“The core idea is that nature, imaginative by necessity, has already solved many of the problems we are grappling with. Animals, plants, and microbes are the consummate engineers. They have found what works, what is appropriate, and most important, what lasts here on Earth... The conscious emulation of life’s genius is a survival strategy for the human race, a path to a sustainable future. The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone.”

- Janine Benyus,

_Biomimicry: Innovation Inspired by Nature_
CONCRETE WITHOUT QUARRIES

Sam Stier, Dona Boggs, and Dave Jones

Introduction

Biomimicry is an innovation method that seeks solutions to humankind’s sustainability challenges by applying principles underlying nature’s time-tested strategies (Benyus 1997). Modern day manufacturing, for example, presents myriad challenges to environmental sustainability. Materials mined from the earth, processed using fossil fuels and hazardous chemicals, and resulting in pollutants discharged into the environment characterize our species’ dominant manufacturing paradigm. Concrete provides an illustrative case: cement used in concrete is manufactured by extracting calcium carbonate from open-pit mines, cooking the material at 2642 degrees Fahrenheit (1400 degrees Celsius), and discharging approximately 6% of humanity’s annual greenhouse gas emissions into the atmosphere.

In this science lesson plan for middle school children, students learn that the prevailing manufacturing model on planet Earth—practiced by millions of other species—is one in which raw materials for manufacturing are actually acquired benignly from the environment. By emulating a physiological process used by corals to create calcium carbonate out of seawater and carbon dioxide, children experience first-hand a cutting-edge biomimetic technology with the promise of transforming conventional concrete manufacturing into a more sustainable industry. Moreover, students learn that there is a universe of biological models around us to serve as inspiration for sustainable chemistry methods and other kinds of innovation. The lab is safe, meets national and state educational standards, can be conducted within one to two 50 minute periods without specialized scientific knowledge or equipment, and uses materials that cost less than $50 to obtain.
GRADE LEVEL | 6th – 9th  
AREA | General Science  
DURATION | Approximately one to two 50-minute sessions, longer if desired  
MATERIALS |  
• A source of carbon dioxide, such as dry ice (100% CO₂). Many grocery stores carry dry ice. Cost: ~$3.00 (enough for 5 groups of 4 students each).  
• A source of seawater or a seawater analog. Actual seawater can be used, if available. Alternatively, a seawater mix found at any pet store for aquariums can be used. Cost: ~$4.00 (enough for 5 groups of 4 students each). A solution of calcium chloride will also work well.  
• Aquarium bubbler (optional but recommended), which can be found at any pet store for aquariums. Cost: ~$0.57 each (http://bit.ly/RAYX7y); total $3.00 (to supply 5 groups of 4 students each).  
• A source of sodium hydroxide (NaOH), such as household 100% lye drain opener, which can be found in grocery or hardware stores. Cost: ~ 4.00 (enough for 5 groups of 4 students each).  
• Glass containers, rubber tubing, and connectors. These can be chemistry lab grade or recycled glass food jars. Rubber tubing can be found at any chemistry supply outlet (e.g., http://bit.ly/13ajSlq). Tubing cost: ~$1.30 for 2 feet; total $7.00 (to supply 5 groups of 4 students each).  
• Filter paper, which can be ordered online (e.g., at Amazon.com). Cost: ~$2.00 (enough for 5 groups of 4 students each).  
• Small bag of cement (e.g., Quikrete). Cost ~$8.00 (enough for 5 groups of 4 students each).  
• Vinegar (optional). Cost: ~$3.00 (enough for 5 groups of 4 students each).  

SAFETY |  
Dry ice, cement, and sodium hydroxide should be handled with a skin barrier (e.g., gloves). Sodium hydroxide is caustic; avoid skin or eye contact or inhalation of vapors.
Main Lesson Plan Goals and Objectives

This activity addresses the following key educational themes:

1. Conventional manufacturing methods used by humans generally start with the extraction of raw materials from the environment, using processes that result in some degree of environmental damage. These processes over time have resulted in large-scale damage to the earth’s living systems and, given the earth’s inherent limits, cannot continue indefinitely.

2. Well-adapted organisms use sustainable technologies in the process of survival and reproduction; mal-adapted organisms do not, and as a result, they eventually go extinct.

3. Harm to the environment is not a necessary consequence of raw material extraction; the prevailing manufacturing model on Earth, practiced by billions of species, is actually one in which raw materials are acquired benignly.

4. By emulating manufacturing processes widespread in the rest of the natural world, humans can transform their production methods to be more benign, and even beneficial to the environment of which humans are a part.

Other themes covered include:

5. Calcium carbonate is a compound central to corals and many other kinds of organisms, as well as to the production of concrete by humans. Calcium carbonate is composed of atoms of calcium, carbon, and oxygen, and forms a compound with varying crystalline formations (i.e., polymorphs) and properties.

6. Corals offer an example of how organisms interact and have different functions that enable the ecosystem to survive. Human technologies and processes could similarly strive to become a positive influence on the ecosystems of which we are a part.

7. This lesson plan fits well with many aspects of the technology and engineering standards. The lesson plan is fundamentally about systems (in this case, manufacturing systems) and compares systems currently predominant in human manufacturing with those found in the rest of the natural world. The specific case focused on is the manufacturing of concrete (the goal), with the emphasis of the lesson plan being on how inputs (in this case, raw materials for making cement) differ between human and coral concrete manufacturing systems. The processes used by both humans and corals are also described in age-appropriate detail. The outputs in both systems are reactive cement, but a contrast is also drawn between non-target manufacturing outputs (net increase release of CO₂ in the case of humans, net decrease in the case of corals). The lesson plan also provides an exploration of manufacturing, construction, and energy.
Standards

This activity can be used to address chemistry education standards. The list below, which is not exhaustive, is drawn from the current version of Benchmarks for Science Literacy (Standard D: The Structure of Matter), which also incorporates standards from Science for all Americans (1991), and the National Science Education Standards (1996).

- All matter is made up of atoms, which are far too small to see directly through a microscope.
- The atoms of any element are like other atoms of the same element, but are different from the atoms of other elements.
- Atoms may link together in well-defined molecules, or may be packed together in crystal patterns. Different arrangements of atoms in groups compose all substances and determine the characteristic properties of substances.
- In solids, the atoms or molecules are closely locked in position and can only vibrate. In liquids, they have higher energy, are more loosely connected, and can slide past one another; some molecules may get enough energy to escape into a gas. In gases, the atoms or molecules have still more energy and are free of one another except during occasional collisions.
- The temperature and acidity of a solution influence reaction rates. Many substances dissolve in water, which may greatly facilitate reactions between them.
- Chemical elements are those substances that do not break down during normal laboratory reactions involving such treatments as heating, exposure to electric current, or reaction with acids. All substances from living and nonliving things can be broken down to a set of about 100 elements, but since most elements tend to combine with others, few elements are found in their pure form.
- Most substances can exist as a solid, liquid, or gas depending on temperature.
- Substances react chemically in characteristic ways with other substances to form new substances with different characteristic properties.
- If broken down, samples of both the original substances and the final substances involved in a chemical reaction are found to be made up of the same set of elements.
- The idea of atoms explains chemical reactions: when substances interact to form new substances, the atoms that make up the molecules of the original substances combine in new ways.
Teaching Strategy

There are many ways to engage students and contextualize this lesson. The essential element is to get students to think about how humans acquire most of their raw materials (through environmentally destructive means) in contrast to how many other species acquire theirs. An effective approach is to get students to consider where the materials around them come from (e.g., in the classroom), and to draw a contrast with how corals are able to create cement.

Middle-school children are within an ideal age range to direct learning about biomimetic design. In terms of cognitive development, middle-school-age children are capable of analogical reasoning. In addition, students of middle-school age have also begun the formal operational cognitive stage, which includes greater capacity and interest in thinking about the future and concern about the world around them.

Humans make glass by mining silicon dioxide and heating it to 1,575°C. This venus flower basket, a deep-sea marine sponge, makes its glass skeleton at ambient ocean temperatures from silicon dioxide filtered out of seawater.

Neissera meningitidis, a bacteria that can cause meningitis, is not an organism people generally appreciate. But this bacteria inspired Dr. Irving DeVoe at McGill University to develop a method of extracting precious metals out of spent mining tailings rather than have to mine virgin material.

While similar in structure and composition, plastics source their carbon predominantly from petroleum, while plants obtain it from air (CO₂). The plant kingdom served as inspiration for Dr. Geoffrey Coates of Cornell University, who recently developed a way to manufacture plastics using carbon atoms acquired from the air.
Procedure

1 | Form the students into small groups (2-4 people) and explain the procedure to them, the materials involved, and safety considerations. Assign tasks to different students within each group, so each child has a tangible role to play in the process.

2 | Use seawater or create a seawater analog mix, either from a seawater mix from a pet store, or by providing students with a pre-mixed solution, or by having them create a solution of 0.1 M CaCl₂ (i.e. 1.47 g in 100 ml). Explain to students that this solution is like the seawater that corals use and contains calcium atoms that will become part of the calcium carbonate (CaCO₃) compound they are creating.

3 | Prepare a 1 M solution of NaOH (i.e. 3.99 g in 100 ml). Household lye can serve as a source of NaOH. Students should wear goggles and gloves when handling this material. Explain to students that corals get calcium to bind with carbon and oxygen by controlling the solution in which the atoms are placed, increasing the concentration of some atoms and reducing the concentration of others using special biological pumps. The sodium hydroxide acts to help do this without the special pumps used by corals.

4 | Using gloves, place a piece of dry ice in a glass jar or side arm flask and enclose with a screw-top lid or stopper through which the tubing passes.

5 | Add several drops of the NaOH solution to the seawater solution. While precipitate forms, continue adding NaOH as desired or needed.

6 | Insert tube into the container of seawater solution. White, cloudy precipitate should form immediately, falling slowly to the bottom of the container. To produce enough precipitate, run the reaction for at least 3-5 minutes. During this time, you can review with students the chemical reaction happening, emphasizing that, like corals, they are making something solid and valuable come out of simply a waste gas (CO₂) and an abundant liquid (seawater).

7 | Remove the tubing from the seawater solution and let the solution sit for a few minutes. You will see the solution clearing up at the top as the precipitate falls to the bottom. Have students write their initials on the filter paper, and then slowly pour the solution through the filter paper to collect the precipitate.¹

8 | Place the filter paper on a window ledge to dry overnight, or place in a drying oven (if available) for approximately 20 minutes. Once dry, allow students to rub the powdered calcium carbonate between their fingers.²

¹ Filtration by gravity works fine. Placing the filter paper in a büchner funnel using a vacuum filtration system will also work.

² The product may contain other compounds in addition to CaCO₃, especially depending on the seawater mixture. X-ray crystallography analysis of the product created with this lab procedure using dry ice and a calcium chloride solution yielded 100% CaCO₃.
9 | (Optional) Place a few drops of vinegar on the precipitate to help illustrate to students the presence of carbon dioxide, once sequestered in the calcium carbonate and now returning to the atmosphere.

![Side view of the Venus flower basket.](image)

**Evaluation**

In order to evaluate the effectiveness of the lesson, consider using the following questions:

1. How would you describe what you learned from this activity?

2. Because the Earth’s natural resources are limited, how would you describe what will happen as humans continue to consume them?

3. What is an important difference between how humans typically acquire raw materials for cement manufacturing, and how corals do it, explored in this activity?

4. What other materials do humans make and how do we make them? Give at least one example. What impact on the environment does each process have?

5. For each material you mentioned in #4, try to identify an organism that makes a similar material. What impact on the environment does each organism’s process have?

6. What is biomimicry?
References


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BIOMIMICRY 3.8

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