Foundations Paper

How the Twig Science Core Curriculum Aligns with the Four Cs of STEM

The Four Cs of STEM and Twig Science

STEM (science, technology, engineering, and math) education is critical for preparing students for the workforce. The U.S. Department of Education has unequivocally declared that all students "belong in STEM and that they deserve to have rigorous and relevant educational experiences that inspire and empower them to reach their full potential as productive, contributing members of our nation's workforce" (U.S. Department of Education, YOU Belong in STEM, 2023).

Workforce skills have changed dramatically in the 21st century. Jobs with more "routine" work have decreased and have been replaced by jobs that require adaptability for nonroutine work and analytic, interactive communication skills (National Education Association, n.d.). To prepare for college and careers, students in Grades K–12 need to acquire skills aligned with the realities of today's work environments. In response to changes in demand for skilled labor, the National Education Association (n.d.) identified the Four Cs of STEM as essential for all students to acquire. Specifically, the Four Cs are: critical thinking, communication, collaboration, and creativity (defined in Table 1).

The Four Cs are part of a broader range of skills defined by contemporary literature as 21st-century skills. Enhancing the quality of STEM education is important for supporting all students in acquiring skills needed to obtain jobs in the current environment. The Four Cs of STEM are vital for success after high school, regardless of whether students choose college, careers in STEM, or careers in non-STEM fields such as education, hospitality, or transportation.

TABLE 1: FOUR Cs OF STEM

Four Cs	*Definition*	*Importance*
Critical Thinking	Critical thinking is the ability to reason effectively, use systems thinking, make judgments and decisions, and solve problems.	Learning requires critical thinking. Critical thinking leads students to develop other skills, such as improved thought processing and higher levels of concentration.
Communication	Communication is the ability to articulate thoughts, listen and extract meaning, and interact in diverse environments.	Students must be able to clearly communicate and effectively analyze and process various forms of communication for success in school and careers.
Collaboration	Collaboration is the ability to work effectively with others to achieve common goals.	Considering the complexity of issues and challenges companies, institutions, and governments face, collaboration with diverse individuals is critical for identifying relevant solutions and making informed decisions.
Creativity	Creativity is the ability to explore and analyze a wide range of ideas and perspectives, generate original and inventive solutions, view failure as an opportunity to learn, and turn ideas into tangible solutions.	The rapid pace of change in the 21st century requires adaptation and continual innovation. Students will need to know how to create and innovate to successfully address workforce and social challenges.

The purpose of this paper is to explore how 21st-century skills are integral to STEM education and to describe research recommendations for fostering the development of these 21st-century skills in STEM education.

The Research

As previously discussed, STEM refers to science, technology, engineering, and mathematics. In the process of learning STEM subject-matter content, students develop computational and critical thinking, including skills such as problem solving and creative thinking. STEM disciplines also require strong collaboration and communication, which foster persistence and the development of confidence as students engage with others in solving scientific, technological, and mathematical problems (Bottoms & Sundell, 2016; Burbaite et al., 2018). For this paper, we focus specifically on science.

Science

Science is knowledge, or a system of knowledge, concerned with the physical world and its phenomena, covering the operation of general laws as obtained and tested through the scientific method. Therefore, science cannot be defined outside of scientific inquiry. The study of science naturally supports the development of critical thinking. Science education fosters the development of critical thinking through scientific reasoning (Friedler et al., 1990), formal reasoning (Lawson, 1985), and the identification of logical fallacies (Dreyfus & Jungwirth, 1980). However, critical thinking is more than a range of behaviors or activities, such as problem solving or inquiry activities. Critical thinking requires not only following specific scientific procedures, but doing so while evaluating evidence, questioning emerging results, and drawing conclusions using one's scientific knowledge (Bailin, 2002; Facione, 1990). Thus, scientific thinking processes and scientific knowledge are both integral parts of critical thinking.

Collaboration is also an essential part of scientific work and has increasingly become so in the last century (Subramanyam, 1983; Lu & Zhang, 2009). Scientific work includes scientific reviews and collaboration on scientific projects and research. Feedback associated with scientific reviews is essential for refining scientific theories and improving and validating scientific work. Some research indicates that collaborative science interactions in schools can improve attitudes toward science and decrease anxiety (Hong, 2010). Collaboration in science education can be achieved as students work with peers to complete science projects and assignments, engage in purposeful classroom and/or online discussions, and share research in science fairs and competitions at the classroom, school, and/or regional level.

Scientific discourse and communication skills are essential to applying these teaching strategies. Scientific discourse and communication skills in the classroom "hold the key to how students frame their positions, build a case for argument, [and] become aware of fallacious reasoning" (Zeidler, 2003). Thus, fostering communication skills occurs naturally in science education, as the curriculum includes richness in both content and scientific literacy. As Duschl and Osborne (2002) state, "developing an understanding of science and appropriating the syntactic, semantic, and pragmatic components of its language requires students to engage in practicing and using its discourse in a range of structured activities" (p. 40).

Finally, science fosters creativity (Curriculum Development Council, 2017). McCormack and Yager (1989) proposed a science education taxonomy comprising imagination and invention. Creativity is fostered through both experience and existing knowledge. Scientific knowledge supports creativity through visualization, the multiple interactions between objects or physical observation and ideas, the exploration of diverse uses of objects for alternative solutions, the suggestions of reasonable explanations for observable phenomena, the design of tests to validate explanations, and the communication of new evidence (Yager, 2005). According to Cheng (2011), students need to observe, classify, ask questions, form scientific hypotheses, plan tests, apply measurement methods, and analyze empirical data to develop scientific reasoning. Imagine Learning offers both core and supplemental science programs that align with the Next Generation Science Standards (NGSS) for instruction and emphasize the Four Cs of STEM through inquiry and project-based learning activities and assignments.

Twig Science Description

Twig Science is a comprehensive science core curriculum for Grades Pre-K–8 that fully addresses the NGSS. The program employs a blended learning design centered on "phenomenon-based" instruction. Through this approach, students engage in inquiry- and problem-based activities in service of examining specific real-world science phenomena. This design puts student ideas and student sensemaking at the center of all instructional activities, with students exploring phenomena through hands-on learning experiences and peer-to-peer interactions. Students acquire scientific thinking skills as they engage in scientific practices.

Within the program, each curricular unit orients around anchor phenomena and investigative problems, which in turn act as the launch points in examining content that spans three dimensions of science learning—ensuring all students have an interwoven understanding of science and engineering practices (SEPs), disciplinary core ideas (DCIs), and crosscutting concepts (CCCs).

Twig Science includes performance-based and three-dimensional assessments—measuring student performance across science and engineering. Together, these program components represent a robust program that stimulates students' interest in learning science, engages them in scientific practices, and prepares them for college, careers, and making contributions to society.

Critical Thinking

The use of scientific thinking helps people make sense of the world (Larm & Jaros, 2017). "Specifically, scientific thinking focuses on finding the best rational explanation of a phenomenon among different possible explanatory proposals" (Garcia-Carmona, 2023, p. 10). Skills associated with scientific thinking include managing scientific knowledge related to specific inquiries, formulating questions and hypotheses, obtaining data and evidence, and elaborating explanations from evidence (Garcia-Carmona, 2023). Critical thinking is the ability to choose the most defensible idea or position among others that might also be defensible. Critical thinking integrated with scientific thinking involves evaluating evidence and assessing the reliability of data and information, interpreting data and making inferences, constructing arguments from evidence, communicating ideas and opinions in understandable ways, and understanding the strengths and limitations of one's own thinking and the ideas of others (Garcia-Carmona, 2023).

Anchor Phenomenon—Elementary

In Twig Science Elementary, each unit of instruction, or module, is centered around an Anchor Phenomenon that aligns to specific NGSS performance expectations. Through smaller units of instruction, called Driving Questions, students make sense of the Anchor Phenomenon by exploring Investigative Phenomena and by taking on Engineering Design Challenges. Through these inquiry-based investigations, students use the DCIs, SEPs, and CCCs to build scientific knowledge and ultimately explain the Anchor Phenomenon.

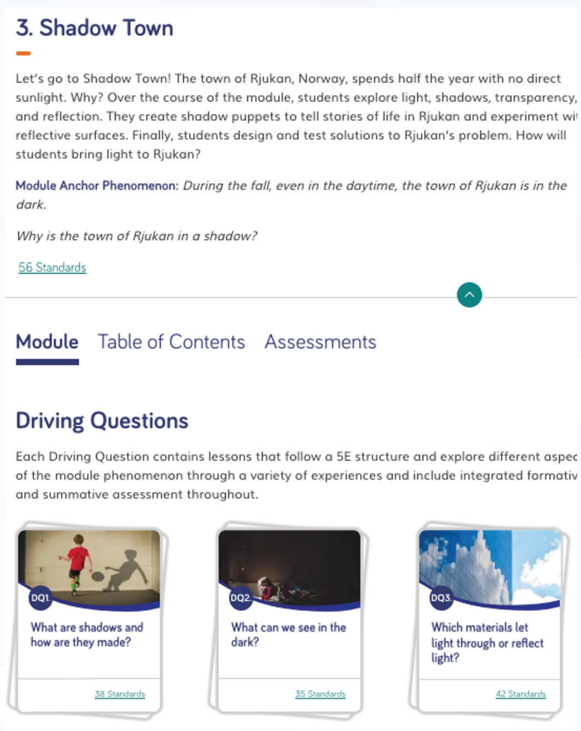
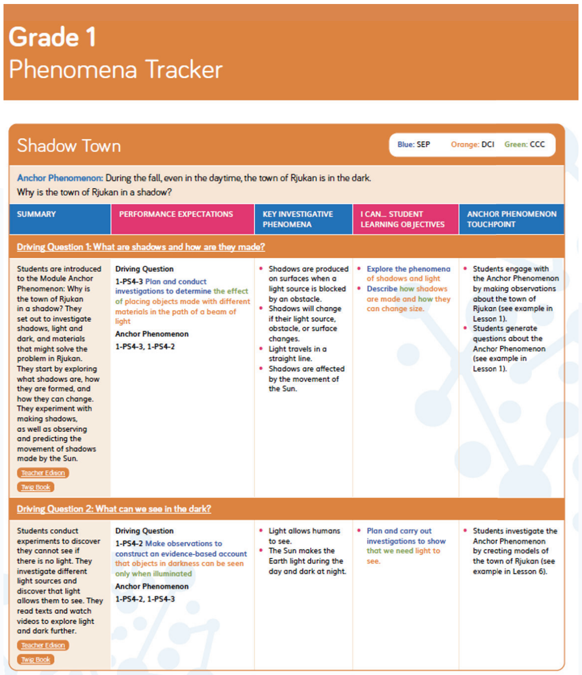


Figure 1. Grade 1, Module 3, Shadow Town introduction and Driving Questions (teacher digital experience).

For example, in Grade 1, Module 3, Shadow Town, students take on the role of STEM detectives to explain why the town of Rjukan, Norway, remains in darkness half of the year, even during daytime.

When students first engage with the Anchor Phenomenon at the start of a module, they work as a class to generate and record the questions they want to investigate to make sense of the Anchor Phenomenon. Students return to their questions at regular touchpoints in the module as they use their learning to construct their own explanations of the phenomenon.

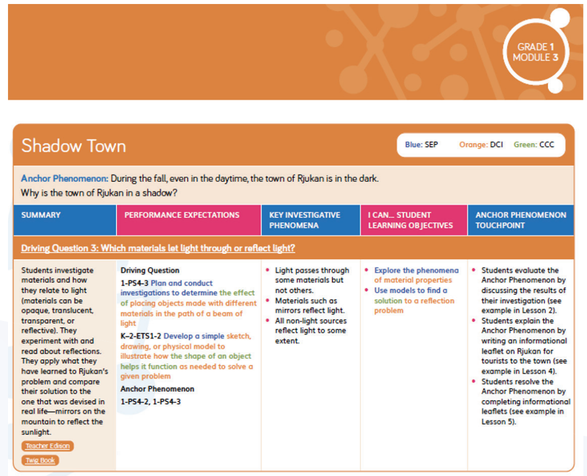


Grade 1
Phenomena Tracker

Shadow Town — Blue: SEP Orange: DCI Green: CCC

Anchor Phenomenon: During the fall, even in the daytime, the town of Rjukan is in the dark.
Why is the town of Rjukan in a shadow?

SUMMARY	PERFORMANCE EXPECTATIONS	KEY INVESTIGATIVE PHENOMENA	I CAN… STUDENT LEARNING OBJECTIVES	ANCHOR PHENOMENON TOUCHPOINT
Driving Question 1: What are shadows and how are they made?				
Students are introduced to the Module Anchor Phenomenon: Why is the town of Rjukan in a shadow? They set out to investigate shadows, light and dark, and materials that might solve the problem in Rjukan. They start by exploring what shadows are, how they are formed, and how they can change. They experiment with making shadows, as well as observing and predicting the movement of shadows made by the Sun. Teacher Edition Twig Book	**Driving Question** 1-PS4-3 Plan and conduct investigations to determine the effect of placing objects made with different materials in the path of a beam of light **Anchor Phenomenon** 1-PS4-3, 1-PS4-2	• Shadows are produced on surfaces when a light source is blocked by an obstacle. • Shadows will change if their light source, obstacle, or surface changes. • Light travels in a straight line. • Shadows are affected by the movement of the Sun.	• Explore the phenomena of shadows and light • Describe how shadows are made and how they can change size.	• Students engage with the Anchor Phenomenon by making observations about the town of Rjukan (see example in Lesson 1). • Students generate questions about the Anchor Phenomenon (see example in Lesson 1).
Driving Question 2: What can we see in the dark?				
Students conduct experiments to discover they cannot see if there is no light. They investigate different light sources and discover that light allows them to see. They read texts and watch videos to explore light and dark further. Teacher Edition Twig Book	**Driving Question** 1-PS4-2 Make observations to construct an evidence-based account that objects in darkness can be seen only when illuminated **Anchor Phenomenon** 1-PS4-2, 1-PS4-3	• Light allows humans to see. • The Sun makes the Earth light during the day and dark at night.	• Plan and carry out investigations to show that we need light to see.	• Students investigate the Anchor Phenomenon by creating models of the town of Rjukan (see example in Lesson 6).



GRADE 1 MODULE 3

Shadow Town — Blue: SEP Orange: DCI Green: CCC

Anchor Phenomenon: During the fall, even in the daytime, the town of Rjukan is in the dark.
Why is the town of Rjukan in a shadow?

SUMMARY	PERFORMANCE EXPECTATIONS	KEY INVESTIGATIVE PHENOMENA	I CAN… STUDENT LEARNING OBJECTIVES	ANCHOR PHENOMENON TOUCHPOINT
Driving Question 3: Which materials let light through or reflect light?				
Students investigate materials and how they relate to light (materials can be opaque, translucent, transparent, or reflective). They experiment with and read about reflections. They apply what they have learned to Rjukan's problem and compare their solution to the one that was devised in real life—mirrors on the mountain to reflect the sunlight. Teacher Edition Twig Book	**Driving Question** 1-PS4-3 Plan and conduct investigations to determine the effect of placing objects made with different materials in the path of a beam of light K–2-ETS1-2 Develop a simple sketch, drawing, or physical model to illustrate how the shape of an object helps it function as needed to solve a given problem **Anchor Phenomenon** 1-PS4-2, 1-PS4-3	• Light passes through some materials but not others. • Materials such as mirrors reflect light. • All non-light sources reflect light to some extent.	• Explore the phenomena of material properties • Use models to find a solution to a reflection problem	• Students evaluate the Anchor Phenomenon by discussing the results of their investigation (see example in Lesson 2). • Students explain the Anchor Phenomenon by writing an informational leaflet on Rjukan for tourists to the town (see example in Lesson 4). • Students resolve the Anchor Phenomenon by completing informational leaflets (see example in Lesson 5).

Figure 2. Grade 1, Module 3, Shadow Town Phenomena Tracker (teacher digital experience).

The Grade 1, Module 3, Shadow Town Phenomena Tracker provides an overview of the key Anchor Phenomenon touchpoints and summarizes how students should progress through the module: making observations and predictions; gathering evidence; using models to explain the Anchor Phenomenon; and finally proposing a solution to Rjukan's problem.

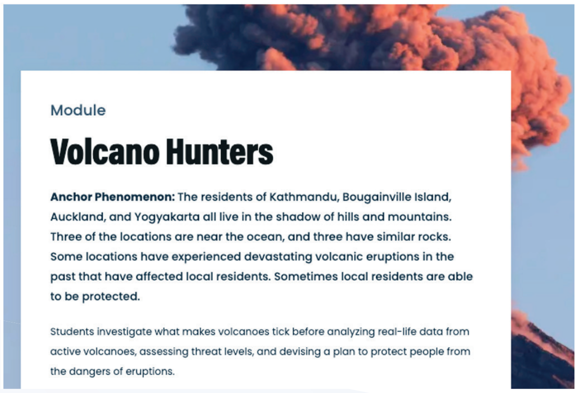
Anchor Phenomenon and Engineering Design Challenge —Middle School

In Twig Science Middle School, each unit of instruction, or module, is centered around an Anchor Phenomenon or Engineering Design Challenge that aligns to specific NGSS performance expectations. Through smaller units of instruction, called lessons, students make sense of the Anchor Phenomenon or solve the Engineering Design Challenge by exploring Investigative Phenomena or Investigative Problems. Through these inquiry-based investigations, students use the DCIs, SEPs, and CCCs to build scientific knowledge and ultimately explain the Anchor Phenomenon or solve the Engineering Design Challenge.

For example, in the module Volcano Hunters, students join a team of volcanologists to figure out why some mountainous areas have volcanoes and others do not by analyzing real-life data from active volcanoes, assessing threat levels, and devising a plan to protect people from the dangers of eruptions.

At the start of each module, students engage with the Anchor Phenomenon or Engineering Design Challenge and generate Wonder Questions using the Co-Craft Questions language routine. Lessons focus on using student questions to drive instruction and support sensemaking as they complete investigations to generate, refine, organize, prioritize, and answer their questions.

Students visualize their developing understanding of phenomena and design challenges using a tool called the Phenomena Tracker or Engineering Design Tracker. At multiple points during a lesson, students use the tracker to document the evidence they gathered and explain what they figured out, including how they used SEPs and CCCs. The trackers help students craft their explanation of the Anchor Phenomenon or their solution to the Engineering Design Challenge.



Module

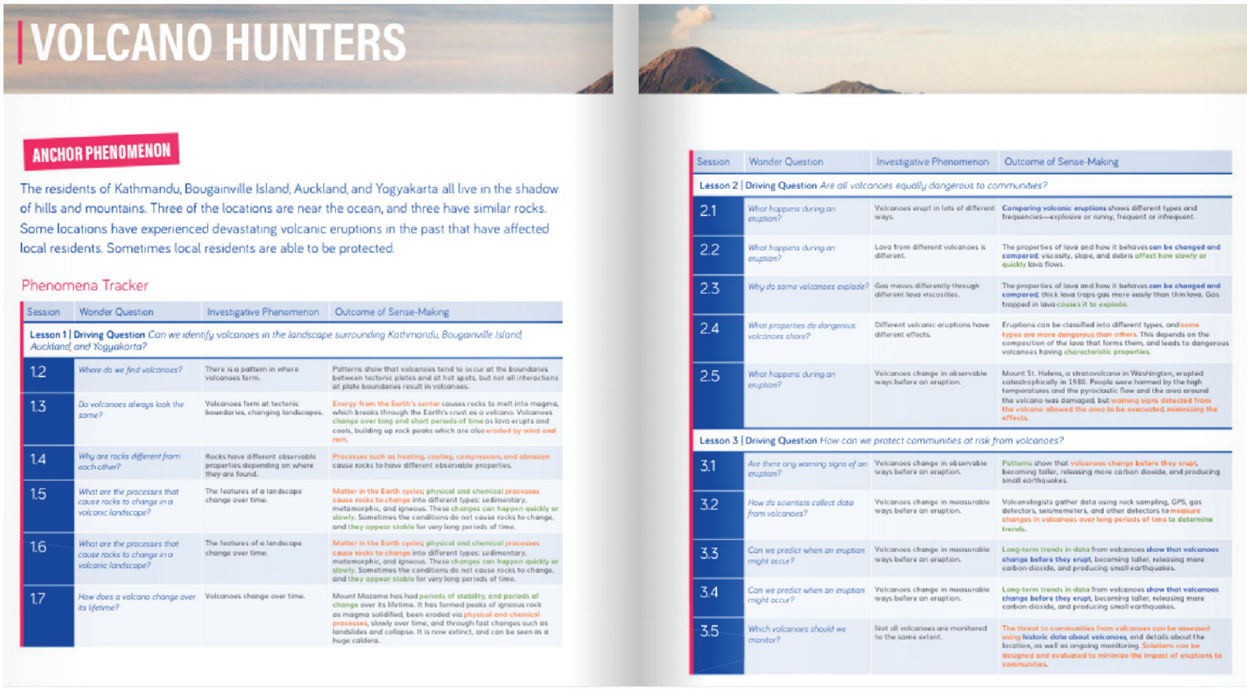
Volcano Hunters

Anchor Phenomenon: The residents of Kathmandu, Bougainville Island, Auckland, and Yogyakarta all live in the shadow of hills and mountains. Three of the locations are near the ocean, and three have similar rocks. Some locations have experienced devastating volcanic eruptions in the past that have affected local residents. Sometimes local residents are able to be protected.

Students investigate what makes volcanoes tick before analyzing real-life data from active volcanoes, assessing threat levels, and devising a plan to protect people from the dangers of eruptions.

Figure 3. Volcano Hunters module introduction (teacher digital experience).

The teacher support for the Volcano Hunters Phenomena Tracker summarizes how students should progress through the module, including the expected outcomes of their sensemaking.



VOLCANO HUNTERS

ANCHOR PHENOMENON

The residents of Kathmandu, Bougainville Island, Auckland, and Yogyakarta all live in the shadow of hills and mountains. Three of the locations are near the ocean, and three have similar rocks. Some locations have experienced devastating volcanic eruptions in the past that have affected local residents. Sometimes local residents are able to be protected.

Phenomena Tracker

Session	Wonder Question	Investigative Phenomenon	Outcome of Sense-Making
Lesson 1 | Driving Question *Can we identify volcanoes in the landscape surrounding Kathmandu, Bougainville Island, Auckland, and Yogyakarta?*			
1.2	*Where do we find volcanoes?*	There is a pattern in where volcanoes form.	Patterns show that volcanoes tend to occur at the boundaries between tectonic plates and at hot spots, but not all interactions at plate boundaries result in volcanoes.
1.3	*Do volcanoes always look the same?*	Volcanoes form at tectonic boundaries, changing landscapes.	Energy from the Earth's center causes rocks to melt into magma, which breaks through the Earth's crust as a volcano. Volcanoes change over long and short periods of time as lava erupts and cools, building up rock peaks which are also eroded by wind and rain.
1.4	*Why are rocks different from each other?*	Rocks have different observable properties depending on where they are found.	Processes such as heating, cooling, compression, and abrasion cause rocks to have different observable properties.
1.5	*What are the processes that cause rocks to change in a volcanic landscape?*	The features of a landscape change over time.	Matter in the Earth cycles; physical and chemical processes cause rocks to change into different types: sedimentary, metamorphic, and igneous. These changes can happen quickly or slowly. Sometimes the conditions do not cause rocks to change, and they appear stable for very long periods of time.
1.6	*What are the processes that cause rocks to change in a volcanic landscape?*	The features of a landscape change over time.	Matter in the Earth cycles; physical and chemical processes cause rocks to change into different types: sedimentary, metamorphic, and igneous. These changes can happen quickly or slowly. Sometimes the conditions do not cause rocks to change, and they appear stable for very long periods of time.
1.7	*How does a volcano change over its lifetime?*	Volcanoes change over time.	Mount Mazama has had periods of stability, and periods of change over its lifetime. It has formed peaks of igneous rock as magma solidified, been eroded via physical and chemical processes, slowly over time, and through fast changes such as landslides and collapse. It is now extinct, and can be seen as a huge caldera.

Session	Wonder Question	Investigative Phenomenon	Outcome of Sense-Making
Lesson 2 | Driving Question *Are all volcanoes equally dangerous to communities?*			
2.1	*What happens during an eruption?*	Volcanoes erupt in lots of different ways.	Comparing volcanic eruptions shows different types and frequencies—explosive or runny, frequent or infrequent.
2.2	*What happens during an eruption?*	Lava from different volcanoes is different.	The properties of lava and how it behaves can be changed and compared; viscosity, slope, and debris affect how slowly or quickly lava flows.
2.3	*Why do some volcanoes explode?*	Gas moves differently through different lava viscosities.	The properties of lava and how it behaves can be changed and compared; thick lava traps gas more easily than thin lava. Gas trapped in lava causes it to explode.
2.4	*What properties do dangerous volcanoes share?*	Different volcanic eruptions have different effects.	Eruptions can be classified into different types, and some types are more dangerous than others. This depends on the composition of the lava that forms them, and leads to dangerous volcanoes having characteristic properties.
2.5	*What happens during an eruption?*	Volcanoes change in observable ways before an eruption.	Mount St. Helens, a stratovolcano in Washington, erupted catastrophically in 1980. People were harmed by the high temperatures and the pyroclastic flow and the area around the volcano was damaged, but warning signs detected from the volcano allowed the area to be evacuated, minimizing the effects.
Lesson 3 | Driving Question *How can we protect communities at risk from volcanoes?*			
3.1	*Are there any warning signs of an eruption?*	Volcanoes change in observable ways before an eruption.	Patterns show that volcanoes change before they erupt, becoming taller, releasing more carbon dioxide, and producing small earthquakes.
3.2	*How do scientists collect data from volcanoes?*	Volcanoes change in measurable ways before an eruption.	Volcanologists gather data using rock sampling, GPS, gas detectors, seismometers, and other detectors to measure changes in volcanoes over long periods of time to determine trends.
3.3	*Can we predict when an eruption might occur?*	Volcanoes change in measurable ways before an eruption.	Long-term trends in data from volcanoes show that volcanoes change before they erupt, becoming taller, releasing more carbon dioxide, and producing small earthquakes.
3.4	*Can we predict when an eruption might occur?*	Volcanoes change in measurable ways before an eruption.	Long-term trends in data from volcanoes show that volcanoes change before they erupt, becoming taller, releasing more carbon dioxide, and producing small earthquakes.
3.5	*Which volcanoes should we monitor?*	Not all volcanoes are monitored to the same extent.	The threat to communities from volcanoes can be assessed using historic data about volcanoes, and details about the location, as well as ongoing monitoring. Solutions can be designed and evaluated to minimize the impact of eruptions to communities.

Figure 4. Volcano Hunters Phenomena Tracker (teacher digital experience).

Engaging students with an Anchor Phenomenon or Engineering Design Challenge that they must explain or solve supports the development of critical-thinking skills as they build scientific knowledge and use the DCIs, SEPs, and CCCs to communicate their understanding and ideas.

Communication

Extensive research indicates that providing students with ongoing opportunities to talk in class and engage in rich discursive processes supports deeper scientific learning (e.g., Colley & Windschitl, 2016; Murphy et al., 2017).

“Science discourse, which refers to the representation of phenomena in the natural world through language including text and various modes of spoken and figural representation, lies at the heart of students’ science learning” (Bae, Mills, Zhang, et al., 2021). The “text and talk in the science classroom constitute two of the primary vehicles by which students gain knowledge and make meaning” and “reading, writing, and well-structured talk are all authentic aspects of engaging in the sense-making process in science classrooms” (NRC, 2014, p. 19).

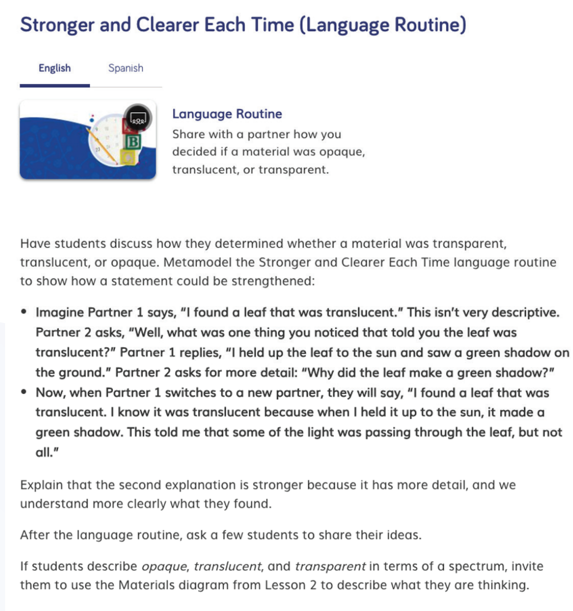
Twig Science supports the development of scientific discourse skills through language routines. Within the NGSS, science and engineering understanding and language competence develop interdependently. The language demands of the NGSS are rigorous, and the applications in the classroom require attention to both disciplinary content and language. With Twig Science language routines, disciplinary content and language are addressed simultaneously for the following reasons:

- The common thread of language connects all three dimensions of the NGSS, as students are asked to communicate, evaluate, argue, explain, define, describe, predict, analyze, and question.
- Evidence from cognitive psychology suggests learning occurs when students are encouraged to think deeply about the specific topics in question. Structured, complex conversations in the classroom place a higher cognitive demand on students, making learning more likely.
- Discussion is an effective, but sometimes underused, form of formative assessment, with the potential to engage more deeply with the NGSS and develop scientific literacy.
- Engaging in classroom discourse is particularly effective when teaching English learners. The everyday language used by students supports the process of learning, as students articulate scientific ideas verbally without the need for perfection. Informal language can act as a bridge to deeper understanding.
- Scientific terminology needs to be used and practiced, and using new vocabulary regularly is an effective way of understanding its meaning.

Language Routines—Elementary

To ensure that Twig Science provides robust support for meeting the NGSS, the creators of Twig Science partnered with Stanford University’s Stanford Center for Assessment, Learning and Equity (SCALE) team to build the following elementary language routines:

- The Stronger and Clearer Each Time language routine is designed to provide a structured opportunity for students to revise and refine both their ideas and their verbal and written output, by having repeated paired conversations. The final step in the routine asks students to develop final explanations, which helps them to understand the effect that talking about a problem or an idea can have on their ability to explain it.
- The Collect and Display language routine enables the teacher to capture the everyday language students use during discussions and activities. Students can use this as a reference in developing their scientific language. This routine also helps students see their progress over time.


Stronger and Clearer Each Time (Language Routine)

English Spanish

Language Routine
Share with a partner how you decided if a material was opaque, translucent, or transparent.

Have students discuss how they determined whether a material was transparent, translucent, or opaque. Metamodel the Stronger and Clearer Each Time language routine to show how a statement could be strengthened:

- **Imagine Partner 1 says, "I found a leaf that was translucent." This isn't very descriptive. Partner 2 asks, "Well, what was one thing you noticed that told you the leaf was translucent?" Partner 1 replies, "I held up the leaf to the sun and saw a green shadow on the ground." Partner 2 asks for more detail: "Why did the leaf make a green shadow?"**
- **Now, when Partner 1 switches to a new partner, they will say, "I found a leaf that was translucent. I know it was translucent because when I held it up to the sun, it made a green shadow. This told me that some of the light was passing through the leaf, but not all."**

Explain that the second explanation is stronger because it has more detail, and we understand more clearly what they found.

After the language routine, ask a few students to share their ideas.

If students describe *opaque*, *translucent*, and *transparent* in terms of a spectrum, invite them to use the Materials diagram from Lesson 2 to describe what they are thinking.

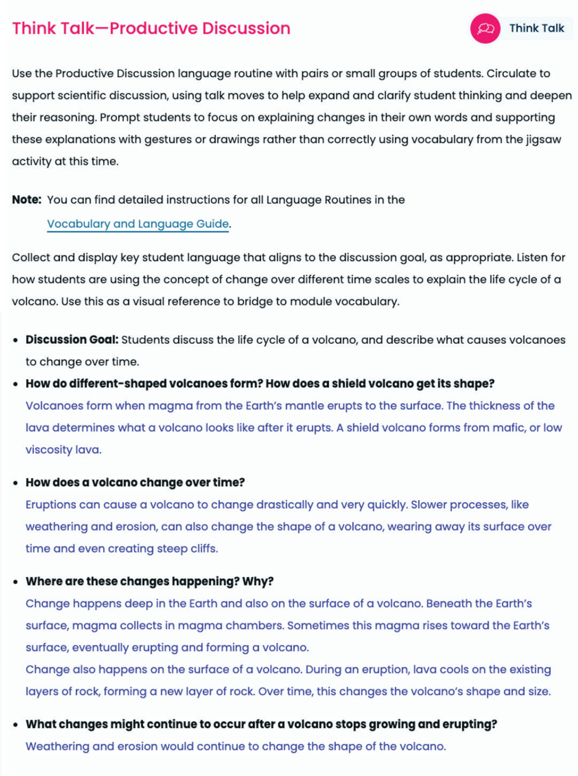
Figure 5. Grade 1, Module 3, Shadow Town, Stronger and Clearer Each Time (teacher digital experience).

Language Routines—Middle School

For middle-school discourse, the Twig Science team partnered with the SCALE team to build middle-school language routines that support students in generating questions and engaging in scientific discussions. The routines are described as follows:

- The Co-Craft Questions language routine guides the teacher to help students generate Wonder Questions about the Anchor Phenomenon and Driving Questions of the module. As students generate questions, they are prompted to share and compare these with other students before adding them to their Phenomena Trackers. This language routine allows students to experience and express curiosity when they encounter a novel phenomenon or problem without feeling pressure to produce correct answers. It creates space for students to generate scientific questions in their own language, based on their curiosity, and to use conversation skills to brainstorm and improve questions. Through this routine, students develop meta awareness of the language used in scientific questions and problems.
- The Productive Discussion language routine supports teachers in fostering productive classroom discussions among pairs or small groups of students. It is also an opportunity for the teacher to collect and display the key vocabulary students use as they discuss, providing students with a visual reference to bridge to the module academic vocabulary. The Productive Discussion and Collect and Display language routines facilitate rich

and inclusive discussions that develop students' reasoning skills and deepen their understanding about phenomena, SEPs, DCIs, and CCCs. They provide feedback for students in a way that increases sensemaking while simultaneously supporting meta awareness of language. They also honor the language that students are using and developing.



Think Talk—Productive Discussion

Think Talk

Use the Productive Discussion language routine with pairs or small groups of students. Circulate to support scientific discussion, using talk moves to help expand and clarify student thinking and deepen their reasoning. Prompt students to focus on explaining changes in their own words and supporting these explanations with gestures or drawings rather than correctly using vocabulary from the jigsaw activity at this time.

Note: You can find detailed instructions for all Language Routines in the Vocabulary and Language Guide.

Collect and display key student language that aligns to the discussion goal, as appropriate. Listen for how students are using the concept of change over different time scales to explain the life cycle of a volcano. Use this as a visual reference to bridge to module vocabulary.

- **Discussion Goal:** Students discuss the life cycle of a volcano, and describe what causes volcanoes to change over time.
- **How do different-shaped volcanoes form? How does a shield volcano get its shape?**
  Volcanoes form when magma from the Earth's mantle erupts to the surface. The thickness of the lava determines what a volcano looks like after it erupts. A shield volcano forms from mafic, or low viscosity lava.
- **How does a volcano change over time?**
  Eruptions can cause a volcano to change drastically and very quickly. Slower processes, like weathering and erosion, can also change the shape of a volcano, wearing away its surface over time and even creating steep cliffs.
- **Where are these changes happening? Why?**
  Change happens deep in the Earth and also on the surface of a volcano. Beneath the Earth's surface, magma collects in magma chambers. Sometimes this magma rises toward the Earth's surface, eventually erupting and forming a volcano.
  Change also happens on the surface of a volcano. During an eruption, lava cools on the existing layers of rock, forming a new layer of rock. Over time, this changes the volcano's shape and size.
- **What changes might continue to occur after a volcano stops growing and erupting?**
  Weathering and erosion would continue to change the shape of the volcano.

Figure 6. Volcano Hunters, Productive Discussion (teacher digital experience).

Collaboration

Research indicates that students working in small groups outperform students working individually in key areas such as knowledge development and social skills (Johnson & Johnson, 1994; Strobel & Van Barneveld, 2009). Collaborative learning heavily emphasizes students' interpretation of texts, critical thinking, and use of multidisciplinary skills, and is thought to be ideally suited for scientific inquiry applications (Brown & Campione, 1994). Collaborative inquiry in science provides an opportunity for students to identify information needed to answer a question or solve a problem, engage in self-directed learning, apply new knowledge to the problem, and reflect on learning (Sawyer & Obeid, 2017). When engaging in collaborative, inquiry-based problems, students become part of a community of learners and thinkers in the classroom (Brown & Campione, 2022).

Twig Science provides a variety of opportunities for students to collaborate in pairs or teams to explain phenomena and solve problems. Examples of collaborative learning activities include planning and completing hands-on investigations, analyzing information, and sharing proposals, results, and conclusions.

Twig Science Elementary

Elementary students engage in collaborative learning in module activities. For example, in Grade 1, Module 3, Shadow Town, students work in teams to write a short story about what it is like to live in Rjukan, Norway—a town that remains in darkness half of the year even during daytime. Students use what they have learned about shadows to tell their stories with shadow puppets. Teams collaborate to plan the characters and parts of their stories, create the shadow puppets, and build a shadow-puppet theater. Then, teams decide on a role for each team member—two are responsible for moving the puppets, one controls the flashlight, and one narrates the story. Each team performs its story for the class and uses what members have learned to further reflect on why Rjukan, Norway, is in shadow.

Twig Science Elementary also includes 3-D Team Challenges at the beginning of Grades 2–6 that require students to use scientific knowledge and the SEPs to solve engaging Engineering Design Challenges. As students work together to solve the challenges, they also complete activities that are designed to foster teamwork skills, introduce team roles, and establish routines and expectations for science class.

For example, in Grade 4, students investigate balanced and unbalanced forces through learning about catapults and the relationship between the design of a catapult and how far it can throw an object. In teams, students follow instructions to build a catapult and then discuss how different variables might affect its performance. In their teams, students brainstorm and discuss variables and then collaborate on a plan to redesign and build a new catapult. Each team shares its test results with the class and reflects on how well the team worked together.

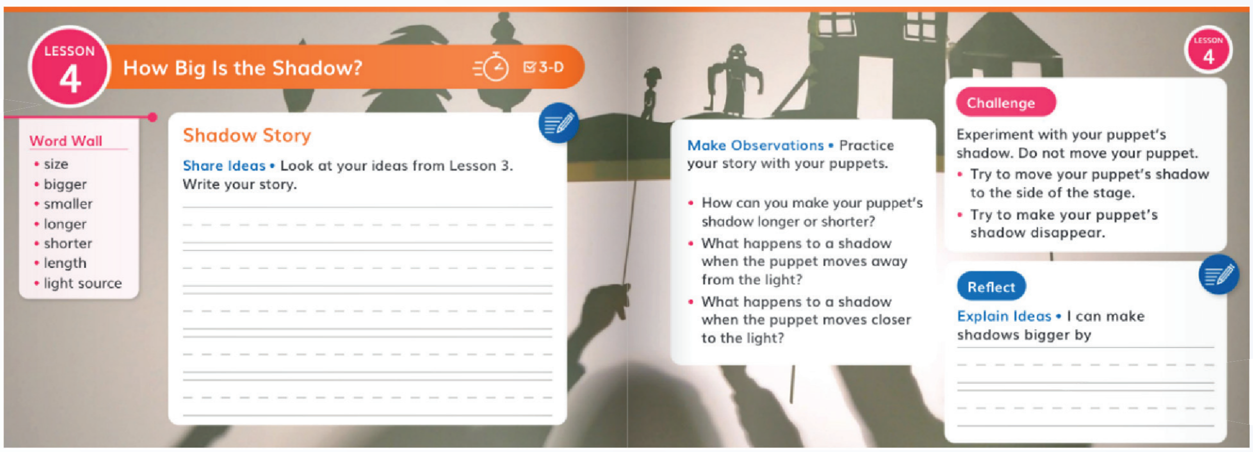
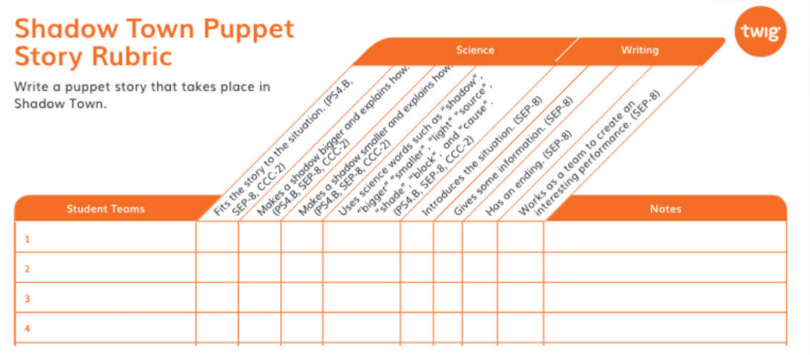


Figure 7. Grade 1, Module 3, Shadow Town, Student Twig Book.



Shadow Town Puppet Story Rubric

Write a puppet story that takes place in Shadow Town.

	Science				Writing				
Student Teams	Fits the story to the situation. (PS4.B, SEP-8, CCC-2)	Makes a shadow bigger and explains how. (PS4.B, SEP-8, CCC-2)	Makes a shadow smaller and explains how. (PS4.B, SEP-8, CCC-2)	Uses science words such as "shadow", "bigger" "smaller", "light" "source", "shade", "block", and "cause". (PS4.B, SEP-8, CCC-2)	Introduces the situation. (SEP-8)	Gives some information. (SEP-8)	Has an ending. (SEP-8)	Works as a team to create an interesting performance. (SEP-8)	Notes
1									
2									
3									
4									

Figure 8. Grade 1, Module 3 Shadow Town, Puppet Story Rubric (teacher digital experience).

Twig Science Middle School

In Twig Science Middle School, students work in teams to solve large-scale Engineering Design Challenges. For example, in the module CreATe Network, students design and test assistive technology solutions for people with disabilities. In teams, students begin with the first step of the engineering design process—defining the problem—by asking questions, conducting research, and identifying criteria and constraints. Then, students collaborate to develop, compare, evaluate, and iterate 2-D models of their proposed design solutions and work together to evaluate each design as a team. They use these evaluations to develop a team 2-D model that best meets the criteria and constraints, which they use to build the first iteration of their prototype. Each team continues following the engineering design process by testing and refining its prototype to optimize its design solution. Finally, teams prepare and present design arguments to explain why their design solution is optimal.

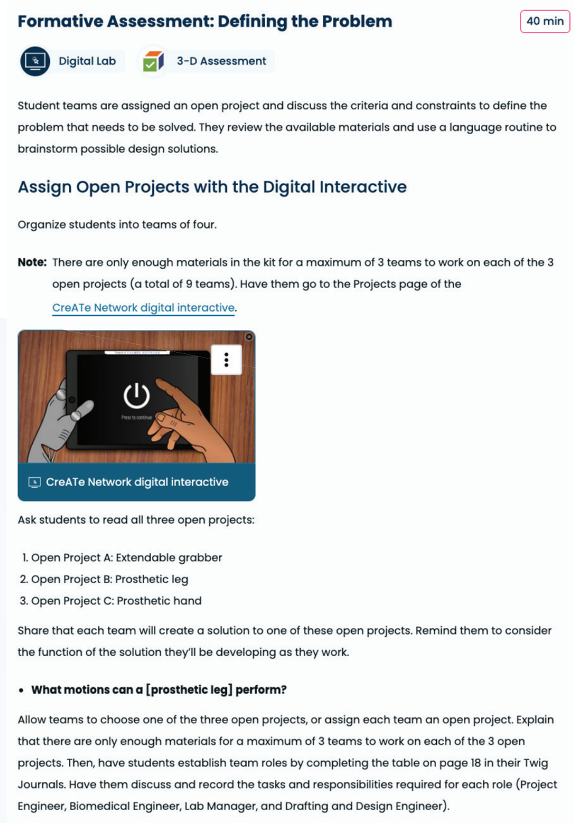


Figure 11. CreATe Network, Lesson 1, Session 4 (teacher digital experience).

The collaborative learning activities integrated within Twig Science help students develop essential collaboration skills and foster a dynamic environment for inquiry-based learning, enabling them to engage actively in problem solving, critical thinking, and applying scientific knowledge within a collaborative community of learners.

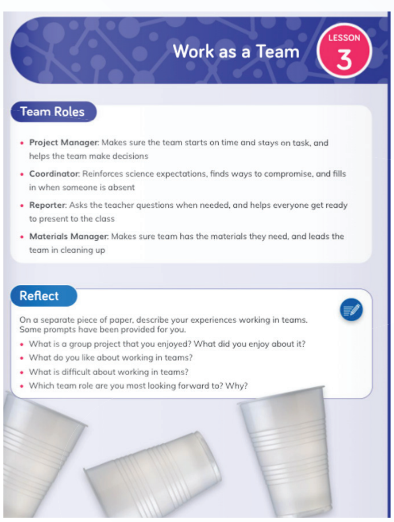


Figure 9. Grade 4 3-D Team Challenge, Catapult Challenge, Student Twig Book.

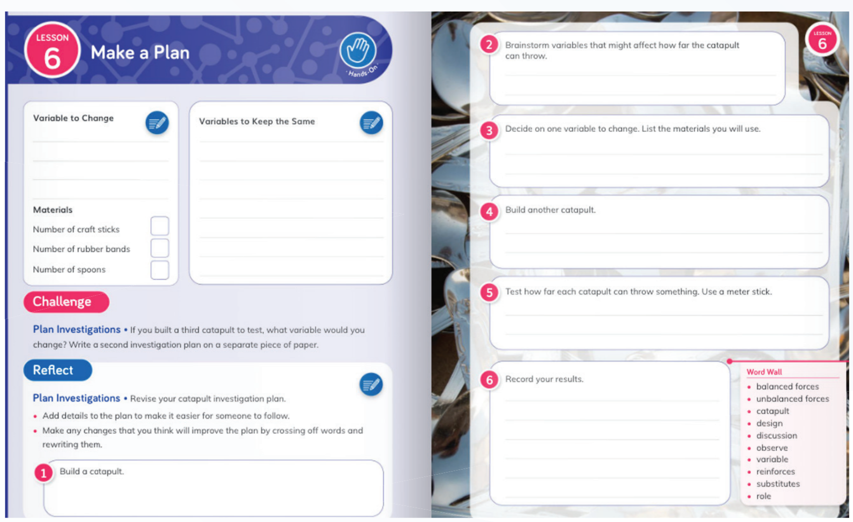


Figure 10. Grade 4 3-D Team Challenge, Catapult Challenge, Student Twig Book.

Creativity

Creative-thinking skills can be developed through learning (Fasko, 2001). In science, inquiry-based approaches are the most widely used approaches to encourage creativity (Johnson, 2000; Kind & Kind, 2007). Scientific creativity is characterized by curiosity for understanding the world, the ability to solve novel problems, seeking solutions, designing inquiry or experiments, formulating hypotheses or predications, and generating conclusions (Aktamis & Omer, 2008). The ability to think flexibly and originally are therefore central features of creativity.

Twig Science engages students in real-world scenarios through inquiry-based activities that require creative thinking and problem solving. From small-scale investigations to large-scale investigations that span an entire module, students are given the opportunity to develop their own questions and to design and carry out innovative plans and procedures to come up with original explanations and creative solutions.

Twig Science Elementary

For example, in the Twig Science Elementary Grade 4, Module 3, Time-Traveling Tour Guides, students prepare to become tour guides who will need to answer questions about the Grand Canyon by investigating how changes over time caused it to look the way it does today. Over the course of multiple lessons in Driving Question 3, How Did the Colorado River Sculpt the Grand Canyon?, students create stream trays with sand and water to model how water can change the land. As they experiment with the stream trays, students design and investigate a single variable of their choice, such as changing mountain slope, sediment size, water volume, or water speed to observe water flow and erosion in their stream trays. With a partner, students use what they have learned in Driving Question 3 and previous Driving Questions to explain a specific feature of the Grand Canyon to their "tour group," which is the rest of the class.

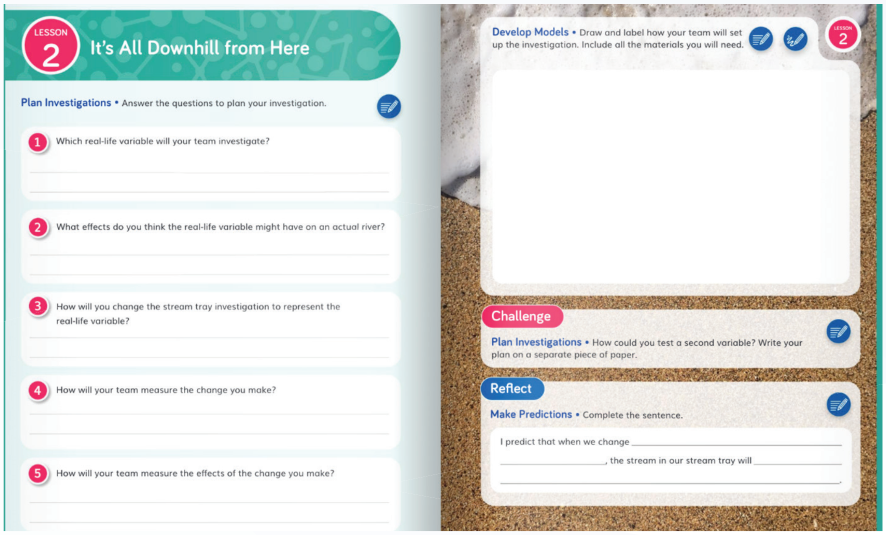


Figure 12. Grade 4, Module 3, Time-Traveling Tour Guides, Student Twig Book.

Twig Science Middle School

In the Twig Science Middle School module The Bees' Needs, students take on the role of ecosystem engineers, creating microhabitats to protect the needs of honeybees and the communities that depend on them. After they learn about the requirements for honeybee health, students establish criteria and constraints for a beehive model considering how temperature and humidity affect honeybee colonies. Then, students develop, share, and discuss 2-D models of their beehive solutions. In teams, students agree on a design to build a 3-D model, selecting materials that best align with their design. Finally, teams test and improve their models through building multiple prototypes as they reflect on their results to better meet the criteria and constraints.

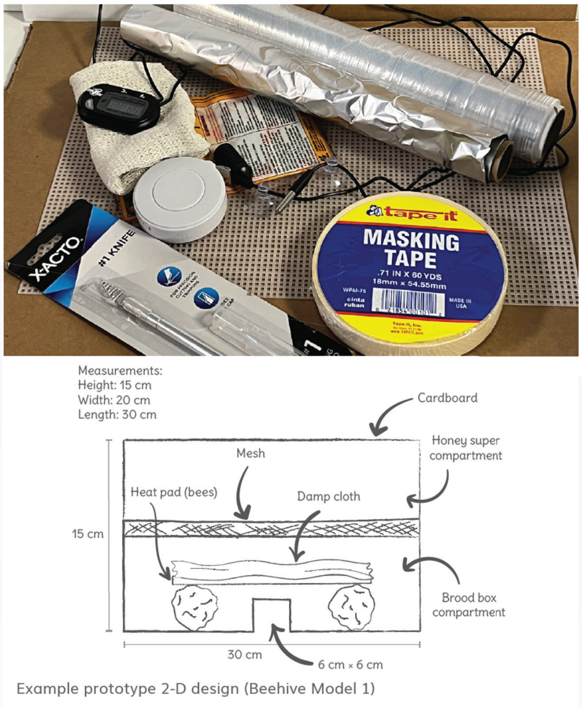


Figure 13. The Bees' Needs, example student materials and student 2-D model (teacher digital experience).

Twig Science Middle School also includes Integrated 3-D Challenges, which help students make cross-disciplinary connections and apply their growing scientific knowledge and skills to make sense of phenomena and solve problems. These challenges inspire students' creativity, by encouraging them to find engaging ways to demonstrate what they know and to apply science and engineering practices and crosscutting concepts to real-world contexts.

Students can communicate their explanations and solutions by making high-quality videos quickly and easily, without any prior knowledge of video editing, by using an intuitive video makerspace embedded in the Twig Science Middle School digital platform.

For example, in the Integrated 3-D Challenge Mission to Mars, students apply their understanding of forces from multiple modules, and analyze data and maps of Martian landscapes to explain how scientists can successfully land a rover on Mars. Through a series of 15–25-minute sessions, students take on the role of film directors and use the video makerspace to create short science documentaries about landing a rover in an ancient crater on Mars. Their journey includes planning and researching their own script, recording notes in their Director's Notebook, and ultimately selecting video clips and recording voiceover to edit into a video.

Scientific and engineering practices are inherently creative processes. Twig Science supports creative expression, thinking, and output as students ask questions, design inquiry and engineering investigations, solve research problems, and determine how best to evaluate and communicate new learning and understanding.

Twig Science is a robust core curriculum that fully aligns with and addresses the NGSS.

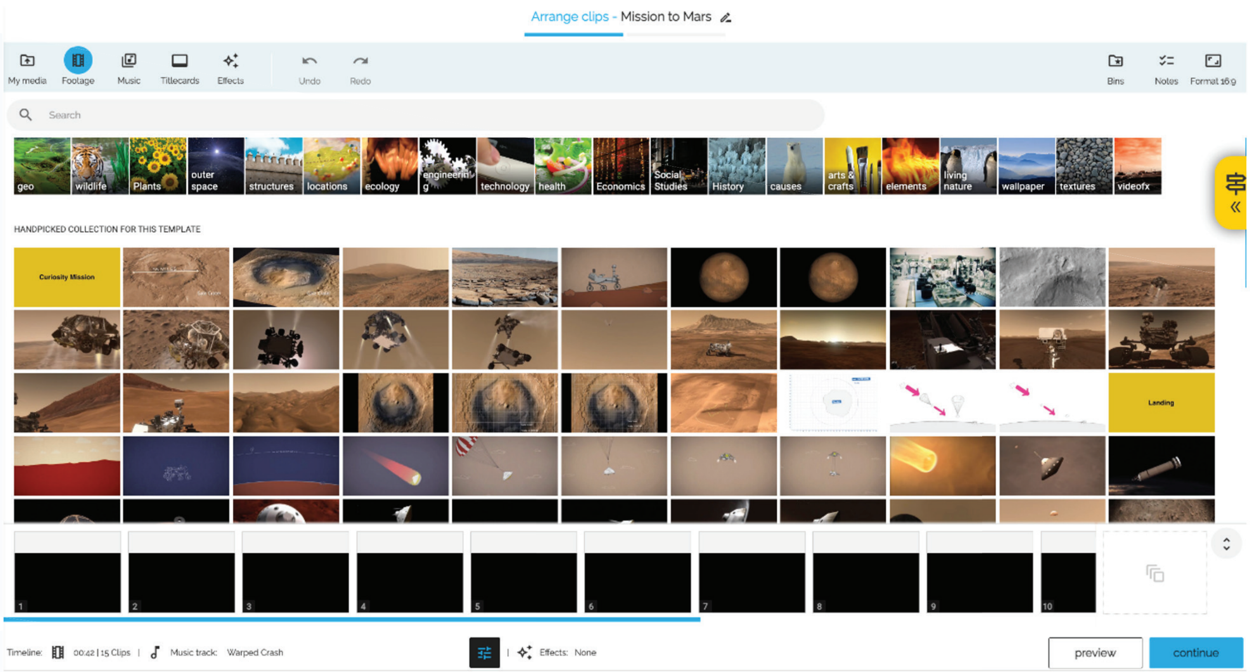


Figure 14. Integrated 3-D Challenge: Mission to Mars video makerspace (student digital experience).

The program is designed to support not only the acquisition of scientific knowledge but a phenomenon-based approach, with inquiry and problem-based learning activities that enable students to use and develop the STEM skills of critical thinking, communication, collaboration, and creativity. Critical thinking is activated as students formulate questions, and engage in scientific and engineering practices. Students acquire scientific communication skills through classroom discourse that focuses on connecting everyday language with academic, scientific vocabulary. As students collaborate in completing investigations and challenges, they develop and refine their ability to work with peers to achieve specific goals and articulate their understanding of scientific phenomena. Creativity is activated as students explore questions of interest to them, design their own explorations and engineering projects, and synthesize learning in ways that reflect their unique understanding and integration of knowledge. Acquiring these essential STEM skills prepares students to contribute to a rapidly changing world in ways that we might not have the ability to fully anticipate at present.

References

Aktamis, H., & Omer, E. (2008). The relative effectiveness of guided discovery and demonstration teaching methods on achievement of chemistry students of different levels of scientific literacy. *Asia-Pacific Forum on Science Learning and Teaching*, *9*(1), 1–15.

Bae, C. L., Mills, D. C., Zhang, F., Sealy, M., Cabrera, L., & Sea, M. (2021). A systematic review of science discourse in K–12 urban classrooms in the United States: Accounting for individual, collective, and contextual factors. *Review of Educational Research*, *91*(6), 831–877. https://doi.org/10.3102/00346543211042415

Bailin, S. (2002). Critical thinking and science education. *Science & Education*, *11*(4), 361–375.

Brown, A. L., & Campione, J. C. (1994). *Guided discovery in a community of learners*. The MIT Press.

Brown, A., & Campione, J. (2002). Communities of learning and thinking, or context by any other name. In P. Woods (Ed.), *Contemporary issues in teaching and learning* (pp. 120–126). Routledge.

Bottoms, G., & Sundell, K. (2016). *The future of K–12 computer science instruction*. National Association of State Boards of Education.

Burbaite, R., Drasute, V., & Stuikys, V. (2018). Integration of computational thinking skills in STEM-driven computer science education. *2018 IEEE Global Engineering Education Conference (EDUCON)*, 1824–1832.

Cheng M. Y. V. (2011). Infusing creativity into Eastern classroom: Evaluations from students' perspectives. *Journal of Thinking Skills and Creativity*, *6*, 67–87.

Colley C., & Windschitl M. (2016). Rigor in elementary science students' discourse: The role of responsiveness and supportive conditions for talk. *Science Education*, *100*(6), 1009–1038. https://doi.org/10.1002/sce.21243

Curriculum Development Council. (2002). *Supplement to the science education key learning area curriculum guide: Science (Secondary 1–3)*. Education Bureau Kowloon Education Services Center. https://www.edb.gov.hk/attachment/en/curriculum-development/renewal/SE/SE_KLACG_Supp_S1-3_Eng_2017.pdf

Dreyfus, A. & Jungwirth, E. (1980). Students' perceptions of the logical structure of curricula as compared with everyday contexts—study of critical thinking skills, *Science Education 64*(3), 309–321.

Duschl, R. A., & Osborne, J. (2002). Supporting and promoting argumentation discourse in science education. *Studies in Science Education, 38*, 39–72. https://doi.org/10.1080/03057260208560187

Facione, P. A. (1990). *Critical thinking: A statement of expert consensus for purposes of educational assessment and instruction: Research findings and recommendations (the Delphi report)*. Prepared for the Committee on Pre-College Philosophy of the American Philosophical Association.

Fasko, D. J. (2001). Education and creativity. *Creativity Research Journal*, *13*(3–4), 317–327.

Friedler, Y., Nachmias, R., & Linn, M. C. (1990). Learning scientific reasoning skills in microcomputer laboratories, *Journal of Research in Science Teaching*, *27*(2), 173–191.

Garcia-Carmona, A. (2023). Scientific thinking and critical thinking in science education. *Science and Education*, https://doi.org/10.1007/s11191-023-00460-5

Hong, Z. R. (2010). Effects of a collaborative science intervention on high achieving students' learning anxiety and attitudes toward science. *International Journal of Science Education*, *32*(15), 1971–1988.

Johnson, A. P. (2000). Up and out: *Using creative and critical thinking skills to enhance learning*. Allyn and Bacon.

Johnson, D. W., & Johnson, R. T. (1994). Learning together. In S. E. Sharan (Ed.), *Handbook of cooperative learning methods*. Greenwood Press.

Kind, P. M., & Kind, V. (2007). Creativity in science education: Perspectives and challenges for developing school science. *Studies in Science Education, 43*(1), 1–37.

Larm, B., & Jaros, A. (2017). The art of scientific thinking: *Why science is important for early childhood development*. Michigan State University Extension. https://www.canr.msu.edu/news/art_of_scientific_thinking_in_early_childhood_development

Lawson, A. E. (1985). A review of research on formal reasoning and science teaching, *Journal of Research in Science Teaching 22*(7), 569–617.

Lu, S., & Zhang, J. (2009, July). Collaborative scientific workflows. In *2009 IEEE International Conference on Web Services* (pp. 527–534). IEEE. https://doi.org/10.1109/ICWS.2009.150

McCormack, A. J., & Yager, R. E. (1989). A new taxonomy of science education. *Science Teacher, 56*(2), 47–48.

Murphy, P. K., Firetto, C. M., & Greene, J. A. (2017). Enriching students' scientific thinking through relational reasoning: Seeking evidence in texts, tasks, and talk. *Educational Psychology Review, 29*(1), 105–117. https://doi.org/10.1007/s10648-016-9387-x

National Education Association. (n.d.). Preparing 21 century students for a global society. *An educator's guide to the "Four Cs."*

dl.icdst.org/pdfs/files3/0d3e72e9b873e0ef2ed780bf53a347b4.pdf

National Research Council. (2014). Literacy for science: *Exploring the intersection of the Next Generation Science Standards and Common Core for ELA standards: A workshop summary*. National Academies Press.

Sawyer, J., & Obeid, R. (2017). Cooperative and collaborative learning: Getting the best of both worlds. In R. Obeid, A. Schartz, C. ShaneSimpson, & P. J. Brooks (Eds.) *How We Teach Now: The GSTA Guide to Student-Centered Teaching*. http://teachpsych.org/ebooks/

Strobel, J., & Van Barneveld, A. (2009). When is PBL more effective? A meta-synthesis of meta-analyses comparing PBL to conventional classrooms. *Interdisciplinary Journal of Problem-based Learning, 3*(1), 44–58. https://doi.org/10.7771/1541-5015.1046

Subramanyam, K. (1983). Bibliometric studies of research collaboration: A review. *Journal of Information Science, 6*(1), 33–38.

U.S. Department of Education. (2022). Science, technology, engineering, and math, including computer science: YOU belong in STEM. https://www.ed.gov/stem

Yager, R. E. (2005). A vision for what science education should be like for the first twenty-five years of a new millennium. *School Science and Mathematics, 100*, 327–341.

Zeidler, D. L., & Zeidler, L. (Eds.). (2003). *The role of moral reasoning on socio-scientific issues and discourse in science education*). Springer Science & Business Media.

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