Investigating Biomimicry using 4D Printed Shape Memory Polymers (SMP)
(Performance-based Assessment PBL/ADI)

Authors

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SUBJECT/GRADE LEVEL

Subject Area(s): Physics, Chemistry and Physical Science

Grade Level(s): 9-12

Materials

- TinkerCAD or similar 3D Modeling Software
- PRUSA or compatible 3D Splice Software
- Creality Ender 3 3D Printer - or other 3D Printer
- PLA, PETG, ABS, TPU - or other 3D printer filaments that would be suitable for the capabilities of the 3D printer. Recommendations are PLA due to the lower operating temperatures and ease of printing.

3D Printing Special Notes: This lesson plan was tested with the above software and materials. However, due to the variability of software and 3D printers available on the market, the focus should remain on 4D thermoplastic printing based on plantoid biomimicry and not on the intricacies of 3D printing.

STANDARDS

Next Generation Science Standards

- HS-PS2-6 Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials
- HS-PS3-4 Plan and conduct an investigation to provide evidence that the transfer of thermal energy when two components of different temperatures are combined within a closed system results in a more uniform energy distribution among the components in the system (second law of thermodynamics).

Mathematics Standards | Common Core State Standards

- HSN.Q.A.1 Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays. (HS-PS2-6)
- HSN.Q.A.2 Define appropriate quantities for the purpose of descriptive modeling. (HS-PS2-6)
- HSN.Q.A.3 Choose a level of accuracy appropriate to limitations on measurement when reporting quantities. (HS-PS2-6)

English Language Arts Standards | Common Core State

- 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. (HS-PS2-6)
- WHST.11-12.2 Write informative/explanatory texts, including the narration of historical events, scientific procedures/ experiments, or technical processes. (HS-PS2-6)

LESSON OBJECTIVE(S)

Students design and conduct an investigation on the concept of biomimicry and the various trophic mechanisms that plants use to animate by determining the shape recovery ratio of either different 3D printed materials or the shape of a single filament 3D printed material.

CAREER CONNECTION(S)

Mentor Background: Dr. Brendan Hanrahan - received his B.S. degree in Ceramic and Materials Engineering from Clemson University in 2006, and the M.S. and Ph.D. degrees in Materials Science and Engineering from the University of Maryland in 2009 and 2013, respectively. For his Ph.D., Brendan determined the fundamental materials properties dictating the performance of micro ball-bearing platforms, which could serve as enabling technologies for future microsystems.

STEM Careers: Mechanical Engineering, Materials Science, Botany

RESEARCH QUESTION(s)

Brief Description: The goals of this lesson are two-fold. The first is to teach students to break through plant awareness disparity to help them understand the importance of natural plant movement and the research done to synthetically replicate those movements using robotics. The second goal is to introduce students to 4-Dimensional printing, which uses thermoplastics' shape memory effect to produce a desired, plant-based (plantoid) movement in response to environmental stimuli. This lesson will answer the following research questions:

How and why do plants move?

How can we develop 4D printed thermoplastics to replicate the movement of plants?

What are the possible applications of plantoids and biomimicry?

VOCABULARY

Essential (Domain Specific):

Biomimicry, Nastic, Turgor, Tropism, Geotropism, Phototropism, Chemotropism, Hydrotropism, Thigmotropism, Traumatropism, Galvanotropism, Electrotropism, Plantoids, Soft robotics, polymer, shape memory polymer, Thermoplastic

Supplemental:

Parent phase, Deformed phase, Glass transition temperature, Bimorphism

ENGAGEMENT

Brief Description: This stage aims for students to appreciate plants for more than their aesthetic or nutritional value. Plants typically take a backseat when it comes to interest in biology. “To counteract this relative lack of interest in plants, Strgar (2007) suggested that teachers need to take a more active role in terms of their knowledge, enthusiasm, and interest toward plants”.

Procedures:

Phenomenon (or lack thereof):

Bring a healthy plant to class. Have the students prepare their lab notebooks. Discuss the requirement that students must take detailed recordings of their qualitative and quantitative observations. Set the plant in front of the class and then have them make observations regarding the plant's movement. It is obvious that the plant will not visually move in the time frame given to the students. However, lead them to the discussion as to what factor must we account for to observe a plant moving. That factor would be time. Plants move very slowly as a function of time. We are not conscious because we are looking for an immediate visual clue, but if we scale our time on plant time, we can see how plants move.

Discuss with students the following paper on Plant Awareness Disparity and how it relates to your particular lesson of the unit. The idea is that we humans do not appreciate their importance to the biosphere. As an example, for a physics-focused unit, discuss how we do not appreciate the ability of plants to physically move either through growth mechanisms or responses to environmental stimuli. Reveal the plan to the class and then have them write their observations. The students will likely count the number of stems, leaves, or heights for the quantitative observations. For the qualitative observations, students will describe the color or shape of the plant.

The goal is to steer students toward observing plant movement. The plant will not be moving in the concise time frame of the observation activity. Ask the students to consider watching this plant over a more extended time (days or months). Ask the students to predict what we may expect to see over that more prolonged period. Lead students to realize that plants are not stationary and exhibit efficient natural movement in response to environmental stimuli.

EXPLORATION

Brief Description: Plants exhibit movement patterns for both growth environmental responses that are very sophisticated yet very slow. If we were to leverage our understanding of the mechanics of the movement patterns we can possibly create soft robotics that use environmental stimuli (external energy) to achieve processes autonomously. Students will explore the website: Plants in Motion by Dr. Roger Hangarter of the University of Indiana. The students will have an opportunity to learn on their own about the different nastic and trophic movements of plants.

Procedures:

Allow students at least 30 minutes to explore the different plant movement videos. The guiding question for their exploration is: How and why do plants move?

After 30 minutes, divide the students into partners and assign them a specific plant movement listed in the essential vocabulary (Tropism, Geotropism, Phototropism, Chemotropism, Hydrotropism, Thigmotropism, Traumatropism, Galvanotropism, Electrotropism). The student team will then create an eye-catching infographic that will teach their peers the fundamentals of that plant movement. Students can also use the Science Hub website to find additional resources to support their infographics. After completion, the students will participate in a peer review activity to explain their infographic and elicit feedback from their peers. An example of this peer review activity is called the: High-Low-Buffalo

Activity:

Poster creation and "Elevator Presentations":

Objective: Students will present a 2-minute or less, multimedia (visual, audio, physical) presentation of an assigned trophic or nastic movement to teach fellow peers the characteristics of that movement.

Materials:

- Computer with Internet access
- Chart Paper
- Colored Markers
- Scissors
- Colored construction paper
- Any other common poster making materials

Activity: Divide students in groups of 2-3 depending on your class size. Provide groups with a single sheet of flip chart paper, access to all poster making materials and a computer with Internet access. Assign student groups a single topic to review using this list of plant movements that still needs the link. Students will then create a poster and then a 2-minute or less presentation to teach each other the characteristics of their assigned plant movement.

Virtual option: This lesson can be done using breakout rooms and a collaborative tool such as google slides or Google Draw to create the poster. Limit the student groups to a single slide and the same 60s or less presentation time.

Whole Group - Presentation Protocol: Each group is given the presentation floor to give their presentation.

Peer Review Protocol: At the end of this unit, students will be giving a more in-depth presentation on their investigations of Biomimicry using 4D Printed Shape Memory Polymers (SMP). The goal here would be to model a basic peer-review protocol to get students used to providing feedback and asking relevant STEM questions. An example of a peer review protocol would be "High, Low, Buffalo". To model after a presentation, provide feedback consisting of content presented well in the presentation ("high"), content presented that can be improved ("low"), and something random ("Buffalo") about the multimedia, or delivery of the presentation. After you model, allow the student audience to provide the High Low Buffalo feedback. Ensure that the students are keeping focus on the content delivered for the High and Low and then they can option to provide a Buffalo based on either content, mutimedia, or presentation delivery.

Closing Activity (Exit ticket):

STEM QUESTIONS: At the end of the lesson, students will generate 3 general "request for clarification" questions that they could use to ask peers at the end of presentations. For example, "I like how you… but can you please clarify…?", "If you had more time, what would you add to your presentation?, or "If you could remove one thing from your presentation, what would that be?"

The resulting quesitons will be put into a bank that students can use during the Peer Review protocol for future presentations.

Optional or Supplemental Lesson to understand movement on a plant's time scale: NSTA Plant Movement Lesson Plan

EXPLANATION

Brief Description: This teacher-driven lesson will focus on understanding shape-memory thermoplastic and how 3D printed shapes can be manipulated with precise thermal changes to induce a desired shape-change. Students will apply the 4D print process to mimic various nastic and trophic plant movements.

Procedures:

Lesson Opening: Entrance Quiz on Essential Vocabulary

Presentations of infographics in a small-group setting

Presentation: Recap of Fundamental Plant Movements - by Jayla Wade (Howard University)

Discussion: Shape memory polymer

ELABORATION

Brief Description: This part of the lesson will require several class periods to investigate the efficiency of plant-inspired 3D printed shape memory polymer to transform from deformed to parent. The activities in this stage involve using a hot water bath at about 80C. Therefore it is advisable to ensure that students understand all heat safety precautions. There is a clear and present danger of getting injured with the hot water and heating plates. With the printed structures in their parent state, they will heat their prints for a few seconds and, while heated, re-shape (program) their structures into a temporary shape. Ensure students are mindful that they can use a basic protractor to measure the angle from parent to deform shape and back to parent shape. The goal is to have several 3D printed samples that can be programmed sequentially in this project stage. Precaution: Do not overheat the materials too long. If heated too long, the 3D printed materials will undergo a shape change that will be permanent and will no longer "remember" its original post-3D printed shape.

Optional:

TinkerCAD - Biomimicry Lesson Plan

Safety Precautions:

The following experiments require glassware, hot plates, and heated water baths of 80C and 50C - 75C for thermally manipulating PLA. PLA (polylactic acid) thermoplastic used for this experiment has a lower operating temperature compared to other standard filaments such as PET-G (Polyethylene terephthalate glycol). Therefore it is advisable to use PLA in the classroom setting for 4D printing experimentation.

Extreme heat caution should be considered based on the students' abilities and the layout of the laboratory. For example, if a teacher's class has many students of more than six lab stations, or less depending on the space available, consider performing the experimental procedure as a demonstration.

Milestone 1: Design an Experiment to determine the percent recovery of a shape memory polymer (PLA)

Procedures: Using the Research Design Template, students will design an experiment to determine the percent recovery of a plantoid-inspired 3D printed shape. Students will evaluate a single independent variable to test the shape memory effect of the plantoid form. Some examples include incremental glass temperature changes, parent/deformed shape change ratio, differences in printing settings (infill percentage, number of shells, differences in size-ratio print percentage, or, if available, differences in polymer material. To simplify, guide student groups to focus on incremental temperature changes or parent/deformed shape change ratio.

Milestone 2: Design and Build 3D printed plantoid models.

Procedures: Students will first complete the tutorial (9 mins): TinkerCAD Tutorial for beginners to get a crash course using a simple but powerful 3D modeling software. Students will then design simple, plant-inspired structures based on their understanding of biomimicry as learned in the Exploration Stage. Finally, guide the students to create their structures to follow the shape memory effect based on thermal stimulation at the material's glass transition temperature. When the designs are completed, have the students download the .stl model files into a shared cloud-based drive where you can then use splicer software to prepare the files to be 3D printed. Depending on the students' skill levels, the teacher may continue the printing process or directly supervise students to print the files. Some advice would be to keep the print sizes small, no more than 20mm in any dimension, settings on the printer: 100% infill, 2x shell as a start. The print material should be test printed before ensure correct technical print settings. This youtube channel called CHEP "Filament Fridays" by Chuck Hellebuyck will help you get started.

Milestone 3: Deform plantoid models into deformed-shapes

Procedures: After the students print their plant structures, the next step is to deform them using thermal radiation (heat). This involves using a hot water bath at about 80C. Therefore it is advisable to ensure that students understand all heat safety precautions. There is a clear and present danger of getting injured with the hot water and heating plates. The freshly printed parts are in their parent state. The students will then heat their prints for a few seconds and while heated, re-shape (program) their parts into a temporary shape. Ensure students are mindful that they can use a basic protractor to measure the angle from parent to deform shape and back to parent shape. The goal is to have several 3D printed samples that can be programmed sequentially in this stage of the project. Precaution: Do not overheat the materials too long. If heated too long the 3D printed materials will undergo a shape change that will be permanent and will no longer "remember" its original post-3D printed shape.

Milestone 4: Shape memory recovery experiment

Procedures: With several printed and deformed plant structures in hand, the next part of the experiment is to apply heat to the structures close to the material's glass transition temperature. For PLA, that range is between 55 C and 75C. Student teams will conduct their experiment based on the independent variable they chose to investigate. For example, some groups may vary the temperatures in 5 trials and +5C ranging from 55C to 75C. Other teams may keep a set temperature but perform multiple trials of varied time exposure to heat in increments of 20 seconds. Remind the students that they should not apply any more external pressure to the thermoplastic and allow the structure to return to its parent shape as much as possible without intervention.

Milestone 5: Analysis of shape recovery ratio

Procedures: With several printed and deformed plant structures in hand, the next part of the experiment is to apply heat to the structures close to the material's glass transition temperature. For PLA, that range is between 55 C and 75C. Student teams will conduct their experiment based on the independent variable they chose to investigate. For example, some groups may decide to vary the temperatures in 5 trials and +5C ranging from 55C to 75C. Other teams may keep a set temperature but perform multiple trials of varied-time exposure to heat in increments of 20 seconds. Remind the students that they should not apply any more external pressure to the thermoplastic and allow the structure to return to its parent shape as much as possible without intervention.

EVALUATION

Brief Description: Provide a concise overview of the proposed activity.

Procedures:

The end of this lesson will culminate in a science seminar where students will present infographics of their research using the ADI poster template. The students should provide reasonable responses to the initial research questions:

How and why do plants move?

How can we develop 4D printed thermoplastics to replicate the movement of plants?

What are the possible applications of plantoids and biomimicry?

After the students create their infographics, they will perform a few rounds of the "High-Low-Buffalo" peer review sessions. Finally, they will make final revisions to their poster before final submission. Consider printing the infographics in a large format, 11x17 or larger, to be posted in the classroom.

REFERENCES

- British Plastics Federation. (n.d.). Shape Memory Polymers - A Complete Guide. Retrieved from https://www.bpf.co.uk/plastipedia/applications/shape-memory-polymer.aspx
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- Strgar, J. (2007). Increasing the interest of students in plants. *Journal of Biological Education*, **42**(1), 19– 23. https://doi.org/10.1080/00219266.2007.9656102
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APPENDIX

ADI poster template

CHEP "Filament Fridays"

High-Low-Buffalo

Plants in Motion

Recap of Fundamental Plant Movements - by Jayla Wade (Howard University)

Shape Memory Polymers - A Complete Guide

TinkerCAD Tutorial for beginners

TinkerCAD Biomimicry Lesson Plan

TinkerCAD

PRUSA

Creality Ender 3 3D Printer

3D printer filaments