Learning about Osmosis through Engineering Design Process

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INQUIRY & INVESTIGATION

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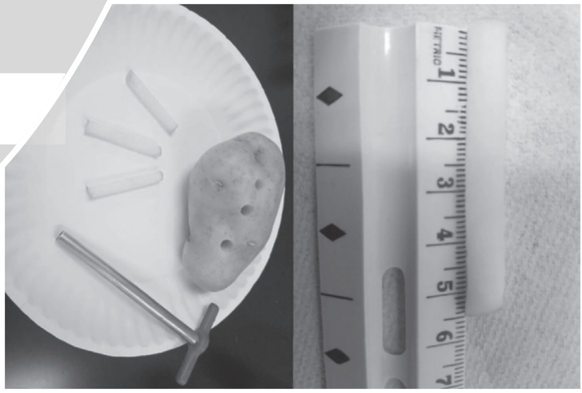

RECOMMENDED FOR *AP Biology*

Matthew Rice, Frackson Mumba, Laura Pottmeyer

Abstract

Students' sound knowledge about osmosis can lead to their understanding of other related biological processes that require the movement of materials across cell membranes, such as photosynthesis, homeostasis, and cellular respiration. However, students have difficulties to understand osmosis. This challenge has been attributed to the abstract nature of the concept and the way it is presented to students. Thus, we present an engineering design, integrated biology unit in which students use the engineering design process to learn about osmosis and its related concepts. A dependent t-test revealed statistically significant differences in students' understanding of osmosis and related concepts, and the engineering design process before and after the unit. Overall, in this unit students developed the understanding of osmosis in a real-world context through an engineering design process.

Key Words: *osmosis; engineering; integration; design; cell membranes.*

○ Background

A sound understanding of osmosis by students can help students learn about homeostasis and cellular processes that require the movement of materials across cell membranes (Lankford & Friedrichsen, 2012; Odom et al., 2017; Reinke et al., 2019). For example, knowledge of osmosis is required to understand water movement into the roots of a plant. However, research has continued to show that osmosis is a difficult concept for students (e.g., Fisher et al., 2011; Sung et al., 2021). Research has attributed this problem to the abstract nature of osmosis concept and the way it is taught in science classrooms. For example, Reinke and colleagues (2019) reported that osmosis is an abstract biological process that occurs at the submicroscopic level and is very difficult for many students to understand when traditional learning and teaching methods are used. Thus, there is a need to teach osmosis in a manner where students develop meaningful understanding of the concept and its application in their everyday lives. One way to effectively teach osmosis is using an engineering design process (NGSS Lead States, 2013). Engineering design integrated science (EDIS) instruction facilitates problem solving in real-world context (Kolodner et al., 2002) and enables students to engage in active learning (Brophy et al., 2008). In this unit, students were engaged in exploring various solutes and solvents through engineering design before formal introduction to terms such as *hypertonic*, *hypotonic*, and *isotonic*. As a result, students were able to develop meaningful understanding of osmosis and its related concepts through the engineering design process.

Teaching difficult biology concepts such as osmosis through engineering design may increase students' content knowledge in biology and engineering design.

○ Overview

This article describes an engineering design integrated biology unit designed to teach osmosis and its related concepts in a high school classroom. Students were provided with a design challenge and tasked to find a solution in which plant cells would not lose or gain too much water. To explore how and why cells change in different osmotic conditions, students worked in their engineering teams to design a liquid solution that can contain a potato and prevent it from losing or gaining too much water. The goal is for students to create an isotonic solution, through initial research, design, and reiteration. Students will be learning about osmotic conditions through research/guided lessons while they also design, test, and iterate their solution. The lesson sequence was designed this way so that students would have a chance to draw conclusions about osmosis through their design solutions before the teacher provides more explanations through guided lessons. This unit occurred over the course of three class periods (90 minutes each). Prior to the start of the unit, students were introduced to the engineering design process as outlined in Figure 1. Students were taught that

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the engineering design process is both iterative and flexible. This means that often steps are repeated and that some steps can occur out of order depending on the project.

Unit Learning Objectives

This unit was designed for students to

- Understand the properties of the cell membrane.
- Describe types of cellular transport—specifically osmosis.
- Explain and apply the engineering design process.
- Understand that engineering design is a process that involves redesigning the solution.
- Demonstrate engineering design skills.

Materials Needed

- Potatoes
- Cylindrical potato corer (cork borer)
- Distilled water
- Cooking oil
- White vinegar
- Tap water
- Table salt
- Granulated sugar
- Cornstarch
- Electronic balance
- Metric ruler with mm scale (1 per group)
- Test tubes and rack (3 test tubes and 1 rack per group)
- 10 mL graduated cylinder (1 per group)
- Paper towels
- Paper plates
- Tweezers

Safety Concerns

The safety concerns for this unit should be mitigated by the teacher preparing the potatoes using the cork borer. Students should wear gloves and goggles during the activity. Student should also wash their hands after working with the solutions. Students should not taste the potatoes or solutions they make. At the end of the activity students should dispose the materials in a trash bin. Additionally, students should observe other lab safety issues.

○ Day 1

Step 1: Identify the Need or Problem

The teacher presented the students with the design challenge (see Figure 2). It should be conveyed to students that the challenge of establishing an osmotic balance of the solution would be only one component of the overall problem. If the teacher desires, the class can engage in a discussion regarding additional challenges that would need to be addressed to achieve osmotic pressure.

Next, the teacher explained the purpose of the design journals (see Figures 4, 5, 8, and 9). Students used the design journals to document their thought process and observations throughout the unit. After students read the design challenge, they defined the problem and identified the specifications and constraints in their design journals. One constraint of the design challenge is to design a solution that is cost effective. Students had a list of materials that

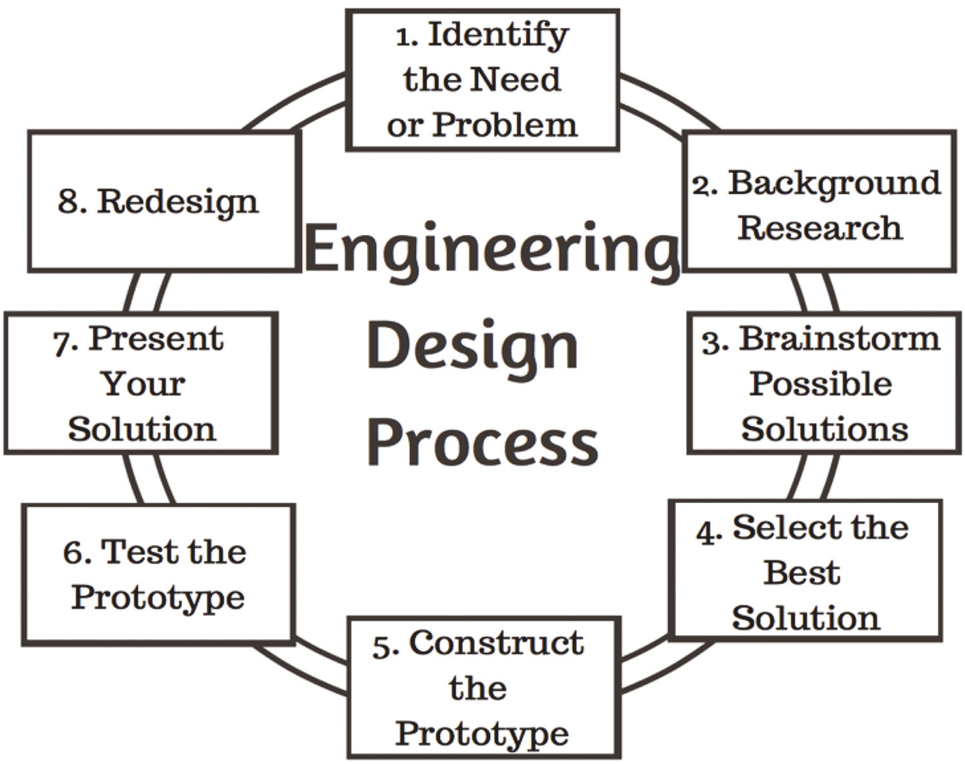

Figure 1. Engineering design process model.

Design Challenge:

You are a group of agricultural engineers who have been asked to look at the phenomena of plant cells losing and gaining water. What is present inside of a cell? Why do plants wilt when they are not watered? What is happening to the solvents and solutes present inside of cells that causes these changes to occur? These are some of the questions that are driving your engineering design team to look into the phenomena of cells losing and gaining water. To explore how and why cells change in this way, you will work with your engineering team to design a liquid solution that can contain a potato and prevent it from losing or gaining too much water.

You have a budget of $2,500 to spend in any way that you choose. You may test multiple solutions at a time, but almost everything has a cost associated with it. Use your background knowledge to come up with several possible prototypes to solve this problem.

For your tests, you will be given a cylindrical core of a potato. You will have to test this potato by placing it in a test tube with 10mL of your engineered solution. Your solution must contain at least one solvent and one solute. In order to analyze the effectiveness of your engineered solution, you will look at the initial and final mass of your potato, the initial and final length of your potato, and the initial and final turgidity (flimsiness or crispness) of your potato. The most effective solution will be one that leaves the potato relatively unchanged.

Figure 2. Solution design challenge.

Materials Available:

- Potatoes cores - *free*
- Cylindrical potato corer -*free*
- Distilled water - *$500 per 10mL*
- Cooking Oil - *$300 per 10mL*
- White vinegar - *$100 per 10mL*
- Tap water - *$250 per 10 mL*
- Table salt - *$500 per gram*
- Granulated sugar - *$500 per gram*
- Cornstarch -*$300 per gram*
- Test Tube – *first is free, additional are $400 each*
- 10 mL graduated cylinder - *free*

Figure 3. Materials available to students.

they could "buy" from the teacher (Figure 3). Students kept track of their expenses in their design journal. Providing students with a cost constraint serves two purposes. First, students gain a greater appreciation for the real-world limits placed on engineers. Second, if students create a "successful" prototype in the first round of designing, they could improve on their prototype by reducing their overall cost.

Steps 2–4: Background Research, Brainstorming & Selecting the Best Solution

Next, students were introduced to the cell membrane via interactive teacher-led instruction. The information presented to students focused on the individual parts of the cell membrane, such as the phospholipid bilayer and protein channels. Students also learned about the concept of selective permeability. Alternatively, teachers can have students complete guided [online] research to learn about the cell membrane. Although students were introduced to the properties of the cell membrane, they were not exposed to osmosis or related terms, such as hypotonic, hypertonic, and isotonic. This information was presented to students after the first round of design solution. By releasing the information to students in two parts, the students were given the opportunity to develop their own understanding of osmosis during the first round of the design solution.

Students then completed steps 2–4 of the engineering design process (Figure 4). During step 2 (background research) and step 3 (brainstorm possible solutions), students worked individually and documented their progress in their design journals. To collect background information and brainstorm solutions, students identified information from the cell membrane lesson that they thought was relevant to the engineering design challenge. Throughout the unit, students were encouraged to access more resources for additional background information. Then, students were placed into groups of three for engineering design step 4 (select the best solution). In step 4, students took turns sharing their ideas with their group members. The groups then selected at least two designs to test. Students were encouraged to test multiple solutions, so that they could see how different solutions affected the potato cores.

Designs needed teacher approval to ensure that students were adhering to both safety guidelines and the project requirements. As

Engineering Design Process Step	Instructions and Responses/Observations
(1) Identify Need or Problem	After reading the design challenge above, define the engineering design problem. This step should be completed independently.
	Response/Observations
	Identify the task that you are set to do.
	Response/Observations
	Identify the constraints with this challenge. What are the challenges that are associated with your design task?
	Response/Observations
(2) Background Research	After learning about the cell membrane, select the relevant cell membrane information that you will use to engineer your solution. You may add additional information from your own research. This step should be completed independently. *(Hint: You want to make sure that the potato stays the same before and after you put it into the solution. Think about what could be moving in and out of the potato.)*
	Response/Observations
(3) Brainstorm Possible Solutions	Next, look at the list of materials being offered to you. If you would like to see the physical materials, ask the teacher. Write the combination of solute and solvent that you would like to try. Also, include the total cost associated with your design. You should come up with multiple design solutions. This step should be completed independently.
	Response/Observations
(4) Select the Best Design Solution(s)	Discuss your possible solutions with your group members. Each group member should present their all of their design solutions. Then, as a group, you should select at least 2 design solutions to test. After you have selected two design solutions and determined the cost of each solution, meet with your teacher to get your designs approved.
	Response/Observations

Figure 4. Student design journal steps 1–4.

Engineering Design Process Step	Instructions and Responses/Observations
(5) Construct the Prototype	After receiving teacher approval of your prototype solutions, work with your group members to create your solutions.
	Response/Observations
(6) Test the Prototype	First collect initial data in the data chart below. *(Tip: Make sure that you blot your potato cores dry with a paper towel so that you are not measuring extra weight from the solutions.)* [data chart below] The next day, obtain your prototype solutions, measure and record your "final" data in the data chart.
	Response/Observations

Solution Materials	Initial Length (cm)	Final Length (cm)	Change in Length (cm)	Percent Change (%)	Initial Mass (g)	Final Mass (g)	Change in Mass (g)	Percent change (%)	Initial Turgidity (flimsy or crisp)	Final Turgidity (flimsy or crisp)

Figure 5. Student design journal steps 5–6.

long as each design contained at least one solvent and one solute and stayed within the budget, the design would be approved. This flexibility gave students the chance to experiment with many different solute and solvent concentrations.

Steps 5–6: Construct Prototype & Initial Testing

After students had two of their designs (prototype solutions) approved by the teacher, they were directed to complete steps 5 and 6 of the engineering design process (Figure 5).

All groups were given a test tube rack with 1 free test tube, a ruler, a 10 mL graduated cylinder, and an electronic balance to use. The teacher provided cylindrical, defect-free potato cores to each group for each design submitted. Potato cores were created using a cork borer (see Figure 6). All additional materials needed to be purchased using the group's budget as they completed their first prototype.

Students then collected their initial data by weighing their potato cores and recording the data in their design journals. Next, students created their solutions, and placed their potato cores in the test tubes (see Figure 7). The potatoes were left overnight to soak.

○ Day 2

Step 6–7: Test the Prototype & Present Solutions

The following day (day 2), students measured and recorded their final data, informally presented their solutions, and began the redesign process (see Figures 8 and 9). *Tip: Students should be instructed to remove the potato from the solution using tweezers and to blot the potato cores dry with a paper towel to remove excess liquid prior to weighing them.* Next, students analyzed their data in step 7 and briefly presented their findings and prototype solutions to the class in an informal setting. Students should include if they think their initial design was an isotonic, hypotonic, or hypertonic solution, based on their results. Keeping in mind that their goal is to create a solution where the potato changes as little as possible (isotonic), this presentation gave them the opportunity to discuss what happened and potentially identify areas for improvement. Students did not need to create a formal presentation at this time.

After students presented their prototype solutions to the class, students returned to their groups. In their groups, students

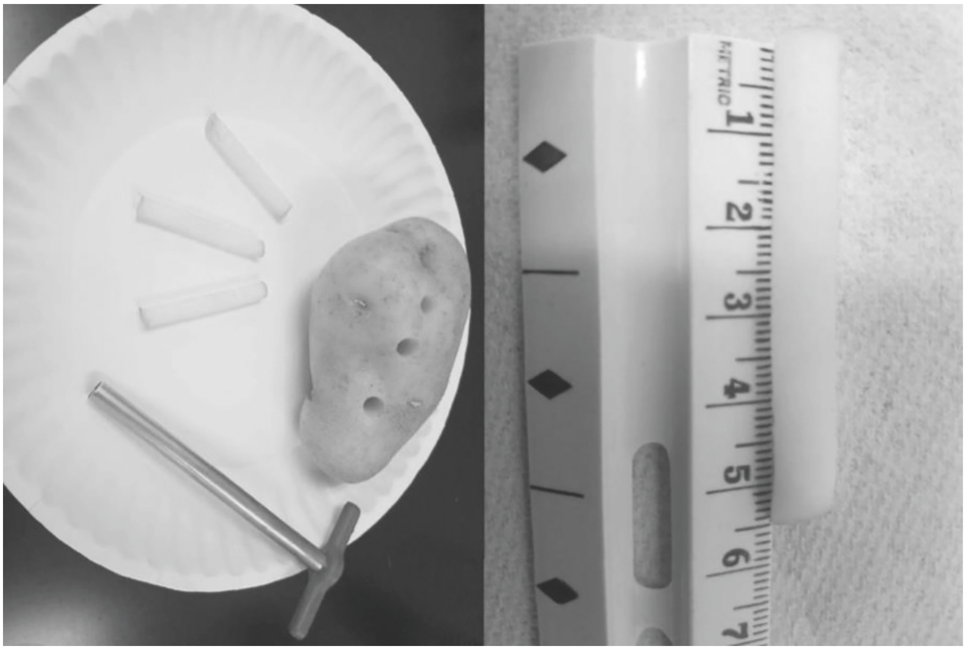

Figure 6. Potato cores with cork borer and approximate core size.

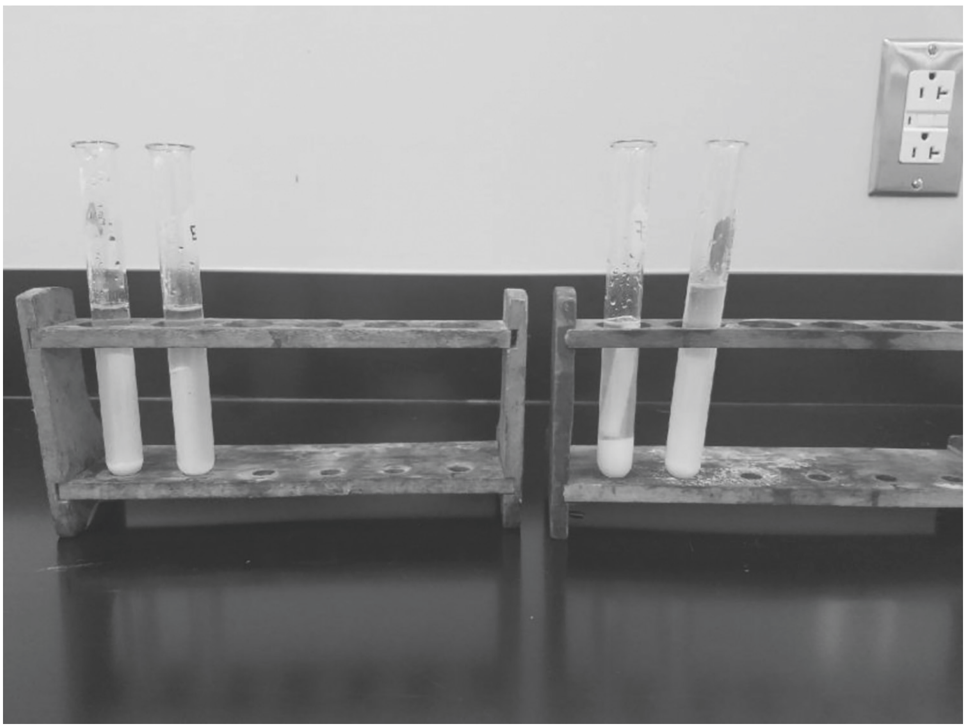

Figure 7. Setup of students' prototypes.

discussed the effectiveness of their prototypes and their classmates' prototypes by comparing them to the original design challenge.

Step 8: Redesign

Next, students completed step 8 (redesign) (see Figure 9). After analyzing the initial prototypes, students were introduced to another aspect of the cell membrane via interactive teacher-led discussion. This information focused on passive and active transport. Students learned about diffusion, facilitated diffusion, and osmosis. While learning about osmosis, the teacher covered the differences between hypertonic, hypotonic, and isotonic solutions and how these relate to equilibrium and homeostasis. The purpose of this presentation was to provide students with additional background information to use in redesigning their prototype.

<table>
<tr><th>Engineering Design Process Step</th><th>Instructions and Responses/Observations</th></tr>
<tr><td rowspan="2">(6) Test the Prototype</td><td>First collect initial data in the data chart below. (Tip: Make sure that you blot your potato cores dry with a paper towel so that you are not measuring extra weight from the solutions.)
<table>
<tr><th>Solution Materials</th><th>Initial Length (cm)</th><th>Final Length (cm)</th><th>Change in Length (cm)</th><th>Percent Change (%)</th><th>Initial Mass (g)</th><th>Final Mass (g)</th><th>Change in Mass (g)</th><th>Percent change (%)</th><th>Initial Turgidity (flimsy or crisp)</th><th>Final Turgidity (flimsy or crisp)</th></tr>
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</table>
The next day, obtain your prototype solutions, measure and record your “final” data in the data chart.</td></tr>
<tr><td>Response/Observations</td></tr>
<tr><td rowspan="2">(7) Present Your Solution</td><td>With your group, analyze your findings and discuss the pros and cons of each solution that you have designed. You will briefly present your data and findings to the class.</td></tr>
<tr><td>Response/Observations</td></tr>
</table>

Figure 8. Student design journal steps 6–7.

At this point, students updated their background research with new information, brainstormed new solutions, and selected the best solution again for the redesign phase. After obtaining teacher approval, students constructed new prototypes and gathered their data. Students operated under the same materials and cost constraints.

○ Day 3

Step 8: Redesign (continued)

On day 3, each group collected the “final” data for their redesign and compared the results of the redesign and initial prototypes. Students presented their findings to the class in a formal presentation, which included the problem, key concepts in their background information, best solution the group adopted, prototype, data from their best solution, identification of the type of solution that they created (isotonic, hypertonic, hypotonic) based on the results of their testing, the overall cost, and potential areas for improvement. An example of one group’s findings for their initial and final designs can be seen in Figures 10 and 11. Despite falling short of achieving 0% change and thus creating an isotonic solution, the students demonstrated an understanding of the solutions and osmosis and were able to reduce the percentage change in their potato core’s mass. Thus, this group was considered “successful” in their ability to better address the design challenge after a round of redesign.

○ Assessment

At the end of the unit, the teacher assessed student design journals, prototypes, presentations, pre- and posttests on osmosis, and engineering design knowledge. Student responses to pre- and posttest items on osmosis and engineering design knowledge were scored on a scale of 0–2 points (0 = completely incorrect, 1 = partially correct, and 2 = completely correct). Table 1 is an example of an assessment rubric used to evaluate students’ progress throughout the unit.

Engineering Design Process Step	Instructions and Responses/Observations
(8) Redesign	Compare your design and the designs of your classmates to the requirements you listed above. Does it meet all of the requirements? If not, what didn't it meet and why not? You now have the opportunity to create a second round of prototypes. You will go through part of the design process again to test your solutions again. After receiving teacher approval of your prototype solutions, work with your group members to create your solutions. First collect initial data in the data chart below. *(Tip: Make sure that you blot your potato cores dry with a paper towel so that you are not measuring extra weight from the solutions.)*

Solution Materials	Initial Length (cm)	Final Length (cm)	Change in Length (cm)	Percent Change (%)	Initial Mass (g)	Final Mass (g)	Change in Mass (g)	Percent change (%)	Initial Turgidity (flimsy or crisp)	Final Turgidity (flimsy or crisp)

The next day, obtain your prototype solutions, measure and record your "final" data in the data chart.

With your group, analyze your findings and discuss the pros and cons of each solution that you have designed. You will briefly present your data and findings to the class. Do you think that there is a way to create a better solution for less cost?

Response/Observations

Figure 9. Student design journal.

Initial Design

Solution Materials	Initial Length (cm)	Final Length (cm)	Change in Length (cm)	Percent Change (%)	Initial Mass (g)	Final Mass (g)	Change in Mass (g)	Percent change (%)	Initial Turgidity (flimsy or crisp)	Final Turgidity (flimsy or crisp)
Cornstarch and Oil	**4.6cm**	**4.4cm**	**-.20cm**	**-4.3%**	**1.10g**	**0.90g**	**-0.20g**	**-18%**	**Crisp**	**Very flimsy**

Type of Solution Created: Hypertonic

Total Cost: $1450

Figure 10. Students' initial design results, prior to learning about hypertonic, hypotonic, and isotonic solutions.

Final Design

Solution Materials	Initial Length (cm)	Final Length (cm)	Change in Length (cm)	Percent Change (%)	Initial Mass (g)	Final Mass (g)	Change in Mass (g)	Percent change (%)	Initial Turgidity (flimsy or crisp)	Final Turgidity (flimsy or crisp)
Cornstarch and Oil	**4.8cm**	**5.0cm**	**+.20cm**	**+4.2 %**	**1.09g**	**1.03g**	**-0.06g**	**-5.5%**	**Crisp**	**Flimsy**

Type of Solution Created: Hypertonic

Total Cost: $900

Areas for Improvement: We could have used cheaper materials, such as water or vinegar and tried to get the same results.

Figure 11. Students' final design results, after learning about hypertonic, hypotonic, and isotonic solutions.

Table 1. Sample student assessment rubric.

Required Components	Available Points				Points Earned
Defining Problem & Identifying Constraints	Identified overall problem: **2 Points**				
	Identified task to accomplish: **2 Points** Identified 2 or more constraints: **5 Points** *or* Identified only 1 constraint: **2 Points**				
Background Research	**15 Points**	**10 Points**	**5 Points**	**0 Points**	
	Maintained up-to-date background research section with information gathered from each day of the unit, outside sources and classroom activities.	Included information gathered from day 1 and day 2 science content but not from additional sources or classroom activities.	Included day 1 science content only.	Has not gathered any background research.	
Test the Prototype	**10 Points**	**5 Points**	**0 Points**		
	Gathered all required quantitative data, calculated percent change, and observed turgidity of potato cores.	Left 1–2 boxes in data chart empty.	Left 3 or more boxes in data chart empty.		
Design Was within the Constraints	Cost of design was less than $2500: **2 Points**				
	Designs used at least 1 solvent and 1 solute: **2 Points**				
Presentation of Findings	Correctly identified solution as hypertonic, hypotonic, or isotonic based on data collected: **5 Points**				
	Identified at least 1 area for improvement: **2 Points**				

Table 2. Connection to the Next Generation Science Standards.

Standards **HS-LS1 From Molecules to Organisms: Structures & Processes** **HS-ETS1 Engineering Design**		
Performance Expectation(s) The chart below makes one set of connections between the instruction outlined in this article and the NGSS. Other valid connections are likely; however, space restrictions prevent us from listing all possibilities. The activities outlined in this article are just one step toward reaching the performance expectations listed below. **HS-LS1-2.** Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms. **HS-LS1-3.** Plan and conduct an investigation to provide evidence that feedback mechanisms maintain homeostasis. **HS-ETS-1.** Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants. **HS-ETS1-2.** Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering. **HS-ETS1-3.** Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.		
Dimension	**Name & NGSS Code/Citation**	**Specific Connections to Classroom Activity**
Science & Engineering Practices	**Developing & Using Models** Develop and use a model based on evidence to illustrate the relationships between systems or between components of a system (HS-LS1-2). **Planning & Carrying Out Investigations** Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design decide on the types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (HS-LS1-3).	Students use a prototype to demonstrate the concepts of diffusion and osmosis. Students brainstorm and design their own individual solutions. They then work in groups to select the best solution and create their prototype. Students work under the constraints provided in the design challenge, including cost.
Disciplinary Core Ideas	**LS1.A: Structure & Function** Multicellular organisms have a hierarchical structural organization, in which any one system is made up of numerous parts and is itself a component of the next level (HS-LS1-2). Feedback mechanisms maintain a living system's internal conditions within certain limits and mediate behaviors, allowing it to remain alive and functional even as external conditions change within some range (HS-LS1-3).	Students connect the structure of the cell membrane to its function and role in diffusion and osmosis. Students observe osmosis in their potato core samples by comparing data from multiple days.
Crosscutting Concept(s)	**Systems & System Models** Models (e.g., physical, mathematical, computer) can be used to simulate systems and interactions—including energy, matter, and information flows—within and between systems at different scales (HS-LS1-2). **Stability & Change** Feedback (negative or positive) can stabilize or destabilize a system (HS-LS1-3).	Students use potato cores in solutions to model the process of osmosis. Students observe osmosis, which is a feedback mechanism to ensure homeostasis is maintained.

○ Summary

This unit was designed to engage students in learning about osmosis and its related concepts using engineering design process. After identifying the engineering problem, students knew that they needed to design a solution where the potato would not gain or lose mass or length. By learning about the different types of osmotic solutions (hypertonic, hypotonic, and isotonic) after the initial design and analysis, students were able to realize that they should create an isotonic solution. This realization guided their thought process throughout the redesign phase. Our students demonstrated understanding of the engineering design process through their design portfolios. The pre-post Likert scale survey on their perception of learning osmosis through engineering design process was scored. There was significant difference between pre- and posttest in students' content knowledge on osmosis ($t = 6.985$, $p < 0.001$; $M = 0.69$; $SD = 0.38$), knowledge of engineering design process ($t = 12.929$, $p < 0.001$; $M = 0.989$; $SD = 0.312$). Overall, these findings show that teaching difficult biology concepts such as osmosis through engineering design may increase students' content knowledge in biology and engineering design. Despite the challenges students are likely to encounter, they should strive for an isotonic solution. Students should be aware that they can request any quantity of material if they stay within the allowed budget.

○ Connection to NGSS

Table 2 shows how the activities in this unit are connected to NGSS core ideas, practices, and cross-cutting concepts.

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