

Ring Polymers



Center for Nanotechnology Education



This material is based on work supported by the National Science Foundation under Grant Nos. 0802323, 1204918, and 1501878. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.



This work is licensed under a [Creative Commons Attribution-NonCommercial-Share Alike 3.0 Unported License](https://creativecommons.org/licenses/by-nc-sa/3.0/).
Based on a work at www.nano-link.org

Ring Polymers

Abstract

This module is a variation on the “Cross-Linked Polymers” activity, and presents much of the same background on polymer structure and properties. This version uses a form of sodium polyacrylate, the water-absorbing polymer often used in diapers, that has a different atomic structure than that of the cross-linked polymer. This polymer captures liquid in a ring structure and is dependent upon the relationship between the forces of cohesion (the attraction between like molecules) and adhesion (the attraction between unlike molecules). This module can also be used for students to practice math skills by calculating the number of water molecules absorbed.

Outcomes

Students will gain a basic understanding of atomic structure and intermolecular bonds in polymeric materials.

Prerequisites

- 8th grade science

Correlation

Science Concepts

- Electrostatic interactions between atoms in a molecule
- The nature of polymers
- Cohesive and adhesive forces
- Capillary action

Nanoscience Concepts

- Forces that act at the nanometer scale, which lead to macroscopic observable phenomena

Background Information

Polymers

A polymer is a material that contains many chemically bonded parts or units which themselves are bonded together to form a solid. The word polymer literally means "many parts." Two industrially important polymeric materials are plastics and elastomers. Plastics are a large and varied group of synthetic materials which are processed by forming or molding into shape. Just as there are many types of metals such as aluminum and copper, there are many types of plastics, such as polyethylene and nylon. Elastomers or rubbers can be elastically deformed a large amount when a force is applied to them and can return to their original shape (or almost) when the force is released.

Polymers have many properties that make them attractive to use in certain applications. Many polymers:

- are less dense than metals or ceramics,
- resist atmospheric and other forms of corrosion,
- offer good compatibility with human tissue
- exhibit excellent resistance to the conduction of electrical current.

The polymer plastics can be divided into two classes, thermoplastics and thermosetting plastics, depending on how they are structurally and chemically bonded. Thermoplastic polymers comprise the four most important commodity materials – polyethylene, polypropylene, polystyrene and polyvinyl chloride. There are also a number of specialized engineering polymers. The term 'thermoplastic' indicates that these materials melt on heating and may be processed by a variety of molding and extrusion techniques. On the other hand, 'thermosetting' polymers cannot be melted after they are formed. They consist of molecular chains that have chemically reacted with each other to form a strong network, through a process known as crosslinking. Thermosetting polymers include alkyds, amino and phenolic resins, epoxies, polyurethanes, and unsaturated polyesters.

Some polymers, such as rubber and cellulose, occur naturally and may be formed by plants or fungi. Synthetic polymers are created by engineering the combination of hydrogen and carbon atoms and the arrangement of the chains they form. A polymer molecule is a long chain of covalent-bonded atoms and secondary bonds that hold groups of polymer chains together to form the polymeric material. Polymers are primarily produced from petroleum or natural gas raw products, but the use of organic substances as polymer feed stocks is growing. Polymers are very useful materials because their structures can be altered and tailored to produce materials 1) with a range of mechanical properties 2) in a wide spectrum of colors and 3) with different transparent properties. For example, the advanced material known as Kevlar is a synthetic polymer that can be used in bullet-proof

vests, strong/lightweight frames, and underwater cables that are 20 times stronger than steel. **Polymer Structure**

Terms

- Mer- The repeating chemical unit in a polymer chain
- Monomer – A single mer unit ($n=1$)
- Polymer – Many mer-units along a chain ($n=10^3$ or more)
- Degree of Polymerization – The average number of mer-units in a chain.

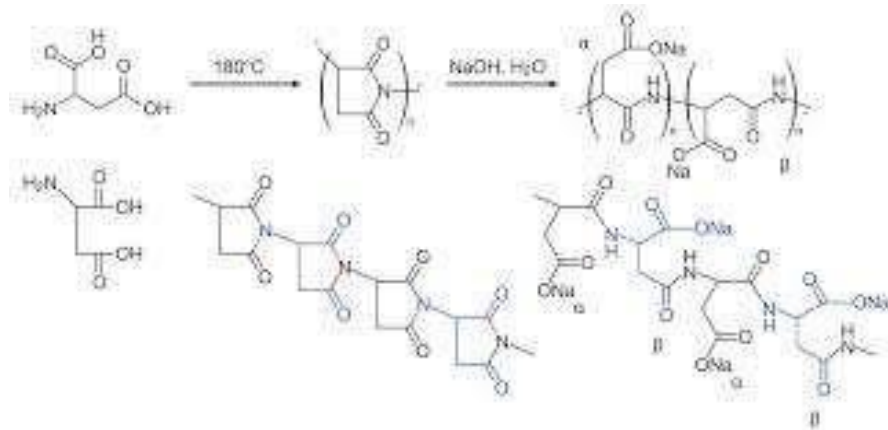
Monomers

A polymer is composed of many simple molecules that are repeating structural units called monomers. A single polymer molecule may consist of hundreds to a million monomers and may have a linear, branched, or network structure. Covalent bonds hold the atoms in the polymer molecules together and secondary bonds then hold groups of polymer chains together to form the polymeric material. Copolymers are polymers composed of two or more different types of monomers.

Ring Polymer

Just as a bubble blower tool can capture and hold a thin film of soap, nanoscale polymer chains (chains of atoms connected together in a repeating pattern) can be created to form very small rings. Because of the attractive forces between atoms and the interactions of the water molecules, these polymer chains can capture and hold a great deal of water. This is the principle of operation behind the moisture-absorbing material used in disposable diapers. Between the outer material and padding of the diaper, materials composed of millions of these polymer chains are placed. These polymer chains with their millions of rings are able to capture and hold a thin film of water—and absorb an amazing amount of fluid. The polymer found in diapers goes by many names and fall under the general category of super absorbing polymers (SAPS).

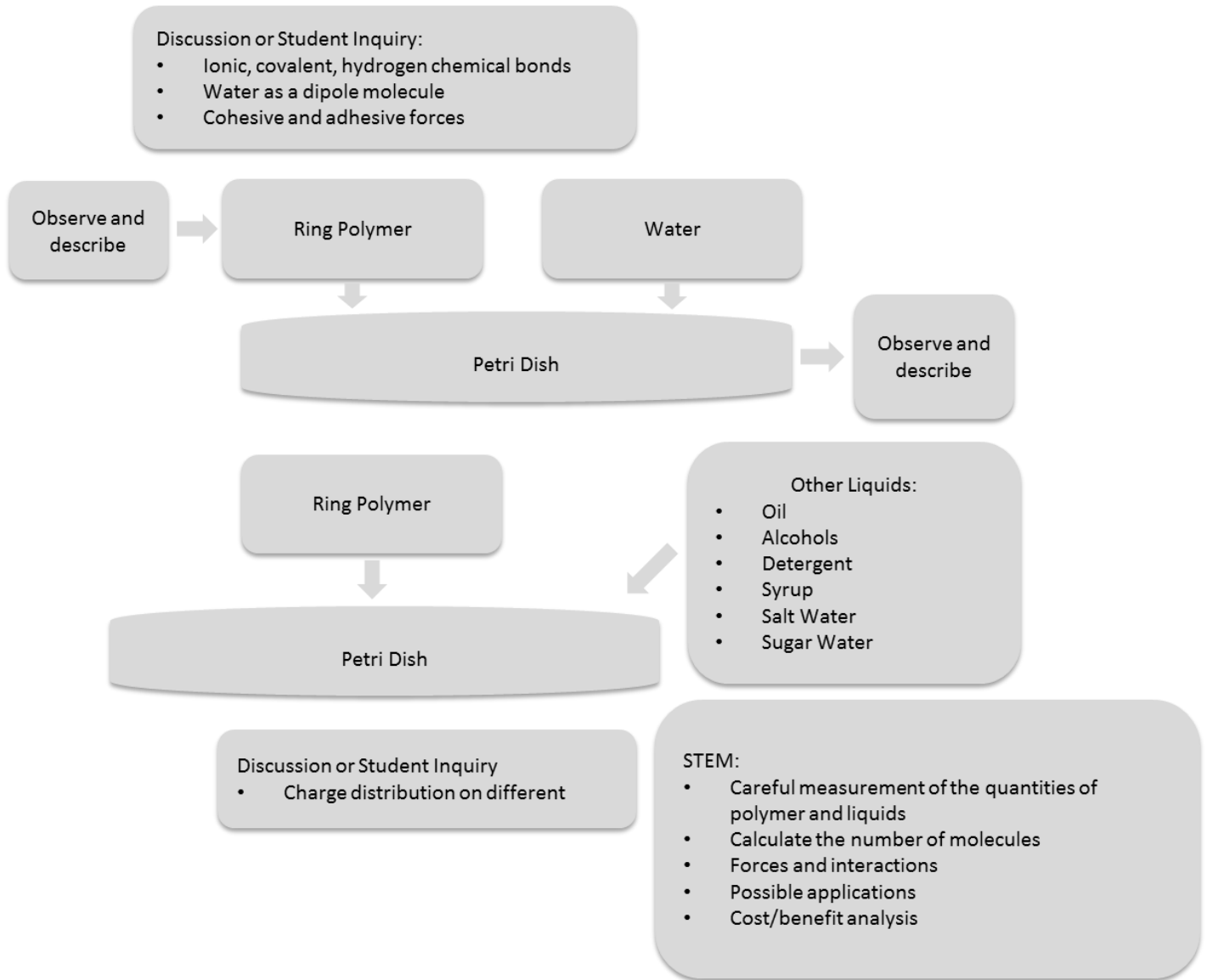
This activity uses a polymer which has a ring type of structure and when water is added to the polymer thin films of water are collected in the ring structure. The thin film of water remains “trapped” in the ring because of the balance between cohesive and adhesive forces. Cohesive forces are the forces between like molecules and adhesive forces are the forces between unlike molecules. The hydrogen bonds between water molecules fall within the umbrella of cohesive forces. The forces between the water molecules and the mers within the polymer rings are adhesive forces. An example of a ring type polymer is shown below.



When different liquids are added to the polymer the physical changes will be different. This is due to the relative strengths of the cohesive and adhesive forces. Molecules of the different liquids will have different strengths for the cohesive bonds between the molecules. The strength of these cohesive bonds is dependent upon the electrical charge distribution with the fluid molecules.

Learning Activity: Ring Polymer

Activity Flow Chart



Ring Polymers Learning Activity

Background

A polymer is a material that contains many chemically bonded parts or units which themselves are bonded together to form a solid. The word polymer literally means "many parts." Polymers occur naturally in the form of starch, cellulose, and chitin (the hard part of shell fish). Synthetic polymers include all types of plastics.

Just as a bubble blower tool can capture and hold a thin film of soap, nanoscale polymer chains (chains of atoms connected together in a repeating pattern) can be created to form very small rings. Because of the attractive forces between atoms and the interactions of the water molecules, these polymer chains can capture and hold a great deal of water. This is the principle of operation behind the moisture-absorbing material used in disposable diapers. Between the outer material and padding of the diaper, materials composed of millions of these polymer chains are placed. These polymer chains with their millions of rings are able to capture and hold a thin film of water—and absorb an amazing amount of fluid. The polymer found in diapers goes by many names and fall under the general category of super absorbing polymers (SAPS).

This simple activity allows you to observe and measure just how much water can be absorbed by this ring-type polymer.

Materials

- Ring polymer
- Petri dish
- Water
- Other liquids such as alcohols, detergent, oil, salt water, sugar water, hydrogen peroxide etc.
- Scale
- Small beakers
- Transfer pipettes

Process:

1. Measure out about 1 cubic centimeter ($\frac{1}{4}$ teaspoon) of the ring polymer
2. Place the ring polymer in a Petri dish and measure its mass.
3. Using the transfer pipette, begin adding drops of water to the polymer

4. Keep adding water until it can no longer be absorbed by the polymer, i.e., when you just begin to see drops or puddles of water leaking out of the dish.
5. Weigh the polymer, Petri dish, and water to determine how much water has been absorbed.

Note: You may also determine the amount of water absorbed by using the graduated cylinder to measure water added—but this may be a bit more inaccurate than weighing.

Observe the physical changes to the polymer. Add different liquids to the dry polymer, observe the differences. These differences are a result of the strength or weakness of the two competing forces; cohesive and adhesive.

Calculations: (optional)

Knowing that the density of water is 1 gm/cm^3 , what is the volume of the water absorbed? If we assume that the thin films of water collected in the polymer rings are each about 2 nm thick, what is the surface area that could be covered by the water collected in the rings?

Questions

1. What are some of the forces that act on all matter?
2. Which of these are most important at the nanoscale?
3. What are polymers? Describe their molecular structure.
4. What is the difference between thermoplastic and thermosetting polymers? Specifically, describe their differences in
 - a. behavior under heat, and
 - b. their molecular structures
5. What is the molecular structure of the super absorbent polymer (SAP) typically used in disposable diapers?

Current and Future Applications

In general, the applications of polymers are widespread and diverse. This is especially true for linear and cross-linked polymers. Any room you are sitting in is likely to have many types of polymers present, from the paints and varnishes on the walls to the polyester threads in your clothes to the synthetic rubber on the soles of your shoes. Although ring polymers are less widely used as an engineering material, they are often found in the cells of many living organisms, and form an active area of research.

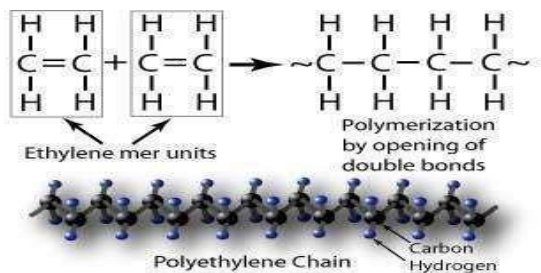
The most common application for the water-trapping polymer sodium polyacrylate is in disposable diapers and other consumer products that are designed to absorb liquids. Sodium polyacrylate is also used in detergents to sequester (bind with) hard water elements such as calcium and magnesium, as thickening agents in processed foods, and for coatings on consumer and industrial products.

Future applications of sodium polyacrylate will no doubt build on its ability to absorb large amounts of water. For example, NASA has incorporated it into the Maximum Absorbency Garment (MAG), a high performance adult diaper worn by astronauts during extravehicular activities or lift-offs and landings, when use of the available facilities is not possible.

OPTIONAL BACKGROUND INFORMATION

Polymer Chains (Thermoplastics and Thermosets)

A polymer is an organic material and the backbone of every organic material is a chain of carbon atoms. The carbon atom has four electrons in the outer shell. Each of these valence electrons can form a covalent bond to another carbon atom or to a foreign atom. The key to the polymer structure is that two carbon atoms can have up to three common bonds and still bond with other atoms. The elements found most frequently in polymers and their valence numbers are: hydrogen, fluorine, chlorine, boron, and iodine with one valence (bonding) electron; oxygen and sulfur with two valence electrons; nitrogen with three valence electrons; and carbon and silicon with four valence electrons.



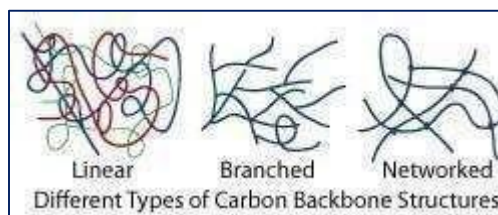
The ability of molecules to form long chains is vital to producing polymers. Consider the material polyethylene, which is made from the monomer ethylene, C_2H_4 . Ethylene is a gas that has a two carbon atoms in the chain and each of the two carbon atoms share two valence electrons with the other. If two molecules of ethylene are brought together, one of the carbon bonds in each molecule can be broken and the two molecules can be joined with a carbon-carbon bond. After the two monomers are joined, there are still two free valence electrons at each end of the chain for joining other monomers or polymer chains. The process can continue linking more monomers and polymers together, until it is stopped by the addition of another chemical called a terminator, which fills the available bond at each end of the molecule. This is called a linear polymer and is the building block for thermoplastic polymers.

The polymer chain is often shown in two dimensions, but it should be noted that they have a three dimensional structure. Each carbon-carbon bond is at 109° to the next and, therefore, the carbon backbone extends through space like a twisted chain of Tinker Toys. When stress is applied, these chains stretch and the elongation of polymers can be thousands of times greater than it is in crystalline structures like silica or iron.

The length of the polymer chain is very important. As the number of carbon atoms in the chain is increased beyond several hundred, the material will pass through the liquid state and become a waxy solid. When the number of carbon atoms in the chain is over 1,000, the solid material polyethylene, with its characteristics of strength, flexibility and toughness, is obtained. The change in state occurs because as the length of the molecules increases, the total binding forces between molecules also increases.

Polymer molecules are not generally found as a straight-line structure; instead, their natural state is more like a tangled mass. Thermoplastic materials, such as polyethylene, can be pictured as a mass of intertwined worms randomly thrown into a pail. The binding forces are the result of van der Waals forces between molecules and mechanical entanglement between the chains. When thermoplastics are heated, there is more molecular movement and the bonds between molecules can be easily broken. This is why thermoplastic materials can be melted, cast into shapes, re-melted, and reused many times.

There is another group of polymers in which a single large network is formed during polymerization, rather than a number of individual polymer molecules. Since polymerization is often initially accomplished by heating the raw materials and bringing them together, this group is called thermosetting polymers or plastics.



For this type of network structure to form, the monomers must have more than two places for bonding to occur; otherwise, only a linear structure is possible. These chains form jointed structures and rings, and may fold back and forth to take on a partially crystalline structure. Since thermosetting polymers are essentially comprised of one giant molecule, there is no movement between molecules once the mass has set. Thermosetting polymers are more rigid and generally have higher strength than thermoplastic polymers. Also, since there is no opportunity for motion between molecules in a thermosetting polymer, they will not become soft or flowable when heated.

Another class of polymers is the ring polymers. These molecules are essentially linear polymers that have formed long, flexible loop structures. This activity is based on a ring form of the linear polymer polyacrylate.

Forces at Different Scales

Over many centuries we have discovered, studied and quantified a multitude of forces or energies – this broad area of phenomena impacts the interaction of all matter. For a long time we were only able to observe the manifestation of these forces at the macro scale. Compass needles moving under the influence of magnetic force, apples falling from trees due to gravity, and dust particles sticking to surfaces due to electrostatic force, are all examples of forces at work. As our tools (both experimental hardware and mathematical) improved, we have been able to observe more and more interactions at smaller scales.

From a physics standpoint there are four fundamental forces: electromagnetism, gravitation, the weak force (which governs certain types of radioactive decay), and the strong force (which holds together the atomic nucleus). All of these forces are field forces as opposed to contact forces. With field forces objects do not have to be in direct contact to experience the force. From introductory physics we are also aware of forces such as friction (static and kinetic) as well as the forces that can be exerted by springs. These types of forces are contact forces.

Our discussion can also be expanded to include interactions, forces and energy that are associated with vibration, rotation, Brownian motion, and chemical bonding at both the atomic and molecular scale. A more comprehensive list of forces might include

- Gravity
- Electromagnetic force
- The strong and weak nuclear forces
- Chemical bonding forces: ionic, covalent, metallic
- The force which causes Brownian motion
- Van der Waals and London (close range) forces
- Friction

- Elastic (“spring-type”) forces
- Casimer force

These different forces and interactions will have a different priority ranking at different size scales. At the level of atoms and molecules, the most important force is electromagnetism. This force dominates the interaction between atoms as they bond with other atoms to form molecules, and is thus responsible for nearly everything we call “chemistry”. Chemical bonding will have an impact at the nanoscale. Whether two atoms may be brought and held together by covalent or ionic bonds will impact the stability, organization, and the crystal structure of a material. The same is true for molecular bonding, where the electromagnetic force gives rise to interactions that go by the names of dipole/dipole, induced dipole/induced dipole, van der Waals force, London force, and so on.

One thing that is absolutely critical in the discussion of forces and interactions at all size scales is that ALL of these forces or interactions are present ALL of the time independent of the size scale we are observing. Gravity does not “go away” at the nanoscale nor do polymer vibrations cease to occur at the macro scale. All of these interactions are occurring all of the time – the difference is in the PRIORITY which impacts our awareness of and ability to measure the force. We will find that at different size scales the ranking or priority in terms of interaction importance will change.

When we are looking at objects in the nanoscale range, we are looking at a different priority of the list of forces; for example, gravity is not a big deal at the nanoscale. But we are also asking students to look at forces that are much less familiar than the classical forces that they may have learned about in introductory science classes.

Multimedia Resources

Videos

- http://www.youtube.com/watch?v=Vais8pL0w8U&feature=player_embedded

Simulations

- www.nanohub.org
- mw.concord.org

Articles

1. “History of Polymers and Plastics for Students”, on the American Chemistry Council Web site: <http://plastics.americanchemistry.com/Education-Resources/Hands-onPlastics/Introduction-to-Plastics-Science-Teaching-Resources/History-of-Polymer-andPlastics-for-Students.html> (accessed 09/03/2014).
2. “Plastics”, on the ExplainThatStuff! Web site: www.explainthatstuff.com/plastics.html (accessed 09/03/2014).
3. “What is a Polymer”, a classroom activity available from the Polymer Ambassadors. Web site: www.polymerambassadors.org (accessed 09/03/2014).
4. “What Is A Polymer: Discovering The Basics of Polymers” on the About.com Web site: composite.about.com/od/whatsacomposite/a/What-Is-A-Polymer.htm (accessed 09/03/2014).
5. “Plastics Recycling”, a primer on types of synthetic plastics and how they are recycled, developed by kid-tech.org. Available as a PDF file at www.kid-tech.org/projects/plastics_students.pdf.

Acknowledgements

This activity was developed by Deb Newberry of Dakota County Technical College based off an activity from NISEnet

Alignment to the Next Generation Science Standards

Tables 1 and 2 clarify the nature of the alignments by Scientific and Engineering Practice (Practice), Disciplinary Core Idea (DCI), and Crosscutting Concept as related to a Performance Expectation.

TABLE 1: ALIGNMENT TO SPECIFIC PERFORMANCE EXPECTATIONS	ALIGNMENT RATING
<i>HS-PS2-6</i> Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.	<i>Partial</i>

TABLE 2. ALIGNED PRACTICES, DISCIPLINARY CORE IDEAS, AND CROSSCUTTING CONCEPTS		
PRACTICE	DCI	CROSSCUTTING CONCEPT
<p><i>HS: Obtaining, Evaluating, and Communicating Information:</i> Communicate scientific and technical information (e.g. about the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically).</p> <p><i>Partial in teacher and student materials</i></p>	<p><i>HS-PS2.B: Types of interactions:</i> Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.</p> <p><i>Strong in teacher and student materials</i></p>	<p><i>HS. Structure and function:</i> Investigating or designing new systems or structures requires a detailed examination of the properties of different materials, the structures of different components, and connections of components to reveal its function and/or solve a problem.</p> <p><i>Partial in teacher and student materials</i></p>

Alignment to the Common Core State Standards for English Language Arts/Literacy and Mathematics

Alignments in Table 2 were made to the Anchor Standards, unless a more specific version of the standard was a closer fit to the skills in the module.

TABLE 3. ALIGNED COMMON CORE STANDARDS FOR ENGLISH LANGUAGE ARTS & LITERACY
<p>CCR.L.6: Acquire and use accurately a range of general academic and domain-specific words and phrases sufficient for reading, writing, speaking, and listening at the college and career readiness level; demonstrate independence in gathering vocabulary knowledge when encountering an unknown term important to comprehension or expression.</p> <p><i>Partial in teacher and student materials</i></p>
<p>RST.11–12.3: Follow precisely a complex multistep procedure when carrying out experiments, taking measurements, or performing technical tasks; analyze the specific results based on explanations in the text.</p> <p><i>Partial in student materials</i></p>
<p>RST.6–8.7: Integrate quantitative or technical information expressed in words in a text with a version of that information expressed visually (e.g., in a flowchart, diagram, model, graph, or table).</p> <p><i>Partial in student materials</i></p>

For mathematics, Table 4 shows alignments found in the 8th through 12th grade levels.

TABLE 4. ALIGNED COMMON CORE STANDARDS FOR MATHEMATICS	ALIGNMENT RATING
<p><i>Note – these standards are aligned to content found in the “Optional” section of the lesson:</i></p>	
<p>MTH.HS.G.MG.1 Use geometric shapes, their measures, and their properties to describe objects (e.g., modeling a tree trunk or a human torso as a cylinder).</p>	<p><i>Partial alignment</i></p>
<p>MTH.HS.G.MG.2 Apply concepts of density based on area and volume in modeling situations (e.g., persons per square mile, BTUs per cubic foot).</p>	<p><i>Partial alignment</i></p>