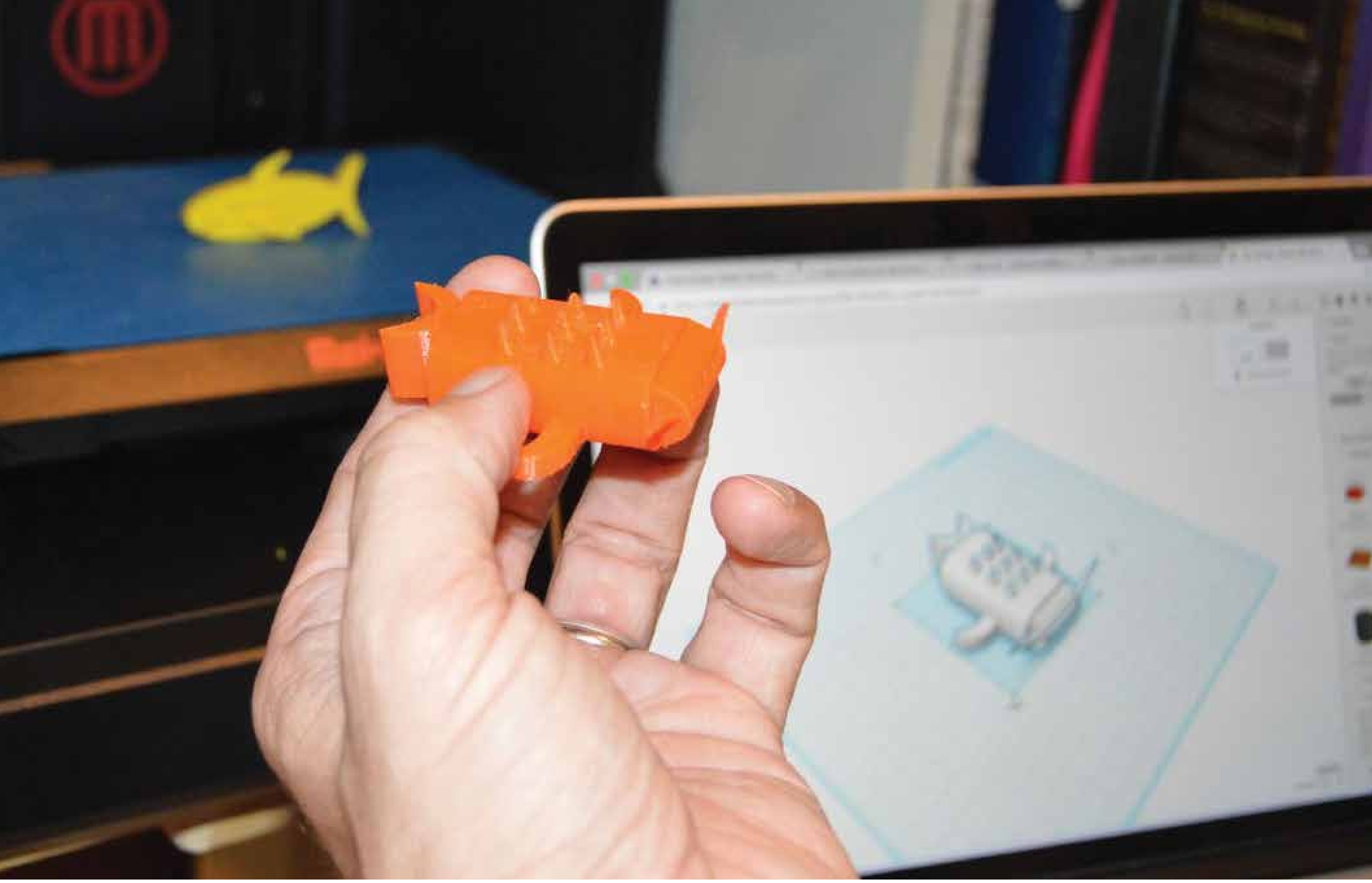


Constructing Arguments With 3-D Printed Models

Fourth-grade students model the external structure and function of bottom-dwelling fish.

By William McConnell and Daniel Dickerson

Finally—it was the day we had all been waiting for. Students rushed in, noticing their colorful 3-D printed fish models from across the room. And it was worth the wait. Within seconds of handling their models, students' excitement bubbled over in the form of scientific explanation and argument.

Cody: What? What's up with your [3-D printed fish model's] giant mouth?

Barry: It's like a dredge. It works like… (uses gestural modeling to simulate the mouth scraping the sea floor).

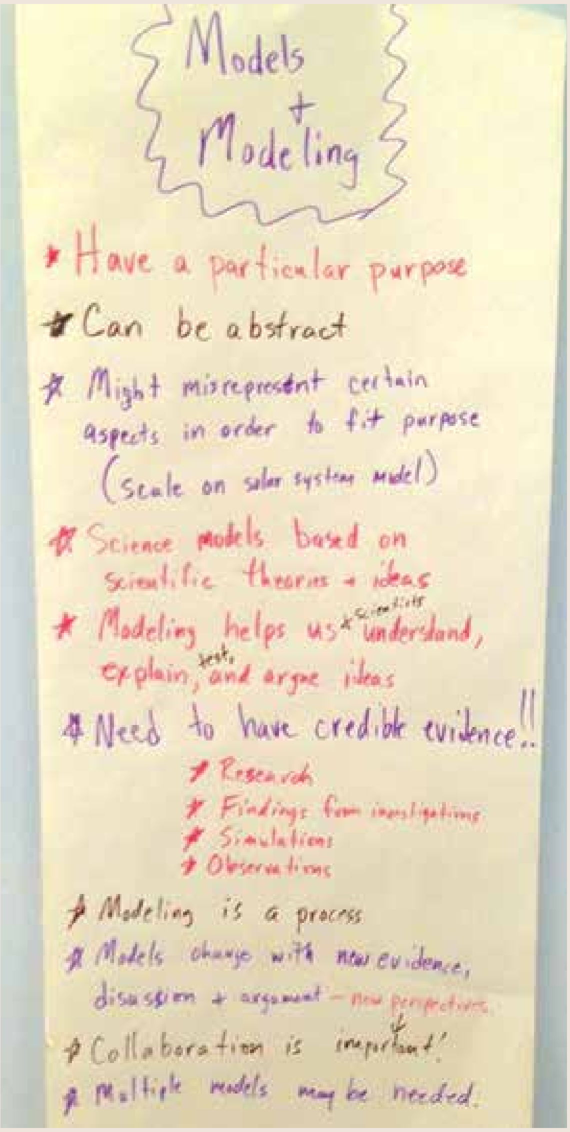
Cody: That's going to eat so much sand!

Barry: Yeah, but the gills will let the sand out (pointing to two holes near the mouth of the model) just like a stingray.

This exchange reveals how students used 3-D printed models to understand, explain, and justify ideas in a way that directly relates to science and engineering practices. Research suggests that student-developed models encourage discussion and a more in-depth learning of science content (Louca and Zacharia 2012). But in each implementation of this lesson, these models surprisingly inspired unprompted and meaningful scientific discourse. In this article, we describe a fourth-grade lesson where 3-D printing technologies were not only a stimulus for engagement but also served as a modeling tool providing meaningful learning opportunities.

FIGURE 1.

Student ideas about modeling.



PHOTOS COURTESY OF THE AUTHORS

Students practiced making justification for claims (above) and incorporated the skill into their design of a fish (below).

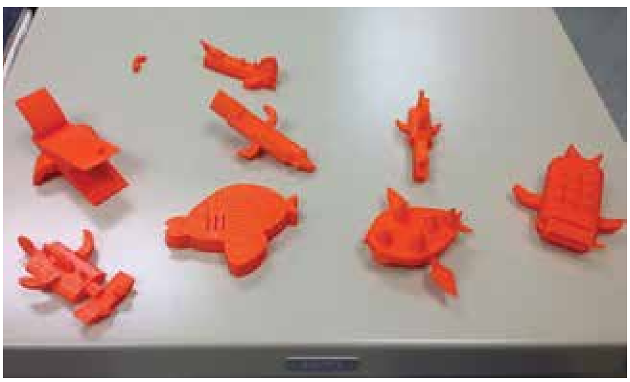
Specifically, fourth-grade students construct an argument that animals' external structures function to support survival in a particular environment (see Connecting to the *Next Generation Science Standards*, p. 37).

This lesson should occur after students gain a basic understanding of adaptations. To develop the lesson, we drew from the designed-based modeling as described by Penner, Lehrer, and Schauble (1998) and Wu's (2010) description of student practices during modeling-based learning. *Design-based modeling* is a form of instruction in which students engage in engineering design process to develop scientific models that assist in scientific argument (Penner, Lehrer, and Schauble 1998).

Discussion of Model Purpose

Young students often mistakenly think that a better scientific model is one that appears identical to its referent. Students must understand the two measures of quality for a scientific model: its fit to the intended purpose of the model and that it embodies attributes of phenomena based on scientific theory (Penner, Lehrer, and Schauble 1998).

To address this issue, we asked students to figure out the purpose of three shark models. This provided opportunities to elicit prior knowledge and allowed us to expose naïve notions of scientific models and modeling. One model was a shark toy with no intended scientific purpose. Most students understood that this model was for entertainment purposes, but we discussed that if one does not understand the purpose of models, one may not understand that this model misrepresents elements of structure and function. Models two (internal diagram of a shark) and three (physical model of a tiger shark jaw) had different purposes, but both allowed us to highlight the crosscutting concept related to structure and function while discussing and listing important points about models and modeling on chart paper (Figure 1).



Students list their models' features, functions, and evidence in a table format. Models are shown below.

Why use 3-D printing technologies to create physical science models?

Teachers' Perspective:

- No need to buy or collect piles of supplies—just print your file!
- Compared to molded clay models or models made from glue, tape, and everyday materials, 3-D printing technologies allow students to develop models that have greater detail and greater durability with less mess. Students can handle and closely examine 3-D printed models without worry of damage.

- Students' unique 3-D printed models represent their scientific understandings at a point in time and can be modified and reprinted with ease. This can provide a physical portfolio of science learning.
- Provides students an opportunity to use cutting-edge technology similar to those in various professional settings

Students' Perspective:

- Most students preferred the design process on Tinkercad better than paper-and-pencil drawings.
- In debriefings with students, we learned that most students felt that 3-D printed models helped them better explain their ideas compared to other forms of models. When speaking of the difference of 2-D and 3-D models, a student stated, "It's easier to support your arguments when you have depth to them."
- Other students expressed that the software program Tinkercad allowed them to, as Cory said, "design it more like what was in my head."
- When students had both their 2-D or 3-D model to assist in explaining their ideas, students overwhelmingly chose their 3-D printed model.

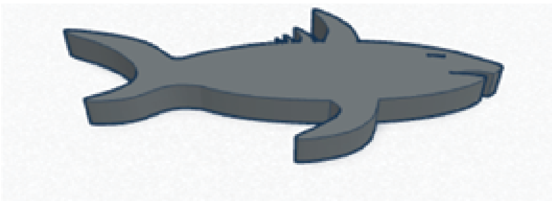
FIGURE 2.

Challenge guide.

Challenge Guide

The fish model below is a representation of a fish living today in the following environment:

- ☐ Clear shallow waters with nearby reef
- ☐ Quick prey that normally travel just above the ocean floor.
- ☐ Quick predators that attack from behind



Fast forward 500,000 years and the environment has gradually changed. The fish lives in an environment with the following characteristics:

- ☐ Murky, shallow water with minimal light and no reef
- ☐ Slow, armored prey living just beneath the sand on the ocean floor.
- ☐ Slow predators that attack from above.

Your challenge is to design a new fish model with external structures common in the type of environment described above. The model's purpose is to assist you in explaining how particular external structures function in order to help the organism to survive in this environment. Below are your tasks:

Iteration 1

1. Each person in your group brainstorms ideas and draws a diagram (paper and pencil) of the model.
2. Discuss your models with your small group.

Design Challenge

After displaying the chart about models and modeling, students received a Challenge Guide (Figure 2; see *www.nsta.org/SC1701* for a copy). We read the design challenge aloud to students and discussed the purpose of designing this model: to assist in the explanation of how certain external structures would function in the given environment.

First Modeling Iteration

We planned the first iteration of student modeling primarily to elicit students' prior knowledge and experiences of common structures of benthic (bottom dwelling) fish. All students began the challenge by constructing a diagrammatic model of a fish, highlighting its external structures (Figure 3). After five minutes of drawing, students evaluated their own and others' diagrammatic models through discussion within small groups. During this discussion, teachers circulated from group to group listening and taking notes on students' dialogue. This allowed us to formatively assess students' models and argumentation skills. In a prior lesson, the classroom teacher had explained elements of scientific argumentation, but this lesson was the first time students took part in the process. The discussion excerpt below reveals how students challenged others' ideas during discussion, but it also illustrates how their arguments consisted of little or no credible evidence or justification.

Molly: I made mine with flat teeth to crush armor. It also has compound eyes to see all around it.

Chris: Wouldn't sharp teeth work better on armor?

Molly: No, the flat ones crush it better. Sharp teeth are smaller and might break.

After 10 minutes of small-group discussion, we addressed the class with questions: "Without naming a person or a model, were you completely satisfied with every idea that was presented during group discussion?" Students overwhelming said "No." We then asked, "What would help you become more satisfied?" With our guidance, students' concluded that, like scientists, they must produce evidence to support their explanations.

Second Modeling Iteration

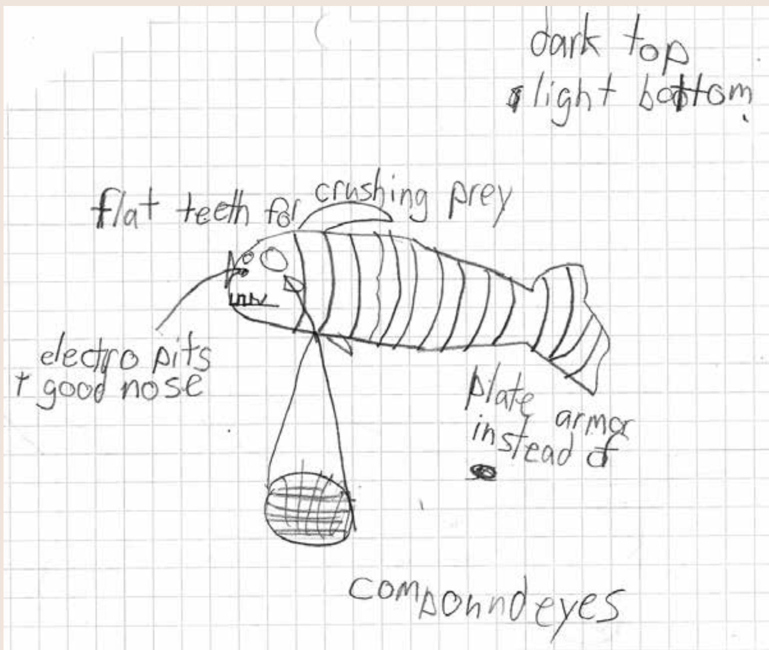
First, students were grouped into heterogeneous small groups of three to four to encourage collaboration among diverse learners and to highlight the benefit of multiple perspectives during the modeling process. Through a search of images on the internet, we prepared a set of 10 photographs of benthic and pelagic fish and put them into small bags for each group (see Internet Resources). The small groups used these photographs to categorize fish into benthic or pelagic (open sea) categories through a card sorting activity and discussed their reasoning. After 10 minutes, volunteers from each group sorted the fish using an interactive whiteboard to compare answers and discuss reasoning as a class. Students then circled and discussed common structural components within each category on the interactive whiteboard. Common structures of benthic fish that students noticed included barbels, flattened bodies, camouflage, and asymmetrical eye placement.

For students to better understand functions of these and other external structures, they needed to observe benthic fish in action. Through the use of two short video clips (see Internet Resources), students observed several fish in different environments to examine common functional differences between pelagic and benthic fishes' external structures (e.g., streamlined vs. flattened bodies). Students listed functions they observed, and we discussed their findings as a class. Through this discussion and the formative assessment of their written lists, we noted that students did not understand how fish obtained prey without ingesting sand. This prompted an investigation of mouth structure.

When students arrived the next day, a simulation was ready for them. Each small group had a bin full of rice (representing a sandy ocean bottom) with 20 black beans (prey) scattered about 2.5 cm (1 in.) under the surface of the rice plus a funnel, stopwatch, and graduated cylinder. Each group also had different kitchen utensils (i.e., ladle, slotted spoon, spoon, slotted spatula, oven mitt, slotted tongs, turkey baster) to represent mouth structure that they used to obtain as many prey as possible in 30 seconds to place into a cup (stomach). Students measured and recorded how many beans they obtained in 30 seconds and how many milliliters of rice ended up in the cup. After each trial, one student from each group also recorded data in an Excel spreadsheet on the classroom computer that was presented on the screen for all to see. This helped us to see the progress of each

FIGURE 3.

Student's diagrammatic model.



Tinkercad With Fourth Graders

In order for students in fourth grade to register for Tinkercad, parent permission is required. We asked parents to register their children at home and send in their child's username and password. Although this program is extremely intuitive and user-friendly compared to most CAD programs, our students had prior experience with the program before this lesson. Several weeks before the lesson, we had students become familiar with the program through our demonstrations, Tinkercad tutorials, and free play. It is very important that students understand how to manipulate common objects and visualizations within the program, but you may be amazed at how quickly they learn.

group. After groups recorded data for four trials, a preloaded formula in a cell displayed the average prey gathered and the average amount of sand in the stomach for each utensil. Because students had not formally learned how to divide or calculate averages at this point, one teacher led students in using a calculator to find averages. This provided students an understanding of the computation process behind the averages displayed on the screen.

To help students understand how scientists sometimes use technology to assist in the display of data, we showed students how easy it was to create a graph in Excel by pushing one button to display a graph of the data. The data allowed students to understand ways that the kitchen utensils could capture beans without sand, but their connections to real fish structures were limited. For example, most students' statements were like Jill's: "The tongs with the holes in them got a lot of beans but not that much sand." To explicitly connect this simulation to fish structures, we replayed one of the short videos. Students noticed several similarities between the utensils and mouth structure. For example, Cory stated, "The stingray is like the tongs because it shoots sand through his gills. The tongs let the sand out, too."

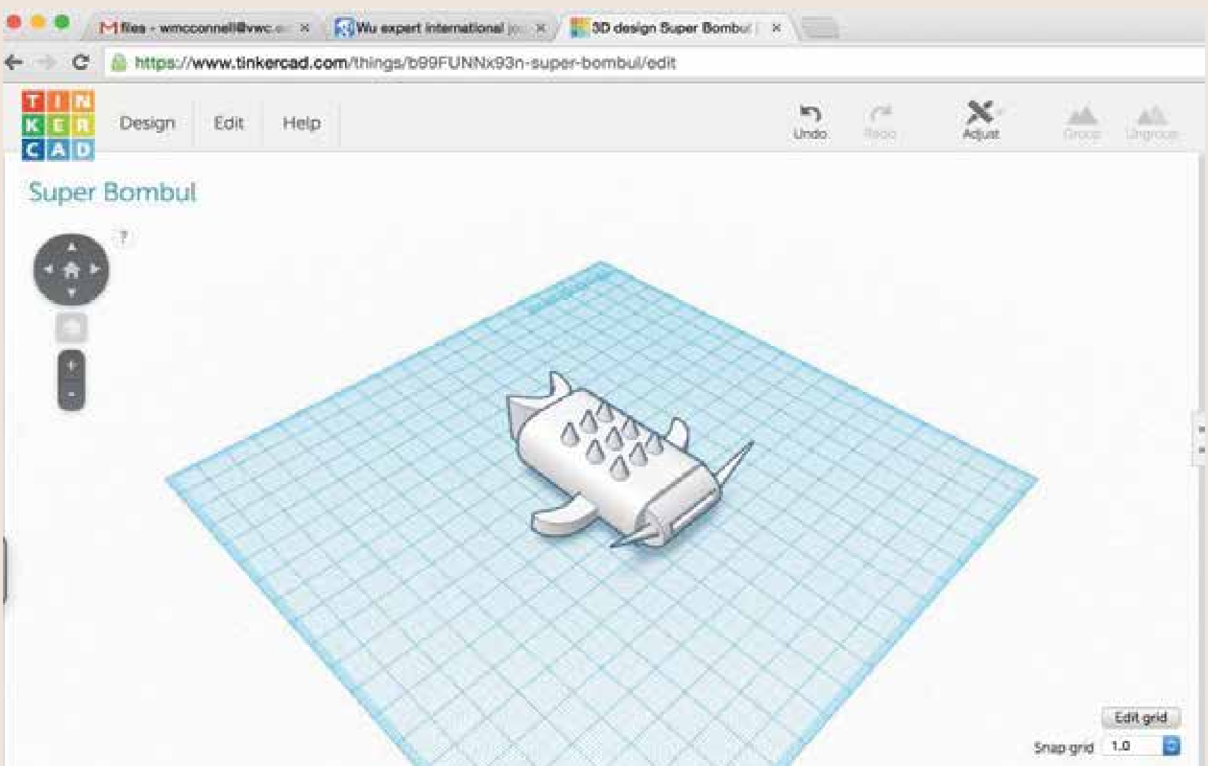
Constructing Models

With students' newfound knowledge of benthic organisms, it was time to develop a revised model. To begin, like in the first iteration, students developed new or revised diagrams and discussed them within their groups. This time, though, we required each group to reach a consensus on at least three structures and related functions to include in one 3-D printed consensus model. After reaching a consensus, students had 45 minutes to use Tinkercad (see sidebar), a free computer-aided design (CAD) program, to develop a virtual 3-D model (Figure 4). Having students create a unique 3-D model challenges them to address aspects of form and function commonly ignored when creating paper-and-pencil diagrams. Students are forced to navigate spatial challenges, such as depth and symmetry, in a new way. The sidebar, "Why use 3-D printing technologies" (p. 31) details some of the benefits teachers and students noted regarding the use of 3-D printing technologies for modeling purposes.

Students paired up onto laptops to design their fish model, and we had them alternate from "driver" (one who controlled the computer) to "passenger" (one who

FIGURE 4.

Tinkercad model.



observed and provided design suggestions) every five minutes. We encouraged discussion during this time so that students could use their peers to help them navigate more difficult spatial challenges. Creating small details, rotating shapes to the perfect angle, and aligning pelvic fins were common design elements that were relatively difficult for some students. When construction time expired, there were two virtual 3-D models for each group, but due to the time needed to print each model (approximately 40 minutes), we decided to only print one model per group. Again, students had to discuss each model within their groups and choose the one that best fit its purpose. In a class of 28, that meant we had seven prints to make.

It is best to end this part of the lesson on a Friday to allow plenty of time to print students' models, which usually takes about 40 minutes per design on a Makerbot Desktop 3-D printer. If you do not have access to a printer, check your local library, or find a local printer through the website *www.makexyz.com*. The prints we made for one class would have cost less than $12 at the local library.

Model Use

The models help students explain their understandings of form and function and how they relate to an organism's environment. For this reason, use of the model is threaded throughout the modeling process, but usage becomes more explicit as students begin to formally develop evidence-based explanations. While we were downloading their design files for printing, students worked as a team to fill out a table in order to better explain features on their model. We then circulated to each group and asked questions about groups' models, prompting them to provide stronger evidence for their explanations. Below is an example of dialogue during this time.

Teacher: Where in the natural world have you seen that type of external structure (barbel) before?

Logan: Well, a catfish has these whisker things to help it find food.

Teacher: Barbels? Do you know of any other animals that have something like it… maybe in a similar environment?

Logan: On the cards the sturgeon had a few of them, and there was another fish that had it too in the movie.

Teacher: Would it make your argument stronger to produce pictures and the names of these animals?

Logan: Oh, yeah.

Model Evaluation

On day three, model evaluation occurs within seconds of students seeing their models. Students inquire, make claims, critique, and justify all on their own. For that reason, we prepared the classroom for discussion before they entered. We numbered and positioned the 3-D printed models around the room underneath each groups' completed explanatory table. Class began with a gallery walk in which groups rotated to each model and were told to write questions, list plausible external structures and ways that they would assist in survival, and list problematic structures and reasons that they would not assist in survival. This was followed by a structured discussion where students sat in a circle surrounding a desk holding all printed models. Each group took turns presenting their model and then fielded questions and comments about their model. This time, students were allowed to use the model to assist in discussion. It was common for students to explain aspects of the model by pointing to its features or even making the model "swim" to better explain functions of certain structures, as in the passage below.

Group 1- Chris: We have this lure that makes light so it will attract prey, and then the mouth is on the bottom so that it can get its [prey] easily. It [the jaw or mouth] is strong and will crush the armor.

Group 3- Jill: (Raised hand) I understand that it will attract prey, but won't it attract predators too?

Group 1- Chris: Well…it is like the Anglerfish.

Group 1- Jacob: It might, but the spines on its back will poison the predator if it touches it.

Group 4- Cheryl: If the prey are under the sand, how will they see the light? And, doesn't an anglerfish live in deep water? Fish don't use light like that in shallow water.

Group 1- Chris: I am not sure. I think they do.

Teacher: How could you find out, Chris?

Group 1- Chris: Um…I guess, find fish that live in shallow water with a lure?

Explanations were not perfect by any stretch, but they were much stronger than students' initial ideas. In all cases, groups provided evidence and justification for their models' external structures, but through scientific argument they began to understand that more thought and evidence was needed to make their claims stronger.

Revising the Models

After the structured discussion, we led a short debriefing session to address the modeling process. In all iterations of this lesson, the majority of students wanted to continue the modeling process to present a more plausible model to their classmates, no matter how well their group fared during discussion. Students understood that each 3-D printed model represented their understandings at a particular point in time and that their models should change with new evidence. This led us to return to the chart from the beginning of the lesson and add that models change with discussion and new evidence. Although time did not allow for another model revision during class, many groups went back to revise their model at home using Tinkercad, reiterating their desire to revise their model.

Assessment

Self, peer, and teachers' formative assessments of students' models were threaded throughout this lesson as crucial elements of science and engineering practices. These assessments provided purpose for student learning and informed the facilitation of learning experiences. As a summative assessment, we had students use their model to provide a written claim and justification of one aspect of form and function of benthic fishes. On the same paper, students described practices of scientific modeling.

Conclusion

This lesson inspires students to become passionate about the process of science. Like Krajcik and Merritt (2012), we often "imagine the type of student who emerges from twelfth-grade science education after repeatedly experiencing instruction since elementary school that supported them in constructing and revising models to explain phenomena!" With user-friendly 3-D printing technologies providing an easier way for young students to construct and modify current science conceptions in physical form, perhaps we will not have to imagine much longer. ■

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Internet Resources

Sites to find pictures of fish:
www.nmfs.noaa.gov/gallery/images
http://animals.nationalgeographic.com/animals/fish

Videos of benthic fish
www.youtube.com/watch?v=w1MAGs4RDD0
www.youtube.com/watch?v=8DqglF2ACQ0
www.youtube.com/watch?v=JvHiZa3ZPxM

Free Computer Aided Design Software
www.tinkercad.com

Find 3D printers nearby
www.makexyz.com

Tinkercad
https://projectignite.autodesk.com

Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013):

4-LS1 From Molecules to Organisms: Structures and Processes

www.nextgenscience.org/dci-arrangement/4-ls1-molecules-organisms-structures-and-processes

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 materials, lessons, and activities outlined in the article are just one step toward reaching the performance expectation listed below.

Performance Expectation	**Connections to Classroom Activity** *Students:*
4-LS1-1. Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction.	• design, construct, and use multiple models to assist in scientific argument regarding fishes' external structures and how their functions support their survival in a particular environment.
Science and Engineering Practices	
Developing and Using Models	• develop and construct evidence-based explanations and argument with evidence, data, and multiple fish models regarding functions of specific external structures in particular environments.
Constructing Explanations and Designing Solutions	• generate and compare multiple solutions (fish models) to a design challenge based on how well the fish model fits the purpose.
Disciplinary Core Ideas	
LS1.A: Structure and Function • Plants and animals have both internal and external structures that serve various functions in growth, survival, behavior, and reproduction.	• observe and investigate external structures of benthic organisms to identify patterns and possible functions related to survival in the particular environment.
ETS1.B: Developing Possible Solutions • Designs can be conveyed through sketches, drawings, or physical models. These representations are useful in communicating ideas for a solution to other people.	• participate in a gallery walk of products, questions, and comments concerning features of each model that represent knowledge of the adaptations.
Crosscutting Concept	
Structure and Function	• model complex structures to illustrate how their function depends on the relationships among its parts and the environment in which it lives.

Connecting to the *Common Core State Standards* (NGAC and CCSSO 2010):

W.4.1: Write opinion pieces on topics or texts, supporting a point of view with reasons and information.

SL.4.5: Add audio recordings and visual displays to enhance the development of main ideas or themes.

- Write explanations of external fish structures and their related functions backed by evidence.
- Develop and display fish models to enhance development of explanations and argument.