Foundations Paper

Practical Approaches to 3-D Science

Introduction

Education is always evolving as educators and researchers attempt to find innovative ways of teaching students in a changing world. As a result of this process, new standards are introduced on a regular basis when there is a need to adapt to developments in understanding and pedagogy.

One area that has changed drastically over the last few decades is STEM. As we tackle modern human problems, such as how to generate sufficient energy or prevent and treat diseases, there is an increasing need for citizens who can think outside the box and use 21st-century skills to discover new, innovative solutions.

The question therefore stands—how do we successfully prepare the next generation for the future? When the National Research Council (NRC) created the Framework for K–12 Science Education in 2012, this question was at the forefront of their research. The old US science curriculum was considered to introduce too many ideas on a surface level, never going into enough depth, and leaving students with disconnected ideas that were impossible to draw on when solving problems and explaining real-world phenomena[1]—something that was to be improved upon with the new framework.

Drawing on modern research on learning and education, as well as past and existing science education standards, the NRC committee created a new framework that then came to inform various state standards. The adoption of these new standards in many US states has brought with it the need for new educational content and new approaches to teaching STEM, while also requiring teachers to think on their toes as they adapt to new ways of teaching science.

How do we successfully prepare the next generation for the future?

1. Krajcik, J., and Merritt, J.D. (2012). Engaging students in scientific practices

What is Three-Dimensional Science?

One significant change in the NRC Framework is the explicit focus on, and integration of, engineering and technology. Traditionally, engineering and technology were taught separately from science disciplines. In the new Framework, these subjects are integrated with the sciences, on the basis that they "relate to the applications of science, and in doing so [...] offer students a path to strengthen their understanding of the role of sciences."[2] In other words, engineers in real life regularly apply scientific knowledge when coming up with engineering solutions to human problems. Closely integrating technology and engineering with science in the classroom is beneficial because it allows students to draw links between the different disciplines—just like real scientists and engineers would. Interdisciplinary STEM education is an ideal way to introduce problem-based and cooperative learning as students collaborate with their peers to find solutions to problems using their scientific knowledge.

To replicate the way that scientists work, the NRC Framework introduced a three-dimensional approach to science. The three dimensions—science and engineering practices, crosscutting concepts, and disciplinary core ideas—connect to create an approach to STEM that is as close as possible to how scientists and engineers work in real life. Together, these three dimensionsform a comprehensive science education for a new generation.[3] Instead of focusing on rote memorization, the NRC Framework stresses the importance of skills such as collaboration and critical thinking and the ability to apply content knowledge to real-life scenarios. Using the three–dimensional approach to science education, teachers are able to make science class more engaging, more intuitive, and more reflective of what is needed when students move into the real world.

2. National Research Council. (2012). A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. Washington, DC: The National Academies Press. https://doi.org/10.17226/13165

3. Keller, T. E. and Pearson, G. (2012). A Framework for K–12 Science Education: Increasing Opportunities for Student Learning.

What Are Science and Engineering Practices?

In the past, many science programs focused on including as many hands-on experiments as possible. However, the NRC shifted the focus to the practices that scientists and engineers actually engage with day-to-day. These include a wider variety of activities and skills that are necessary for students as they move from school into various careers. The practices reflect that scientists and engineers do not just focus on conducting experiment after experiment, and instead use a variety of tools and techniques as they seek to understand our world and find solutions to problems.

Examples:

1. Asking questions and defining problems

Asking questions such as "What makes volcanoes erupt?" and defining problems such as "How can we build earthquake-safe houses?"

2. Developing and using models

Interpreting and creating diagrams, drawings, and physical replicas of phenomena, and using computer simulations and mathematical representations of problems.

3. Planning and carrying out investigations

Investigating scenarios and conducting experiments to answer questions about phenomena or to attempt to find solutions to design problems, such as how to build an earthquake-safe house.

4. Analyzing and interpreting data

Using data collected during investigations to answer questions or solve problems, and critically examining external data to find answers to questions.

5. Using mathematics and computational thinking

Using digital simulations to investigate scenarios, creating and using spreadsheets to record data, and doing mathematical calculations to make sense of data.

6. Constructing explanations (for science) and designing solutions (for engineering)

Explaining phenomena verbally or with drawings and models, and coming up with solutions for design challenges, such as how to protect an egg from breaking when dropped from a height.

7. Engaging in argument from evidence

Using evidence to argue for the best design solution to aproblem, for example—what design of an earthquakeresistant house is the safest?

8. Obtaining, evaluating, and communicating information

Reading scientifi c texts, watching videos on scientific topics, reading and creating graphs and diagrams, and comparing the content and evidence of two texts on the same topic.

What are Crosscutting Concepts?

Crosscutting concepts (CCCs) often feel like the most elusive of the three dimensions, but they are crucial to building content knowledge and understanding scientific processes. CCCs are defined as "concepts that bridge disciplinary core boundaries, having explanatory value throughout much of science and engineering."[4] In other words, they are themes or concepts that appear in both engineering and across the scientific disciplines—and the knowledge of them is therefore beneficial throughout much of STEM education.

For example, if a student is aware of how cause and effect works in one instance, they already know roughly how it works when encountering the same concept in a different discipline.

The inclusion of the CCCs was based on recent research into how people learn, which suggests that people who are experts in certain areas build a "connective tissue"[5] of understanding—something that we want students to be able to do in order to become successful scientists and engineers. The purpose of the crosscutting concepts is therefore to form an "organizational framework for connecting knowledge from various disciplines" that will help students create a coherent understanding of how the world works.

Examples:

1. Patterns

The symmetry of flowers and snowflakes; seasons and weather; moon phases; the structure of DNA.

2. Cause and effect

Sun and water making plants grow; fossil fuels causing climate change; moon phases causing tides; pushing an object to make it move.

3. Scale, proportion, and quantity

Studying the very small (e.g., molecules) and the very large (e.g., the Solar System); looking at phenomena over time (e.g., erosion); using different units of measurement.

4. Systems and system models

The Solar System; ecosystems; the digestive system; and models of these.

4. National Research Council. (2012). A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. Washington, DC: The National Academies Press. https://doi.org/10.17226/13165.

5. Keller, T. E. and Pearson, G. (2012). A Framework for K–12 Science Education: Increasing Opportunities for Student Learning.

5. Energy and matter

Electricity; energy transfer between objects; the flow of water; the energy we get from food (metabolism).

6. Structure and function

Man-made tools and machines; the human skeleton; lungs; flowering plants and their symbiosis with pollinators.

7. Stability and change

The Earth's orbit around the Sun; the life cycle of animals; climate and climate change; tides.

What are Disciplinary Core Ideas?

Disciplinary Core Ideas (DCIs) are key components of science education—simply put, they are big ideas that students need to know to be able to understand the world around them.[6] Out of the three dimensions, DCIs are the most similar to "traditional" science approaches. They are divided into four domains: Life Science; Earth and Space Science; Physical Science; and Engineering, Technology, and the Application of Science—similar to the traditional division of the scientific disciplines. Within these domains, there are several groups of ideas that build in complexity as students progress through their academic careers. They also build upon each other over the course of a student's science education, allowing students to form a deeper understanding of the world and make sense of phenomena.

EARTH AND SPACE SCIENCE:

ESS1: Earth's Place in the Universe

The Solar System and the motion of the Sun, the Moon, and the stars; the orbits of planets; the rotation of the Earth on its axis.

ESS2: Earth's Systems

The geosphere, the hydrosphere, and the biosphere; plate tectonics, earthquakes, and volcanoes; the water cycle and water's movements.

ESS3: Earth and Human Activity

Energy and renewable/ nonrenewable resources; natural hazards; human activities like agriculture; climate change.

LIFE SCIENCE:

LS1: From Molecules to Organisms: Structures and Processes

How animals and plants survive and reproduce; animal and human senses; genetic factors and inheritance; internal and external structure of animals, plants, and organisms.

LS2: Ecosystems: Interactions, Energy, and Dynamics

Matter cycles and food webs; biodiversity and ecosystems; photosynthesis and pollination.

LS3: Heredity: Inheritance and Variation of Traits

Characteristics of organisms, plants, and animals; differences and similarities between parents and offspring; the effect of the environment on traits.

LS4: Biological Evolution: Unity and Diversity

Fossils and their similarities with living organisms; adaptation by natural selection; biodiversity and habitats.

6. NSTA. (2016). What's so Special about Disciplinary Core Ideas? NSTA Blog. https://www.nsta.org/blog/whats-sospecial-about-disciplinary-core-ideas-part-1

PHYSICAL SCIENCE:

PS1: Matter and Its Interactions

The structure of matter; mass and weight; atoms and molecules; chemical reactions.

PS2: Motion and Stability: Forces and Interactions

Pushes and pulls; patterns of objects' motions; electric and magnetic forces; gravitational forces.

PS3: Energy

The movement of energy; the movement and transfer of sound, light, and heat; the interaction between objects; the energy sources of humans, plants, and organisms.

PS4: Waves and Their Applications in Technologies for Information Transfer

Properties of waves in water; sound waves; light and the way it travels; the use of waves in human communication such as computers and cell phones.

ENGINEERING, TECHNOLOGY, AND THE APPLICATION OF SCIENCE:

ETS1: Engineering Design

Defining engineering problems; asking questions, researching, and designing possible solutions; testing different solutions.

Teaching Science and Engineering Practices

It is all well and good knowing what the three dimensions are, but for science teachers the most important question is how to apply them in the classroom. Teachers already have a million things to think about each day, but addressing the three dimensions in the classroom does not have to be complicated.

Asking Questions and Defining Problems

Children naturally ask a lot of questions, but the trick is to make sure that students ask better questions. The important thing here is to not spoon-feed questions/problems to your students. You may have a question in mind, but let your students find their own way to it. Start the first lesson in a unit by displaying an image, video, or similar and then use a visible thinking technique such as "See, Think, Wonder"[7] to harvest their thoughts. Ask them to note down what they see, what this makes them think about, and what it makes them wonder. Then, steer them in the right direction until you have an effective question. With older students, you can use more advanced techniques such as the Question Formulation Technique from the Right Question Institute. Or, if you are focusing on an engineering problem, present a series of images, videos, or scenarios, and let your students tell you what they think is happening. When you have identified the issue, you can use techniques such as "Think, Pair, Share" to encourage learners to think deeper about clarifying the problem.

7. Bell, S., Power, T., and Rich, S. (2019). A Teacher's Guide to Visible Thinking Activities. Inquisitive. https://www.inquisitive.com/blog/2019/03/27/visible-thinking/

Developing and Using Models

Often in science class, students are presented with the "accepted" scientific model developed by scientists. However, to ensure that learners grasp the difference between the scientific model and the phenomenon it describes, it is beneficial for them to attempt to construct their own models. When introducing students to a new phenomenon, let them start by drawing what they think happens. Merritt and Krajcik[8] give the example of studying smells and how odor moves from an object to our noses. In this example, students would draw how they think the odor would move from the object if they were able to "see" the smell. Then, as students gather evidence through various investigations, they can create new models using what they have learned. Finally, let the class create a model together, using the evidence they have gathered, to ensure that everyone has an effective model of the phenomenon.

8. Krajcik, J., and Merritt, J.D. (2012). Engaging students in scientific practices

Planning and Carrying Out Investigations

An important thing to consider with this SEP is that students should get the opportunity to not only carry out investigations but also to plan them. It is beneficial to give students some agency as it forces them to consider what makes an investigation effective. The key to designing a good investigation is to first identify a good question. Then, identify the variables, i.e. what things affect the phenomenon? Pick one variable to focus on and use the other variables as controls. For example, for learners investigating how the design of a parachute affects its drop speed,[9] you can pick a design element of the parachute as your variable (e.g., the size of the canopy) and keep the other control variables the same (e.g., from which height to drop the parachute). After the investigations have been carried out, let the students share their findings in groups, and engage them in a discussion about the results and how you might plan a more effective investigation. Even if they get bad data, the experience will allow them to progress as scientists.

9. Lachapelle, C.P., Sargianis, K., and Cunningham, C.M. (2013). Engineer it, learn it: science and engineering practices in action

Analyzing and Interpreting Data

This SEP is closely connected to the previous one, as students should always engage in analyzing and interpreting the data they collect from their investigations. Younger students can begin by simply taking notes or drawing what they see and find, and telling their peers or their teacher about it. As learners progress, you can introduce them to more simple ways of presenting data, such as tables and simple line graphs. They should also start learning the difference between correlation and causation and begin to compare and contrast different data sets. This can be easily done when carrying out investigations such as the parachute experiment. How would the data from two parachute drops be compared? What does this tell us about parachute design?

To begin with, students will need a lot of scaffolding to know how best to present their information. However, as students progress, they should be left to figure out for themselves which graphs work best for displaying different kinds of data. To help them understand how data can be presented in different ways, it can also be beneficial to look at a range of graphs and discuss what is going on in them. A great starting point is the New York Times' "What's Going On in This Graph?" resource, through which students can explore various types of graphs, discussing what information is presented and how the data is displayed.

Using Mathematics and Computational Thinking

Math is at the core of both science and engineering—without it, scientists would not be able to effectively present and compare findings or improve designs. Today, science has become increasingly dependent on computational thinking—scientists and engineers regularly use computers to record measurements, calculate relationships between data sets, and so on. For today's students, digital approaches are often intuitive, as they grow up with video games and mobile phones. However, students should start with the basics—let them use rulers, thermometers, and timers to discover data and make sure that they take notes. It is also a good idea to get your students used to spreadsheets from an early age, as this is a beneficial skill in most careers. Then, introduce more modern tools like digital simulation softwares; this type of software can really enhance experiments and investigations, allowing you to collect data at a much larger scale. There are many free simulation software programs available online, such as PhET, My NASA Data, and Google Earth.

Constructing Explanations and Designing Solutions

Closely connected to the previous SEPs, this practice requires students to use the evidence they have collected and analyzed to explain phenomena and come up with solutions to engineering problems. For example, students could be challenged with building a balloon car and, through testing various designs, come up with the best solution based on the evidence collected. Which car travels the fastest or the furthest? How is it designed differently from the other cars? This can be done continuously as students perform various tests and adapt their solutions as they gather evidence. When it comes to explaining phenomena, this SEP can be closely linked to developing and using models. Often, the easiest way to explain a phenomenon is by using a model—anything from simple models like drawings and diagrams to physical replicas of, for example, anatomical structures. Students should be encouraged to use what they have learned to create their own models of phenomena.

Engaging in Argument from Evidence

For scientists, the goal is always to come up with the best explanation for a phenomenon—scientific discoveries are usually made by scientists putting forward arguments and then other scientists trying to prove them wrong. In the classroom, students can practice this by using evidence they collect from their investigations to create explanations for various phenomena. Then, encourage them to compare their explanation with those of their peers, engaging in a debate about what explanation is best supported by evidence. Another great way to tackle this SEP is during engineering design challenges. There are often multiple possible solutions to a design problem, and students can use the evidence and data they have collected during investigations to argue for what they think is the best one. This will also help them communicate and collaborate with their peers as they listen to others' arguments and are required to compromise.

Obtaining, Evaluating, and Communicating Information

A significant amount of what scientists and engineers do day-to-day is read other scientists' work. Science and engineering are both highly collaborative fields, and students need to become used to getting information from scientific texts. Reading actual scientific journals is often too difficult for students to do on their own—instead, start with simpler articles, videos, or even podcasts. Give them reading or listening strategies for how to effectively obtain information from these texts— for example checklists with questions to answer when reading a new text. Activities could include reading texts and underlining anything considered evidence, or studying two sets of media that discuss the same topic and compare the different perspectives. Similarly, students need to practice finding effective ways of communicating their discoveries—from oral explanations to written texts and various diagrams and graphs. This is often a natural part of any investigation; once students have collected their data, they should be encouraged to present it in an appropriate way and show this to their peers.

Teaching Crosscutting Concepts

Because of the abstractness of CCCs, it can be difficult to know how to apply them in the classroom. A helpful way to think of them is as lenses that can be used to give students different perspectives of phenomena.[10] For example, studying the phenomenon of wildfires could look very different using the CCC lens of energy and matter in comparison to the CCC lens of patterns.[11] An important part of teaching the CCCs is making them explicit so that students get used to the vocabulary and begin to build connections between the different disciplines.

10. Rivet, A. E., Weiser, G., Lyu, X., Li, Y., & Rojas-Perilla, D. (2016). What are crosscutting concepts in science? Four metaphorical perspectives

11. Marckwordt, J., Nguyen, K., Boxerman, N.Z., and Iveland, A. (2021). Teacher enactment of the crosscutting concepts in next generation science classrooms.

Patterns

With younger students, start by simply noticing and describing patterns. For example, students can be tasked with collecting data on the phases of the moon, the outside temperature, or the number of sunny versus cloudy days. As students progress, they should be able to look at patterns of change to make predictions. In addition, they should start being able to classify. A great task to introduce them to this is organizing various classroom objects into groups and let them argue for the way they classify these things. This will help them understand patterns when, for example, studying classification in the animal kingdom. In middle school, students should start looking at chemical patterns in molecules, using microscopes and illustrations to develop an understanding of these patterns.

Cause and Effect: Mechanism and Explanation

Children are always asking questions about why things happen, which is something that teachers should capitalize on. In science, we also want to make sure to study the specifics. Students need to be able to see and explain causation—if A causes B, what happens in between A and B to create this result? With younger students, start by encouraging them to identify simple cause-and-effect relationships and predict outcomes. A simple investigation could be comparing the growth of a few different plants that get different amounts of sun and water. As they progress, they should also be able to test cause-and-effect relationships and understand the difference between causation and correlation. This concept is also used well in correlation with the SEP of planning and carrying out investigations, as cause-and-effect relationships are at the core of any investigation. For example, if students are investigating the best design for a parachute, encourage them to think about why a specific parachute design worked better.

Scale, Proportion, and Quantity

Younger students should start by simply describing and comparing different phenomena (e.g., bigger and smaller, hotter and colder, faster and slower), as well as using standard units to measure length, weight, time, temperature, etc. They should also start understanding how things can be scaled up and down so that humans can perceive and study them. In the classroom, start by looking at maps—either physical ones, or using interactive resources such as Google Earth. This is an easy way to start teaching them what different scales mean. You can also start using microscopes to look at the tiny details the human eye cannot see and (if possible) telescopes to look at the universe. Students should also be able to apply these skills when completing engineering design projects. Let them create scaled models of their design solutions and encourage them to define the scale. When doing this, they should also begin to use and understand the concepts of proportion and ratio—for example, the proportion between a parachute's canopy and its string should be the same when.

Systems and System Models

Children will come into the classroom with internal models of how certain things work, but it is necessary for them to know how to construct system models—shared explanations of how systems work. At a young age, start by having students create drawings and descriptions in their notebooks, before moving on to making them more specific and including invisible features (such as forces and invisible matter). It is a good idea to start with systems that are more tangible and easier to grasp— such as the human digestive system. Students can use physical representations of the organs to create a model of the digestive system to help them discuss what happens when we eat. Another system that is easy to make a physical model of is the Solar System. As students progress and begin to grasp the concept of systems, you can move on to modelling more abstract systems, such as cell nuclei.

Energy and Matter: Flows, Cycles, and Conservation

Closely connected to the idea of systems is how energy and matter flow through systems, and how they are recycled within a system. It is often easier for younger students to understand matter, as energy is invisible and therefore difficult to visualize. As such, it is a good idea to start with matter. An introduction to matter could be bringing in bread or cookies and letting students crumble these up to effectively illustrate how matter can be broken into smaller pieces. Another way to show them how matter cycles through things is to show them how water flows through plants. There are various ways that this can be turned into a classroom project—for example, putting carnations in water with food dye and waiting to see how this changes the color of the flowers' leaves to illustrate how the water moves through the plants. When students are more comfortable with this concept, they can be introduced to larger systems such as the Earth's water cycle or the carbon cycle, which are most easily explained through drawings or visual models. Then, going into middle school and above, move on to looking at energy flows, for example discussing metabolism.

Structure and Function

This concept highlights how the structure of objects (both man-made and natural) is related to their function, and vice versa. To teach this to students, start with easier mechanical structures and their functions. Man-made objects are a great way to illustrate this—anything from a smaller tool like a hammer or a fork, to a larger structure like a bridge, are easy for younger students to understand. A great way to let them test this out themselves is by building their own structures in class—use things you can find in kitchens, like spaghetti, marshmallows, crackers, etc. and let students build the tallest structure they can, or perhaps a structure that can support the weight of another, specific object. As students progress, move on to studying more complex systems such as the human skeleton—or specific parts of the human skeleton, such as our hands. A good project could be designing robot hands using their knowledge of how the structure of our human hands serve their function.

Stability and Change

The final CCC focuses on how things in our universe remain the same, but also change over time—and how change can be very fast or very slow. This can be tricky for students to understand as some things may appear stable to the human eye, but actually change over time. Start by observing things like the moon phases or the weather, and let students record data over a longer time period before discussing stability and change. Both these examples will show how some things change regularly, but are still stable in that the change is predictable. As such, students learn about concepts like dynamic and static equilibrium, and cyclic change. Studying these phenomena will allow students to begin making predictions. For example, using the data they have collected on weather, what might the weather be like on a specific day in the future?

Teaching Disciplinary Core Ideas

Disciplinary core ideas are the most similar to traditional science education, but the trick with teaching them in the three-dimensional way is ensuring that they are approached through the lens of a crosscutting concept and that students have the opportunity to engage in at least one (but most of the time, several) science and engineering practices as they study the core idea. For example, students can study how plants survive (LS1: From Molecules to Organisms) by planning and carrying out investigations about what plants need to thrive, looking for cause-and-effect relationships between what plants get and how healthy they seem. Or they can study the relationship between plate tectonics and earthquakes (ESS2: Earth's Systems) by analyzing and interpreting data from various types of maps to successfully describe the patterns of where earthquakes occur. Or perhaps they could study light and the way it travels (PS4: Waves) by planning and carrying out investigations about which materials let through, or do not let through, light—considering the structure and function of these materials.

Figuring out how best to teach DCIs while applying CCCs and SEPs can be a lot of work—so finding a science program that covers all the three dimensions is an ideal solution. That way, you can be certain that you are teaching three-dimensional science, everyday! Twig Science is a genuine three-dimensional science program that gives teachers a flexible way of delivering comprehensive, standards-based instruction. Find out more about the program at www.imaginelearning.com/twigscience

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