in IS3.

The difference is more dramatic when they try cooking oil. (Safety reminder: students should always wear protective lab wear including goggles and aprons.) Students might wonder what the difference is between cooking oil and water that makes these materials respond to the heat differently. Before moving on, students should relate the combustion in this experiment to the real world. They should make a list of all the places that they know where things burn and they will revisit them in IS5 as they discuss the impact of burning fossil fuels on global climate (ESS3.D).

IS2

Chemistry in the Earth System Instructional Segment 2: Heat and Energy in the Earth System

As a precursor to understanding endothermic and exothermic chemical reactions, reaction kinetics, or gas laws, students need a robust model of matter moving around as discrete particles that interact. In IS2, students investigate the laws of thermodynamics in systems as small as atoms and as large as the entire Earth.

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 2: HEAT AND ENERGY IN THE EARTH SYSTEM

Guiding Questions

- How is energy transferred and conserved?
- How can energy be harnessed to perform useful tasks?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-PS3-1. Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known. [Clarification Statement: Emphasis is on explaining the meaning of mathematical expressions used in the model.] *[Assessment Boundary: Assessment is limited to basic algebraic expressions or computations; to systems of two or three components; and to thermal energy, kinetic energy, and/or the energies in gravitational, magnetic, or electric fields.]*

HS-PS3-2. Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles (objects). [Clarification Statement: Examples of phenomena at the macroscopic scale could include the conversion of kinetic energy to thermal energy, the energy stored due to position of an object above the earth, and the energy stored between two electrically-charged plates. Examples of models could include diagrams, drawings, descriptions, and computer simulations.]

CHEMISTRY IN THE EARTH SYSTEM INSTRUCTIONAL SEGMENT 2: HEAT AND ENERGY IN THE EARTH SYSTEM

HS-PS3-4. Plan and conduct an investigation to provide evidence that the transfer of thermal energy when two components of different temperature are combined within a closed system results in a more uniform energy distribution among the components in the system (second law of thermodynamics). [Clarification Statement: Emphasis is on analyzing data from student investigations and using mathematical thinking to describe the energy changes both quantitatively and conceptually. Examples of investigations could include mixing liquids at different initial temperatures or adding objects at different temperatures to water.] *[Assessment Boundary: Assessment is limited to investigations based on materials and tools provided to students.]*

HS-ESS2-3. Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection. [Clarification Statement: Emphasis is on both a one-dimensional model of Earth, with radial layers determined by density, and a three-dimensional model, which is controlled by mantle convection and the resulting plate tectonics. Examples of evidence include maps of Earth's three-dimensional structure obtained from seismic waves, records of the rate of change of Earth's magnetic field (as constraints on convection in the outer core), and identification of the composition of Earth's layers from high-pressure laboratory experiments.]

HS-ETS1-4. Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-2] Developing and Using Models [SEP-3] Planning and Carrying Out Investigations [SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)	PS3.A: Definitions of Energy PS3.B: Conservation of Energy and Energy Transfer PS3.D: Energy in Chemical Processes PS4.A: Wave Properties ESS2.A: Earth Materials and Systems ESS2.B: Plate Tectonics and Large-Scale System Interactions ETS1.B: Developing Possible Solutions	[CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation

CA CCSS Math Connections: N-Q.1–3; MP.2, MP.4b

CA CCSS for ELA/Literacy Connections: SL.11–12.4, 5; RST.11–12.1, 2, 8; WHST.9–12.7, 8, 9

CA ELD Connections: ELD. PI.11–12.1, 5, 6a–b, 9, 10, 11a

Energy [CCC-5] is perhaps the most unifying crosscutting concept in all of science. Energy is a property of both matter and radiation and is manifested as the capacity to perform work, such as causing the motion or interaction of molecules on a micro-**scale [CCC-3]**, or the movement of machines or planets on a macro-scale. Energy can be converted in form, but neither created nor destroyed. On the microscopic scale, energy can be **modeled [SEP-2]** as the motion of particles or as force fields (electric, magnetic, gravitational) that enable interactions between such particles. At the macroscopic scale, energy is manifested in a variety of phenomena, such as motion, light, sound, electromagnetic fields, and heat.

The study of thermal energy forms an important bridge between the bulk properties of matter and the atomic scale processes governing chemical reactions. In the middle grades, students developed models of matter made of moving particles, the velocity of which depends on their temperature (MS-PS1-4). In chemistry, they will learn that these particles do not just bounce off one another but can interact, and that sometimes these interactions can break up the particles into smaller constituent pieces. High school chemistry students also rely on measurements of temperature at the bulk scale to interpret chemical changes, so it is essential that students have a robust model of what temperature means. They dissolve materials in water and need to be able to extend their basic model of liquids and solids to explain what happens to both materials when they interact.

As students develop core ideas of thermodynamics, they should always be trying to understand them in the context of a model of matter as discrete moving particles. For example, The Zeroth Law of Thermodynamics states that two systems that are in thermodynamic equilibrium have the same temperature and will not exchange heat with each other. This concept follows from the claim in the middle grades that changes in motion correspond to changes in energy (MS-PS3-5). If, however, two closed systems with different temperatures are brought into thermal contact, heat will flow from the system of higher temperature to the system of lower temperature just as an object can transfer some of its kinetic energy to another object when they collide.

The first law of thermodynamics states that the total **energy [CCC-5]** of an isolated system is constant, and that although energy can be transformed from one form to another, it cannot be created nor destroyed. The **conservation of energy [CCC-5]** is thus a unifying theme in science because energy must always be accounted for in all exchanges, inviting scientists to study its flow throughout the complex biological, chemical, physical, geological, and astronomical systems they study. **Energy [CCC-5]** transfers between organisms in food webs, by wind and ocean currents on Earth, and by light from one astronomical body to another have all been a focus throughout their K–8 experience in the CA NGSS. In the middle grades, students developed specific models for describing energy transfer in moving objects (MS-PS3-5) and systems storing potential energy (MS-PS3-2).

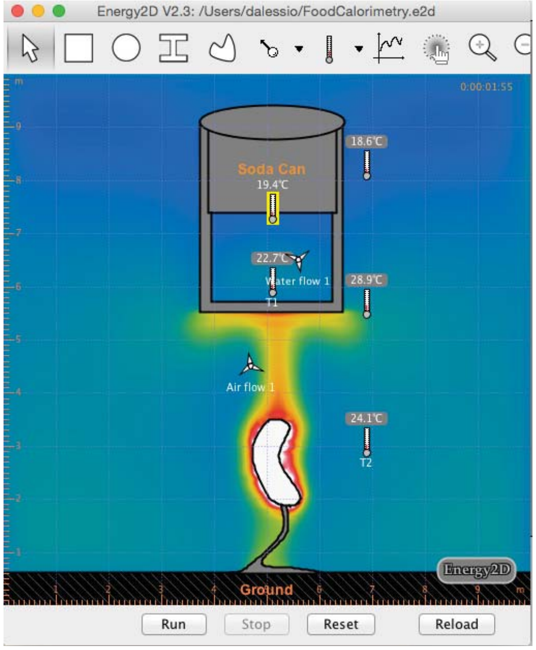
The second law of thermodynamics defines the conditions under which **energy will flow [CCC-5]** between components in a system. Isolated systems always progress toward thermodynamic equilibrium with maximum entropy. In other words, systems strive towards a uniform energy distribution among all the components. At the middle grade level, students **developed a model [SEP-2]** of individual particles that move around at speeds related to their temperature (MS-PS1-4). They also examined the forces involved in colliding objects through an engineering challenge (MS-PS2-1). Now they can combine their intuition about these two systems to enhance their **model [SEP-2]** of heat flow. If a moving car crashes into a stationary one, the moving car slows down while the stationary car receives energy and begins to move. Since **matter [CCC-5]** involves countless particles involved in countless collisions, this process repeats over and over again with the particles having more kinetic energy always transferring energy to objects with less kinetic energy. When two objects are touching, **energy [CCC-5]** is transferred in this manner until the average kinetic energy of the particles in the objects is the same. Energy continues to move back and forth during collisions, but each object gains as much as it loses during any given point in time. Students will **plan and conduct an investigation [SEP-3]** “to provide evidence that the transfer of thermal energy when two components of different temperature are combined within a closed system results in a more uniform energy distribution among the components in the system” (HS-PS3-4).

Despite the fact that a scientific model for the second law is presented earlier in this paragraph before describing the investigation, the order in the classroom would probably differ so that students do more than just verify it experimentally. An inquiry-driven investigation to monitor temperatures that culminates with a scientific **explanation [SEP-6]** resembling the second law is more consistent with the tools in chapter 11 on “Instructional Strategies” in this framework (and would definitely meet this performance expectation). Regardless of the order, students should be provided appropriate materials so that they can perform experiments such as measuring the temperature of two bodies of water before and after mixing, or the temperatures of metal blocks and water prior to, and following immersion. By repeating these **investigations [SEP-3]** with differing quantities of materials, students can apply the concept of **scale, proportion, and quantity [CCC-3]** to predict temperature **changes [CCC-7]**, equilibrium conditions, and magnitudes of energy transferred (HS-PS3-1).

At the macroscopic **scale [CCC-3]**, there are several different heat-flow mechanisms by which the second law operates: conduction, convection, and radiation. Students can relate each of these processes to the motion of individual particles (HS-PS3-2). Conduction involves the direct collision of particles, so denser materials will transmit heat faster than less dense ones. Students can **construct an explanation [SEP-6]** about why solids are much better at transferring heat by conduction than liquids or gases because of their greater density. During their **investigations [SEP-3]** of the second law, students might have noticed that heat transfer involving liquids included mixing and movement of the liquids (easily visualized with food coloring). In liquids and gases, faster moving particles can slide past or push away slower moving particles, allowing density-driven convection to occur. Radiation represents the conversion of kinetic energy to electromagnetic energy due to the movement and collisions of charged particles. Students learn more about this mechanism in the High School Three Course Model: Physics of the Universe course. Online simulations allow students to visualize each of these processes at the microscopic **scale [CCC-3]** (see PhET *Simulations* http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link21).

Computational **models [SEP-2]** are also an excellent way to explore heat transfer at the macroscopic **scale [CCC-3]**. The **investigations [SEP-3]** into the second law of thermodynamics can be done easily using free computer models designed for educational environments where students can set the material properties, geometry of systems, and initial conditions (see Concord Consortium, "Energy2D: Interactive Heat Transfer Simulations for Everyone" at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link22). Unlike a real investigation, there are no measurement errors, the model visualization can be paused or watched multiple times, and scenarios that are impractical to study in real life can be tested easily on the computer. An excellent challenge is to have students revisit the food calorimetry experiment from IS1 and retrace the flow of heat in a computer simulation (figure 7.20). Students can observe convection, conduction, and even simulate the **effects [CCC-2]** of wind blowing through the room. To extend their **modeling [SEP-2]** of heat flow to different contexts, students can use online computational **models [SEP-2]** for simulating the **flow of thermal energy [CCC-5]** through a wall, taking into account numerous criteria such as different wall materials and different initial temperatures on both sides of the wall (HS-ETS1-4).

Figure 7.20. Heat-Flow Simulation



Visualizing heat flow using a computer simulation. Colors represent temperature at every point in the model. *Source*: Concord Consortium n.d.

Heat Transport on Planet Earth

The drive towards thermal equilibrium operates on a massive **scale [CCC-3]** inside the Earth, with major implications for plate motions. Earth's interior is expected to be hot (from heat-generating radioactive elements in the interior), while its surface is adjacent to the cold emptiness of space. Students can **analyze [SEP-4]** temperature measurements from boreholes that show the temperature of rocks is warmer as you probe deeper into the Earth. Students can **support the claim [SEP-7]** that heat transfers from the hot interior outward. Convection is an extremely efficient heat transport mechanism that occurs when hot material rises upward because it is less dense and colder material sinks because it is denser. A simple lava lamp or any of the various published demos involving ice, warm water, and drops of food coloring are simple examples of **models [SEP-2]** of convection. Students **developed a model [SEP-2]** of convection at Earth's surface in the middle grades (MS-ESS2-6), and now they extend it to processes inside the Earth.

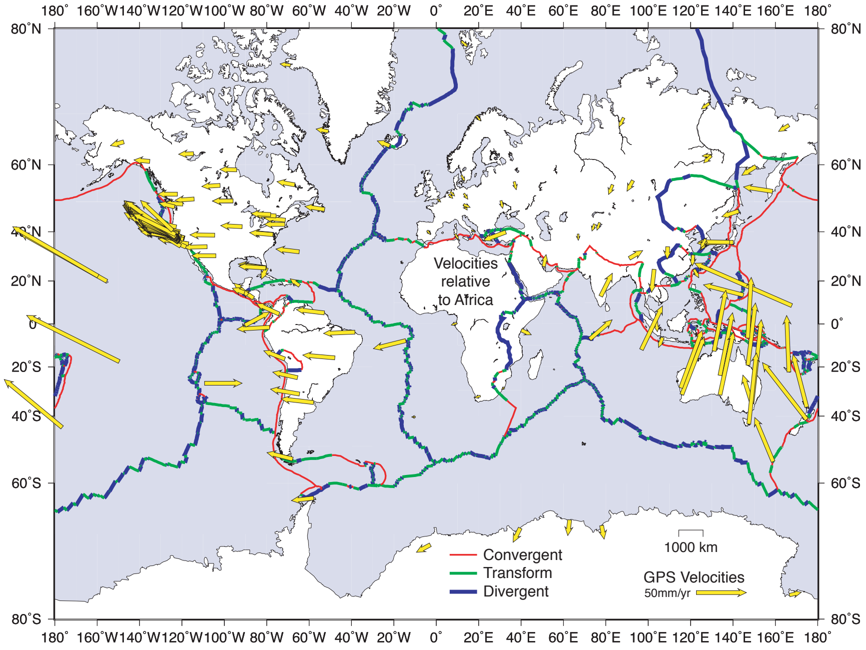
Students must **develop a model [SEP-2]** of Earth's interior and use evidence to **support the claim [SEP-7]** that its interior is convecting. Lava lamps are not perfect **models [SEP-2]** of convection in Earth's interior because there is strong evidence from seismic waves that most of the interior is not a liquid. One type of seismic wave from earthquakes, called S-waves, cannot travel through liquids. When an earthquake occurs on one side of the planet, the shaking can be recorded over a huge section of the planet as waves travel straight through the Earth. Stations on the exact opposite side of the Earth from the earthquake, however, do not record S-waves. This S-wave shadow is evidence that there is a liquid layer within Earth's core. When scientists take common Earth materials in a lab and expose them to the temperature and pressure that would exist in the core, they find that the materials do indeed become liquid when the temperature is high enough. Students can **analyze data [SEP-5]** from simplified seismograms taken from different locations around the world and identify which stations recorded S-waves and which did not. By drawing the path of seismic waves from the earthquake to each station, students can map out how big this liquid layer must be (see IRIS "Determining and Measuring Earth's Layered Interior" http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link23). The rest of the interior must therefore be solid.

If the interior of Earth is solid, how can it convect? After all, traditional chemistry textbooks claim that convection cannot occur in a solid. The paradox is resolved by coming up with a more sophisticated **model [SEP-2]** of solids and liquids that describes them on a spectrum involving both viscous and elastic behaviors rather than being two completely separate phases of matter like students may have discussed in the middle grades (MS-PS1-4). Water flows easily when poured slowly from a pitcher, but can feel painfully solid-like when a person belly flops into a swimming pool because the water cannot flow out of the way quickly enough. Polymer putty bends and oozes like a viscous fluid, but it will bounce if you throw it against a wall. Rock acts in much the same way. The forces causing convection inside the Earth push on the rock so slowly that it oozes like polymer putty. The fact that categories students have been using to describe the phases of matter do not adequately explain these behaviors of rock is an excellent example of CA NGSS's learning progression regarding patterns. While identifying **patterns [CCC-1]** and using them to classify and categorize are cornerstones of the SEPs beginning in kindergarten, by grade twelve students are expected to "recognize classifications or explanations used at one **scale [CCC-3]** may not be useful or need revision using a different scale" (NGSS Lead States 2013a). This revision process is at the heart of the nature of science.

Students can apply their **model [SEP-2]** of density-driven flow in rock not only to help understand heat transfer, but also to see how these flows give rise to plate tectonics. When hot material from Earth's interior reaches the surface, it begins to cool and becomes denser. Some of this dense material begins to sink back down, but unlike liquids in a lava lamp, the sinking solid rock is part of a connected shell of rock that forms Earth's lithosphere, its surface layer. As the dense material sinks, it drags along huge sections of the lithospheric shell with it much like an anchor pulls a rope attached to it as it sinks. A huge section of lithosphere dragged along as a single chunk is what we call a *plate*, and the movement of plates is what we call *plate tectonics*.

There are many pieces of evidence that this motion is occurring: For one, scientists can directly observe these motions using modern day Global Positioning System (GPS) measurements (figure 7.21). One **pattern [CCC-1]** revealed in such measurements is that large sections of the Earth all move together in the same direction at the same time (what we call plates). This measurement technology has only been available since the late 1980s, but scientists were able to observe other evidence that this motion is occurring by looking at the age of the seafloor (figure 7.22). There are long stripes down the middle of many oceans with very young seafloor in the center of the ocean basins and a clear **pattern [CCC-1]** where the ages are symmetrically older in both directions away from the stripe of youngest rocks. Students should be able to use seafloor ages and surface motion rates as evidence that convection occurs in Earth's interior. They can **communicate [SEP-8]** their **argument [SEP-7]** with a pictorial **model [SEP-2]** of Earth's interior that has annotations to indicate how heat transfer drives movement within the Earth (HS-ESS2-3).

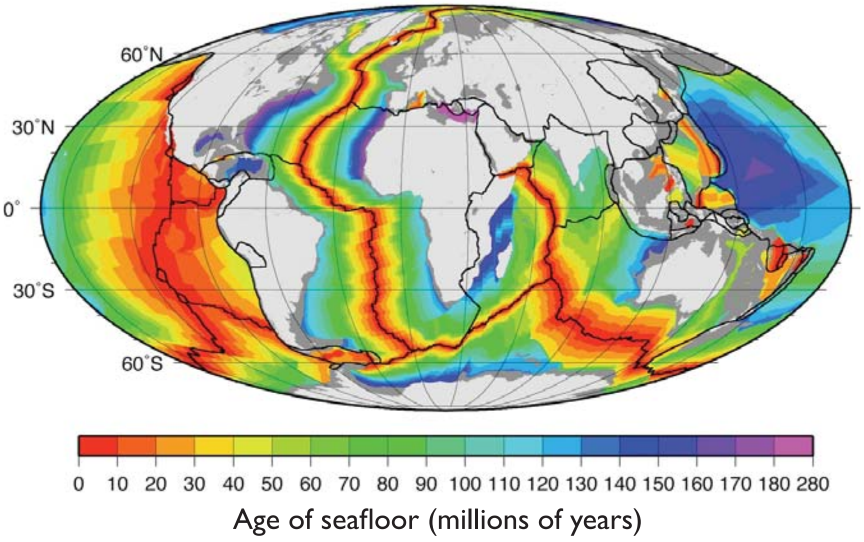
Figure 7.21. Present-Day Plate Motions



GPS velocities recorded at stations around the world reveal present-day plate motions. Arrow size relates to the speed of each point. Image credit: M. d'Alessio n.d.

The mechanism causing new seafloor to form is another example of density-driven flow. When two plates move apart from one another, the release of pressure allows solid material to expand slightly, causing decompression melting. The melted magma is less dense than the surrounding solid rock, so it quickly rises and forms new sections of lithosphere. As the plates continue to move, this rock gets older and is dragged further from the plate boundary.

Figure 7.22. Seafloor Age



Seafloor age. Hot material from the mantle rises up and cools to form new rock material (with age of zero) at the areas shown in red. *Source*: National Oceanic and Atmospheric Administration, National Centers for Environmental Information 2008

This section on heat flow within the Earth illustrates how studying Earth and space science and physical science concepts together enriches understanding of both disciplines. In high school, students are expected to ask questions about whether or not processes that act at one **scale [CCC-3]** are also significant at different scales of observation (appendix 1 of this framework). Students' understanding of physical science benefits from studying the role of convection in the Earth because it highlights the universality of thermodynamics—principles that function at the **scale [CCC-3]** of a laboratory experiment also apply to planetary-scale systems. Students' understanding of Earth and space science benefits because students then develop models that relate the driving forces of plate motions to **energy flow [CCC-5]**. Students' understanding of both sciences benefit from taking the time to collect the evidence supporting plate motions because effective science includes both conceptual models *and* observational evidence that supports those models.