

Intermolecular Bonding in Polymers

Purpose

This lesson covers the topics of intermolecular forces and covalent bonding through the crosslinking of polymers. Students explore a real-world material science application for their knowledge of chemical bonds, elements, and polymer structures—a new type of bioink that is used to 3D print biological implants and scaffolds for growing organs.

Audience

This lesson was designed to be used in an introductory high school chemistry class.

Lesson Objectives

Upon completion of this lesson, students will be able to:

- identify covalent bonds and intermolecular forces in molecular structures and discuss differences in bond properties (i.e., strength, flexibility, etc.).
- relate molecular structure to material properties and polymer applications.

Key Words

bioink, bioprinting, covalent bonding, crosslink, intermolecular forces, polymer, scaffold

Big Question

This lesson addresses the Big Question “*What is life?*”

Standard Alignments

- **Science and Engineering Practices**
 - **SP4.** Analyzing and interpreting data
 - **SP6.** Constructing explanations and designing solutions
- **MA Science and Technology/Engineering Standards (2016)**
 - **HS-PS2-6.** Communicate scientific and technical information about the molecular-level structures of polymers, ionic compounds, acids and bases, and metals to justify why these are useful in the functioning of designed materials.
 - **HS-PS1-3.** Cite evidence to relate physical properties of substances at the bulk scale to spatial arrangements, movement, and strength of electrostatic forces among ions, small molecules, or regions of large molecules in the substances. Make arguments to account for how compositional and structural differences in molecules result in different types of intermolecular or intramolecular interactions.

◦◦ NGSS Standards (2013)

- **HS-PS2-6.** Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.
- **HS-PS1-3.** Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.

◦◦ Common Core Math/Language Arts Standards

- **CCSS.ELA-LITERACY.RST.11–12.1.** Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.
- **CCSS.ELA-LITERACY.RST.9–10.7.** Translate quantitative or technical information expressed in words in a text into visual form (e.g., a table or chart) and translate information expressed visually or mathematically (e.g., in an equation) into words.

Misconceptions Addressed

- This lesson addresses a common misconception about chemical bonding, that a hydrogen bond is simply any bond involving a hydrogen atom. (Question 3)
- Further information about student misconceptions related to this topic can be found [here](#).

Primary Sources

- **Bite** "[A NICE Way to Save Lives](#)" based on:

Chimene, David, Charles W. Peak, James Gentry, James K. Carrow, Lauren M. Cross, Eli Mondragon, Guinea B. C Cardoso, Roland Kaunas, and Akhilesh K Gaharwar. 2018. "[Nanoengineered Ionic-Covalent Entanglement \(NICE\) Bioinks for 3D Bioprinting.](#)" *ACS Applied Materials & Interfaces* 10, no. 12: 9957–9968. doi: 10.1021/acsami.7b19808.

- **Misconceptions**

Taber, Keith. 2002. [Chemical Misconceptions: Prevention, Diagnosis and Cure](#). Cambridge: Royal Society of Chemistry.

Materials

- Sodium polyacrylate with fewer crosslinks (diaper polymer): 1/8 teaspoon per group of 2–3, available for purchase on Amazon
- Sodium polyacrylate with more crosslinks ("instant snow"): 1/8 teaspoon per group of 2–3, available for purchase on Amazon
- 8-oz plastic cups: 3 per group
- Plastic spoons: 1 per group

- Water (tap water is fine, room temp or cool)
- Copies of the Student Handout and Science Bite for each student

Time

This lesson should take approximately one 50-minute class period.

Student Prior Knowledge

Students should be able to classify metals and nonmetals and be familiar with the periodic table. They should have some idea of what Lewis structures of molecules look like and be familiar with different types of chemical bonding.

Instructions and Teacher Tips

◦◦ General Procedure

- For each pair or group, place $\frac{1}{8}$ of a teaspoon of sodium polyacrylate with fewer crosslinks (diaper polymer) in a plastic cup, $\frac{1}{8}$ of a teaspoon of sodium polyacrylate with more crosslinks (“instant snow”) in another cup and put about 50 mL of water in the last cup. Keep some paper towels handy in the event of a spill. Safety goggles are not necessary as long as the powder is dispensed into the cup in advance.
- Split your class into pairs or groups of three for the exploration activity. Sodium polyacrylate is non-toxic, but remind students to wash their hands after exploring the powder. Have students complete the exploration activity with sodium polyacrylate as directed on the student handout, recording their observations in steps 2, 3, 5, and 7. They should then proceed to answer the comparison question in step 7. This part of the lesson should take about 15–20 minutes.
- If some students finish the first part of the lesson very quickly, you may want to allow them to explore exactly how much water $\frac{1}{8}$ of a teaspoon of each type of sodium polyacrylate will absorb. For the diaper polymer, $\frac{1}{8}$ teaspoon is about 0.35 gram, and will absorb about 300 times its weight in tap water (105 grams or ~105 mL)!
- Have students briefly share their observations of the exploration activity before proceeding to the Bite and the rest of the analysis questions.
- Hand out a copy of the Bite and have the students read the Bite. Once they finish the Bite, give them about 20–25 minutes to complete the analysis questions in their groups. Circulate to help any groups that may need clarification or help.
- Briefly discuss any thoughts or issues related to Questions 1–8, then ask two sets of pairs to team up and form groups of four to do a think-pair-share on the Big Question (Question 9). After a few minutes, have each pair in the group share how the other pair answered Question 9 to the whole class. This end of class discussion should last about 5–10 minutes.

◦◦ Tips, Extensions, and Variations

- If any students are confused by the polymer model in **Figure 1** of the Student Handout, try not to get them too caught up in the molecular structure. Instead, reinforce the analogy being drawn. Each of the round “beads” represents a monomer in a polymer chain.
- The gel and powder that results should be thrown in the trash, as they will clog sinks if put down the drain. You can reuse the cups for a different activity or keep to repeat the experiment. If you keep some of the gel and powder around in a cup, students will observe that over a few days, both return to a state that is very similar to the original powder, confirming that the absorption of the water is a physical change.
- For ELL students or others needing extra support, you may want to have them read the Bite aloud to each other, or read the Bite as a class. You may also want to assign specific questions to certain groups, then bring the class together to share their answers.
- If needed to jog students’ memory, show a poster or some images comparing intermolecular forces and covalent bonds.
- If you want to explore polymers further, you can obtain a nylon making kit through Flinn Scientific [here](#) for \$31.50. The sodium polyacrylate can be obtained at [Flinn Scientific](#) as well (25 g is \$5.35), or at [Educational Innovations](#), or on Amazon. You can also purchase Insta-snow, a fake snow also made with sodium polyacrylate, from these sites.

🧑‍🔬 Background Information and Research Details

- Sodium polyacrylate is a non-toxic superabsorbent polymer made up of repeating acrylic acid monomers as shown in **Figure 1** of the Student Handout. Sodium polyacrylate chains form crosslinks between the negative carboxyl groups (COO^-) and the sodium ions. In its dry powder form, sodium polyacrylate is coiled: positively charged sodium ions are tightly bound within a cage of polyacrylate chains, kept close by negatively charged carboxyl groups dangling from the polymer backbone.
- When water is added, the long chains of sodium polyacrylate stretch out. This happens because each repeating unit in sodium polyacrylate contains an area with a partial negative charge that attracts the partially positive hydrogens in water molecules. Without having a positive sodium nearby, the negative carboxyl groups now repel each other to a greater extent. The attraction to the water and the repulsion of the carboxyl groups causes the polymer to stretch out.
- Because of water’s unique structure and polarity, it is capable of associating with two polymer chains. For this reason, two polymer chains surround each layer of water molecules, with each row of water molecules forming a bridge between the two chains. Imagine the polymer–water complex as something of a molecular sandwich, where the polymer chains are the “bread” and the water molecules are the “jam.”
- This clever chemistry means that sodium polyacrylate can absorb and lock away huge amounts of water, hence the common trade name “Waterlock.” It can hold up to 300-

times its mass in the case of tap water (which contains other metal ions that compete with the water molecules) or up to 800 times the mass of ion-free distilled water.

- Super-absorbent polymers, such as sodium polyacrylate, were first developed in the late 1960s by the US Department of Agriculture. They were searching for ways to hold moisture in the soil more effectively. Now, it is used in a variety of common products such as baby diapers, pet pads, water-retaining granules in potting soil, instant snow, and so on.
- Salt causes sodium polyacrylate to release the water it contains by disrupting the attractions between water molecules and the polymer. When salt is added to the solution, it breaks into negative and positive ions, which are also attracted to the water molecules. Each ion attracts several water molecules to it. Eventually, when enough salt is added, the water molecules become more attracted to the ions than the polymer chains, and water leaks out of the mixture, resulting in a watery liquid.
- More information about sodium polyacrylate and other similar polymers can be found on the American Chemical Society's page [here](#) and the Royal Society of Chemistry's page [here](#).
- In the research article described by the Bite, the scaffold material is created by NICE: **n**anoengineered **i**onic **c**ovalent **e**ntanglement. The researchers created flat nanosilicate mineral disks that have a positive side and a negative side. They then combined these discs with two different polymers: GelMA and kCA. The charged sides of the discs interact with the charged regions in both polymers to stabilize them. The ICE part of NICE refers to the entanglement that occurs between the two types of polymers. The entanglement is basically a crossing and mixing of the different strands of polymers so that they form a new composite polymer with properties different from the original polymers.
- The creation of NICE bioinks represents a huge advance in the area of organ scaffold material because previous bioinks did not have the strength or sheer properties that NICE bioinks have.
- There are three technologies for 3D bioprinting: inkjet, laser-based, and extrusion-based. In the article, extrusion technology is used, which basically forces the ink out at a specific temperature. Cells are encapsulated within the bioink, then the composite material is extruded out to form the scaffold. As reported in the paper, the researchers created a honeycomb scaffold of NICE bioink with bone cells as a test to see whether the ink supported cell growth. The cells grew and proliferated, filling in the spaces in the scaffold. Though there are still unanswered questions (like how the nanoparticles degrade), NICE bioink appears to be a better scaffold material than the hydrogels used in the past for a couple of key reasons: The NICE bioink had little or no effect on surrounding tissue when injected under the skin, and the NICE hydrogel is also almost completely reabsorbed by the cells in 28 days under *in vivo* conditions, leaving the cells behind.
- 3D bioprinting has already been used to create skull implants, facial implants, and jaw implants. These 3D printed objects used scaffold material other than the hydrogels mentioned in this article due to their harder nature.
- The National Institute of Health has a technical overview of bioprinting [here](#).

Big Question Discussion

This lesson should get students thinking about the Big Question “*What is life?*” In particular, are engineered human or animal tissues alive? If you choose to delve into the Big Question, consider these suggestions:

- The Big Question discussion should prompt a natural discussion about whether tissue created by scientists for medical purposes is living. But if students are reluctant to talk, you may want to prompt them by asking questions such as:
 - If scientists eventually create a human heart through the NICE bioink and live cells and transplant it into a human, is the heart alive?
 - Scientists are trying to use stem cells to grow them into organs. Are stem cells alive? What about the organs they grow into?
 - Scientists are [growing meat in labs](#). Is the meat alive? If any students are vegetarians, ask them if they’d be okay eating lab-grown meat. (The meat is grown in culture from living animal cells, but animals are not harmed in the process.)
 - Are viruses alive?
- The discussion may bring up religious beliefs. Be prepared in case a student mentions that only God can create living things or has specific religious beliefs on medical treatment. It may cause tension between students with different beliefs. But you may want to respond that all are welcome to express their opinions, that the question is a matter of personal opinion and philosophical debate. Try to avoid judgment of whether it is right or wrong to try to create life, but allow students to discuss the ethics of the technology in an open, objective, and respectful way. High school students may need reminders of how to conduct a respectful and non-judgemental discussion.
- As a wrap-up, you may want to mention books or movies that explore the question of “What is life?” or about organ donations. Here are some suggestions which you may want to preview in advance before mentioning to students:
 - *Frankenstein* by Mary Shelley
 - *Never Let Me Go* by Kazuo Ishiguro
 - *My Sister’s Keeper*, book by Jodi Picoult adapted into a movie
 - 21 Grams, movie from 2003 directed by Alejandro González Iñárritu
 - Traffic, movie from 2016 directed by Rajesh Pillai

Answers

During the initial activity exploring the polymers, you can expect answers such as the following.

- Step 2.** Add water to your cup, about 10 mL at a time (about one plastic spoon full) and write down what you see and feel in the space below. Discuss with your group.

Students should observe the water being absorbed rapidly, and the gel getting increasingly swelled up and more clear as water is added. They may also observe that the gel is cool to the touch.

Step 3. Continue to add water until you run out and write down your final observations.

They will probably continue to mention the absorbance of the water and the jelly-like texture.

Step 5. Add water to your cup, about 10 mL at a time (or one plastic spoon full) and write down what you see and feel in the space below. Discuss with your group.

Students will notice again how quickly the water is absorbed, but this time they will observe the fluffy white texture of the Insta-snow and the expansion of the polymer. They may again notice the coolness of the polymer.

Step 6. Continue to add water until you run out and write down your final observations.

They will continue to notice the absorbance of the water and may notice that the snow looks less white and feels more liquid-like.

Step 7. How was the second polymer different from the first? Be specific in your comparison, cite your observations.

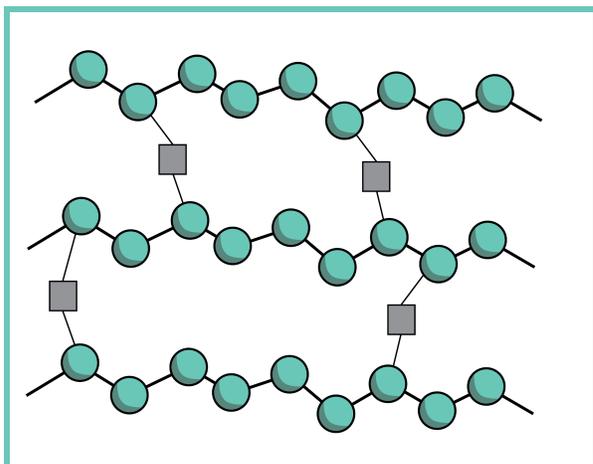
The second polymer was fluffier, less dense, and whiter in color. The first was denser and seemed to absorb more water. The first also became more clear in color.

Analysis Questions

1. The trade name for sodium polyacrylate is “Waterlock.” After seeing it in action, what do you think are some everyday applications of this polymer? How could it be used in real life?

This polymer can be used for anything that needs to soak up liquids made primarily of water such as diapers. It can also be used in potting soil so that the soil helps retain moisture.

2. Thinking about what you just read and the diagram of the crosslinked sodium polyacrylate (**Figure 2**), draw a model of a polymer that has been crosslinked. Use circles to represent the monomers in the polymer and squares to represent the crosslinks. Include at least three polymer chains.



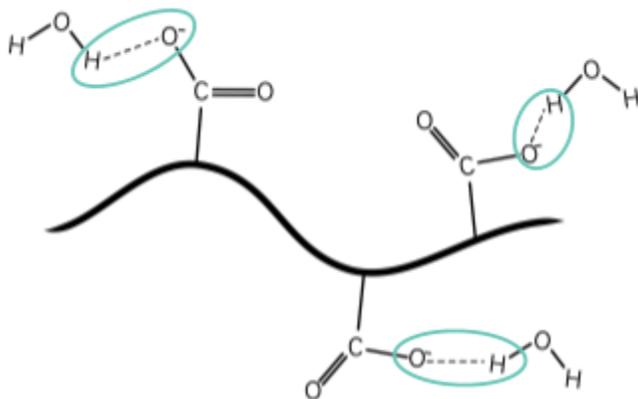
Students may draw crosslinks on monomers directly next to each other. This is unlikely to happen in polymers due to the small spacing between molecules. You may choose to mention it to students; however it is not an essential point for the discussion of polymer properties.

3. The first sample of sodium polyacrylate you investigated has some crosslinks, while the second sample has many more crosslinks between polymer threads.

a. Based on your observations, how did increasing the amount of crosslinking affect the properties of the sodium polyacrylate?

The more crosslinking, the less water the polymer could absorb and the less gel-like the polymer was after absorbing water.

b. Sodium polyacrylate absorbs water by forming hydrogen bonds between the negatively charged oxygens on each monomer and water molecules. On the simplified diagram of the polymer below, draw how the water molecules will interact with the polymer.



In a water molecule, the hydrogens are partially positively charged. These partial positive charges will be attracted to the negative charges on the oxygen in the polymer shown. They will form hydrogen bonds with that oxygen.

c. Recall that when sodium polyacrylate is crosslinked, bonds form between the crosslinking molecule and the negatively charged oxygens shown above. After bonding with the crosslinking molecule, the oxygens are no longer negatively charged. As the amount of crosslinking increases, what do you think happens to the amount of water the polymer can absorb?

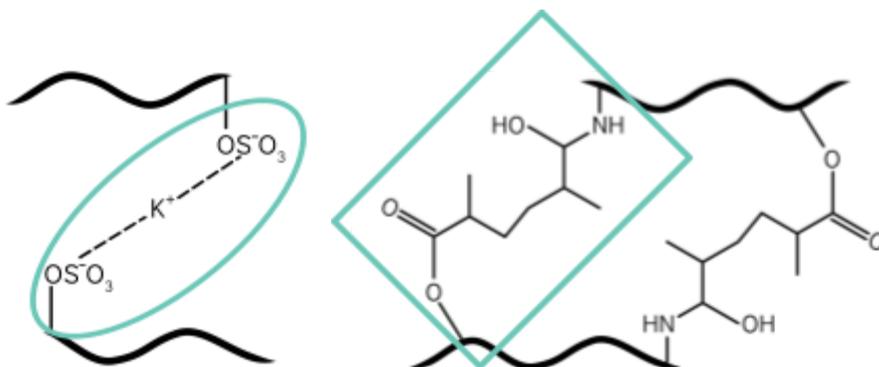
The polymer will absorb less water because there are fewer spots available to form hydrogen bonds with the water.

d. Explain how your answer to part c makes sense based on the observations you made in the activity. Develop a hypothesis as to why the crosslinking affected the properties of the sodium polyacrylate. Base your hypothesis on your observations, your knowledge of what happens to sodium polyacrylate when it is crosslinked, and your answer to part b.

This makes sense, because the polymer with the greater amount of crosslinking was able to absorb less water than the polymer with the smaller amount of crosslinking.

STOP & read **Science Bite**:
A NICE Way to Save Lives

4. Circle the crosslink in KCA and put a square around the crosslink in GelMA.



Kappa-Carrageenan (kCA)

Gelatin Methacrylate (GelMA)

NB: Students can put a square around either crosslink in the GelMA structure.

5. What is different about the structures between the crosslinks in kCA and GelMA? Include a discussion of bonds and intermolecular forces in your response.

The kCA is linked through the attraction of positive and negative charges, while the GelMA is covalently linked. Students may also note that the GelMA crosslink involves more atoms.

6. Use the graph to complete the table below, reporting the amount of stress it takes to compress 1 mm of the polymer 0.6 mm.

Polymer	Amount of stress needed to compress 1 mm of the polymer 0.6 mm
kCA	10-30 kPa
GelMA	100 kPa
NICE	200 kPa

7. The Bite states that the NICE polymer is the strongest. How does the data from **Figure 5** support that conclusion?

You need much more compressive stress to strain the NICE polymer by the same amount as the other polymers.

8. Thinking about what happened when you added water to the sodium polyacrylate, what do you think happens when live cells are incorporated into the NICE bioink scaffold?

Live cells contain a lot of water. They are probably absorbed into the spaces in the NICE bioink, just as water is absorbed into the sodium polyacrylate. Maybe live cells also form crosslink between the polymer strands in the NICE bioink.

9. **Connect to the Big Question.** Projects like the one described here have great potential to save many lives, but they also bring up some ethical questions regarding growing human tissues. Do you think human organs on their own are alive? Would you consider a 3D printed organ as alive?

Sample answers:

Yes, since the cells are alive, the organ is alive. A 3D printed organ would be alive even though it is manmade

No, it is not alive, since an organ can not live on its own. It needs to exist within a human body or in the case of the 3D organ, it needs support from the polymer matrix.