Chemistry in the Earth System

Heat and Energy in the Earth System

Background for Teachers and Instructional Suggestions

Energy 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***, 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** as the motion or particles or as force fields (electric, magnetic, gravitational) that mediate 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.

Chemistry is often described as the “study of matter”, including the identification of the substances of which matter is composed, the investigation of properties of matter, ***energy flows in matter***, and the ways in which matter interacts, combines, and ***changes***. Heat is the form of energy that flows between samples of matter because of differences in temperature. The laws of thermodynamics define the fundamental physical quantities (temperature, energy, and entropy) that characterize matter, and are therefore essential for understanding matter and chemical interactions. 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. 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 until the two systems reach the same intermediate temperature.

The First Law of Thermodynamics states that the total ***energy*** 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*** 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*** transfers between organisms in food webs, by wind and ocean currents on Earth, by light from one astronomical body to another, and between molecules in chemical reactions, to name just a few processes.

The Second Law of Thermodynamics defines the conditions under which ***energy will flow*** 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** 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** 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*** 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*** 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** *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** resembling the Second Law is more consistent with the tools in the Instructional Strategies chapter of this Framework (and would definitely meet this PE). 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** with differing quantities of materials, students can apply the concept of ***scale, proportion, and quantity*** to predict temperature ***changes***, equilibrium conditions, and magnitudes of energy transferred (*HS-PS3-1*).

At the macroscopic ***scale***, there are several different heat flow mechanisms by which the Second Law operates: conduction, convection, and radiation. As students 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. In general, solids are much better at transferring heat by conduction than liquids or gases because of their greater density. During their **investigations** 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 physics course. Online simulations allow students to visualize each of these processes at the microscopic ***scale***[1].

Computational **models** are also an excellent way to explore heat transfer at the macroscopic ***scale***. The **investigations** 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[2]. 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 in the computer. An excellent challenge is to have students revisit the food calorimetry experiment from instructional

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[1] https://phet.colorado.edu/en/simulations/category/physics/heat-and-thermodynamics

[2] http://energy.concord.org/energy2d/

segment 1 and retrace the flow of heat in a computer simulation. Students can observe convection, conduction, and even simulate the ***effects*** of wind blowing through the room. To extend their **modeling** of heat flow to different contexts, students can use online computational **models** for simulating the ***flow of*** thermal ***energy*** 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*).

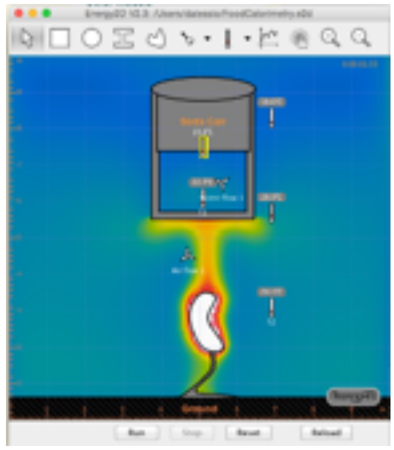

Figure 1. Visualizing heat flow using a computer simulation. Colors represent temperature at every point in the model.

Heat Transport on Planet Earth

The drive towards thermal equilibrium operates on a massive ***scale*** 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. Heat will be transferred 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 more dense. Students **developed a model** of convection at Earth's surface at the middle grade level (*MS-ESS2-6*), and now they extend it to processes inside the Earth. 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** of convection (*HS-ESS2-3*). Within Earth, plate motions are the surface expression of convection happening deep within the Earth. The oceanic crust is cold and dense and sinks downwards where plates crash together while hot, relatively low density magma rises up where plates move apart.

Lava lamps are not perfect **models** 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 waves 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 must be 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.

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** 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 they may have discussed at the middle grade level (*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. Silly 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 silly putty. The fact that categories students have used to describe the phases of matter fails is an excellent example of *CA NGSS's* learning progression regarding patterns. While identifying ***patterns*** and using them to classify and categorize are cornerstones of the SEPs beginning in kindergarten, by 12th grade students are expected to "recognize classifications or explanations used at one ***scale*** 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** 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 more dense. 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. These huge sections of lithosphere that are dragged along as a single chunk are what we call plates, and their movement 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 2). One **pattern** 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 1980's, but scientists were able to observe other evidence that this motion is occurring by looking at the age of the seafloor (Figure 3). There are long stripes down the middle of many oceans with very young seafloor and then a clear ***pattern*** where the ages are symmetrically older in both directions away from the stripe of youngest rocks.

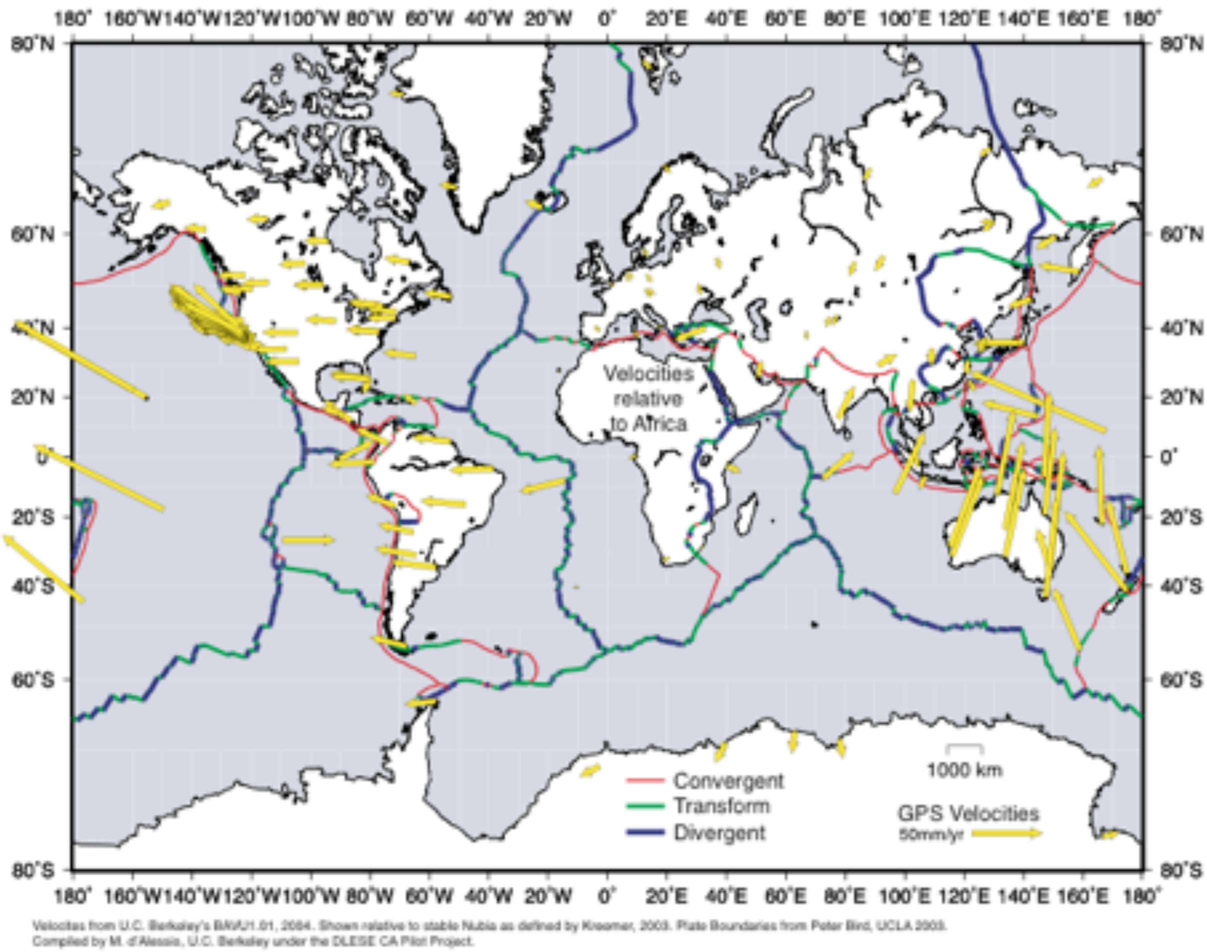

Figure 2. GPS velocities recorded at stations around the world reveal present-day plate motions. Arrow size relates to the speed of each point. Image credit: (CC-BY-NC-SA) by M. d’Alessio

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

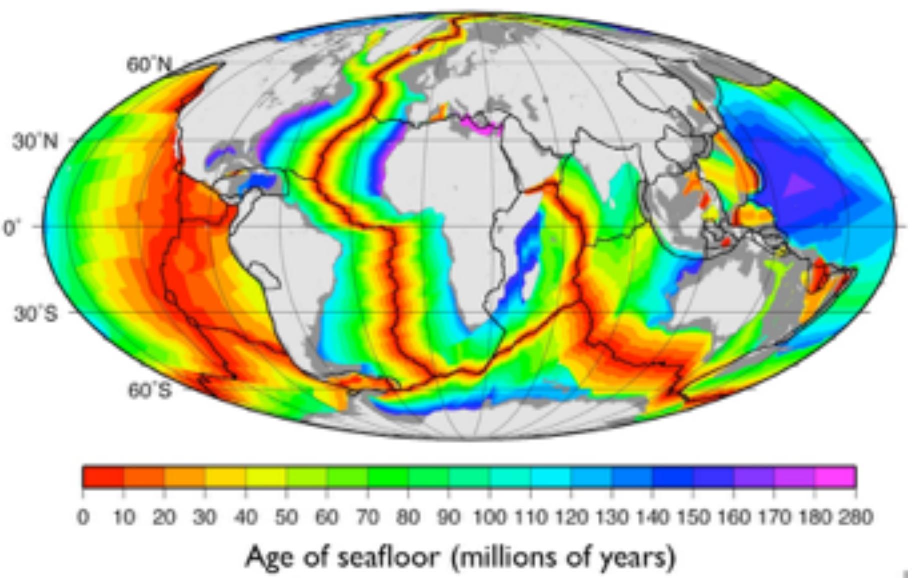

Figure 3. Seafloor age. Hot material from the mantle rises up and cools to form new rock material (with age of zero) at the areas shown in red. (National Oceanic and Atmospheric Administration, National Centers for Environmental Information 2015)