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How to Support Learners in Developing Usable and Lasting Knowledge of STEM

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Abstract

All students need to experience the joy of discovery and innovation. In this study we discussed how STEM education that focuses on design can provide students with these opportunities. Learning environments that focus on STEM questions and engage students in design have the potential help students learn core ideas related to STEM as well as engage students in the learning process. This study presents examples that can be used by educators and also focuses on how STEM learning environments can connect knowledge of scientific and engineering ideas with focusing on scientific and engineering practices.

Introduction

On April 13th 2016, the New York Times reported that a quadriplegic young man regained control of movement in his right hand and fingers by the use of technology that can transmit his thoughts to his hand and finger muscles. The technology, which includes a chip implanted in the man's brain that is connected by a computer to a sleeve on his arm, now enables him to pour from a bottle and stir using a straw. Although these are amazing accomplishments, they are no cure for a person with quadriplegia. Yet they represent what knowledge of science, technology, engineering and mathematics (STEM) can accomplish by working together. To accomplish what was an unthinkable feat just several years ago took a team of scientists, doctors and engineers who were able to apply various aspect of STEM to design a solution to a difficult, real-world problem. This feat presages even more amazing accomplishments to come.

Living fulfilling and meaningful lives in the 21st century requires individuals to have capabilities such as deep, useable knowledge of scientific and engineering ideas and scientific and engineering practices, as well as the creative, problem solving, and communication skills and judgment to apply STEM ideas. STEM permeates the lives of children, adolescents and young adults – literally. For instance, how does Wi-Fi work? How is it that our cell phones can transmit audio and video information over such long distances? How can we reduce carbon emissions in our society and still experience the many of comforts of the 21st century such as travel by car and plane? Although new developments in genetics, nanoscience, neurosciences and technology offer unfathomable opportunities for improving human conditions, these and other scientific, technology, and engineering breakthroughs have also given rise to a myriad of global challenges, like water pollution, health concerns related to obesity, and climate change. Moreover, the careers that will be available for most children alive today will require deep usable knowledge of STEM, the ability to collaborate with others and skills in problem-solving solutions. Every child has the right to develop deep meaningful knowledge of STEM.

What is STEM? One definition of STEM could be the accumulated knowledge of various science disciplines, technology, engineering and mathematics as separate but related fields. However, a richer, more productive manner of thinking is to define STEM as an integration of these fields to focus on solving pressing individual and societal problems. To accomplish complex tasks such as implanting a chip in a person's brain or reducing carbon emissions will require not only that some individuals have deep usable knowledge in one field, supporting learning in developing deeper, more useable knowledge, but also knowledge of other fields so that collaborations to solve pressing complex problems can occur. We take the position that developing integrated knowledge of STEM is essential in K-12 education, as is laying the foundation for a learner to go deep into a particular discipline. Our working assumption is that if learning is structured around big ideas of the various fields, which are inherently complex; if knowledge is organized in such a way that it can be used and applied to new contexts; if students use critical thinking, problem solving, collaboration and communication skills to solve complex problems and make sense of phenomena; and if students learn to be reflective so as to learn how to learn, then they will have a foundation for applying what they know for lifelong learning as active participants in a global society. We also have as a main assumption that all students should have high-quality learning opportunities in STEM subjects and in STEM. Our goal is to foster and develop STEM learners.

How can we support students in building such deep, integrated knowledge of STEM so that they have the useable knowledge and problem solving skills necessary to live in and improve the world? In this manuscript, we will focus on how to design learning environments and develop curriculum resources to promote deep integrated understanding of STEM across the K-12 spectrum.

Making Use of the Framework for K-12 Science Education

The Framework for K-12 Science Education (National Research Council [NRC], 2012) developed by National Research Council in the USA lists five major ideas that are essential to the design of STEM learning environments and curriculum resources: 1) identifying a limited number of core disciplinary ideas of science, 2) using crosscutting concepts, 3) engaging students in scientific and engineering practices, 4) building integrated understanding across time, and 5) coupling scientific ideas, crosscutting concepts and scientific and engineering practices to develop integrated understanding. It is important to realize that the Framework is based upon what is known about the teaching and learning of science and engineering (see *Taking Science to School*, NRC, 2007). What implications do these major ideas have for the design and development of STEM learning environments and curriculum resources? Learners need to use scientific and engineering ideas and practices, mathematics and technology to solve problems throughout their K-12 experience to develop integrated, useable knowledge of STEM. Below we will discuss each of these ideas and discuss what they mean for the design of STEM learning environments.

First, the Framework focuses on a limited number of disciplinary core ideas of science and engineering that are essential to explain and predict a host of phenomena and to solve problems. Disciplinary core ideas are powerful in that they are central to the disciplines of science, serve as thinking tools to make sense of phenomena, and serve as building blocks for learning within a discipline and in making connections to other ideas (Stevens, Sutherland & Krajcik, 2009). This focus on core ideas avoids the shallow coverage of a large number of topics typical of textbooks (Kesidou & Roseman, 2002) and allows students to develop integrated understanding that can be used to solve problems and make decisions. For example, engineers need to make use of various disciplinary ideas in their work as they solve problems. We believe K-12 learning environments need to focus on the big ideas (core disciplinary ideas) of the fields and not disjointed facts in order to support students in explaining phenomena and designing solutions to problems. The recognition of engineering concepts as important science education learning goals is new in the United States. In the Framework for K - 12 Science Education, engineering, technology and applications of science are recognized as core disciplinary core ideas on par with physical science, biological science and earth and space science ideas.

A second major idea in the Framework is that of crosscutting concepts. These consist of major scientific ideas that cut across disciplines but at the same time are essential to each of the disciplines and in making sense of phenomena or in finding solutions to problems. Cause and effect; systems; patterns; size, proportionality and scale; and matter and energy are examples of crosscutting concepts. These ideas are critical in solving problems: how should the system be bound in order to solve a problem? Many learners don't understanding the importance of systems and structure function relationships, but it is critical in the STEM world. Like core ideas, crosscutting concepts are essential to problem-solving and decision making. Core ideas are specific to a discipline, whereas crosscutting ideas, as suggested by the name, cut across disciplines, and are therefore interdisciplinary in nature. To develop useable knowledge in K-12 learners within STEM, crosscutting concepts need to be made explicit in curriculum resources. For instance, scale and structure function are critical thinking ideas for nano-engineers. Curriculum resources need to explicitly point out crosscutting concepts in curriculum materials.

Third, the Framework emphasizes that learning about science and engineering involves the use of scientific and engineering practices to engage students in doing science and engineering design (STEM). Scientific and engineering practices consist of the multiple ways in which scientists explore and understand the world and how engineers improve and solve problems of the designed world. These practices include: 1. Asking questions (for science) and defining problems (for engineering), 2. Developing and using models (science and engineering), 3.Planning and carrying out investigations (science and engineering), 4. Analyzing and interpreting data (science and engineering), 5. Using mathematics and computational thinking (science and engineering), 6.

Constructing explanations (for science) and designing solutions (for engineering), 7. Engaging in argument from evidence (science and engineering), and 8.Obtaining, evaluating, and communicating information (science and engineering) (NRC, 2012). Including what engineers do as one of the dimensions shows the importance of including engineering practices to support student learning and in what students need to learn.

Fourth, the framework presents learning as an ongoing developmental process. A developmental perspective purposefully builds upon and links students' current understanding to previous understanding in order to form richer and more connected ideas over time (NRC, 2007). Such an approach guides the development of students' knowledge toward a more sophisticated and integrated understanding of scientific idea (NRC, 2007; Corcoran, Mosher & Rogat, 2009). However, growth in understanding is not developmentally inevitable, but depends upon instruction and key learning experiences (including assessments), in both formal and informal environments, to support students as they develop more sophisticated and integrated understanding across time (Corcoran et al., 2009). If we have learned anything in the past several years, it is the importance of coherently building and assessing ideas to help learners form integrated understandings (Roseman, Stern & Koppal, 2010). This developmental perspective is essential in supporting all learners in developing the deep STEM knowledge that is necessary for the 21st century. The developmental view is especially appropriate for STEM learning experiences, since STEM experiences can grow in complexity and sophistication.

Fifth, the framework emphasizes that learning about science and engineering involves the coupling or integration of scientific ideas (disciplinary core ideas and crosscutting concepts) with scientific and engineering practices to build deep, useable knowledge necessary for understanding the physical world in which we live and for STEM careers. The integration of the three dimensions is referred to as three dimensional learning. The literature provides evidence that understanding a scientific idea is inextricably linked to the context in which the student develops the understanding (NRC, 2007). As such, the Framework stresses the importance of linking scientific and engineering practices with the scientific ideas for instructional and assessment purposes. Just like science is both a body of knowledge and the process whereby that body of knowledge is developed, the learning of science is similar: you cannot learn a scientific idea without using it with scientific practices, and the converse also holds: you can't learn a practice separate from the scientific idea. If we want learners to be able to apply the scientific idea, then they need to engage with that idea utilizing a particular scientific practice, and if we want students to learn the scientific practice, then we need to use the practice to engage with the scientific idea. In other words, they go hand-in-hand -- you can't learn one without doing the other. To support students in developing useable knowledge, STEM learning environments need to be constructed with these ideas in mind.

Designing and Developing STEM Learning Environments by Integrating the Three Dimensions

How do you design STEM learning environments to promote students' developing deep, usable knowledge and capabilities? Below we describe a process for designing STEM learning environments that is closely aligned to project-based learning (Krajcik & Czerniak, 2013; Krajcik & Shin, 2014). In previous design efforts (i.e., Investigating and Questioning Our World through Science and Technology (IQWST) (Krajcik, Reiser, Sutherland & Fortus, 2012, (Fortus & Krajcik, 2015).), we found that to promote learning it is essential to create learning goals that focus on performances that integrate the three dimensions. We refer to these as "learning performances." The development of learning performance is a critical first step in guiding the design of learning environments. Learning performances provide clear and specific learning goals, showing how students should apply the understanding they are developing. We have used the following process for developing learning performances (Krajcik, McNeill & Reiser, 2008; Shin, Stevens & Krajcik, 2010; Krajcik & Shin, 2014): 1) identify and elaborate specific aspects of the core disciplinary idea, 2) unpack the scientific and engineering practice, 3) unpack the crosscutting concept, 4) construct the learning performance by integrating the three dimensions.

Unpacking consists of identifying the essential components of each dimension and helps to pinpoint the knowledge and capabilities that students need to use for the dimension at a particular grade level. Part of our unpacking of the core disciplinary idea includes brainstorming associated phenomena. A possible learning performance could be: Design an apparatus that will transfer energy to cause a final outcome that requires the transfer of energy.

Notice how this sample learning performance includes all three dimensions:

- Design an apparatus: Scientific and engineering practice of constructing models of design solutions:

- Transfer of energy: Big idea (a core disciplinary idea from the Framework – see below for specific big ideas that are met).
- Cause and effect, one of the crosscutting concepts.

Once we have developed learning performances, we then describe the evidence that can be used to measure students' understanding as described in the learning performances. Evidence statements are essential in determining if the tasks that will be designed support students in developing the understanding expressed in the learning performance. Using learning performances, evidence statements and identified phenomena, we design various sequenced learning tasks to promote student learning. The learning performances, evidence statements and phenomena provide guidance in designing associated tasks. A task related to the above learning performance might be: design an apparatus that will go through three energy transfers and cause a light bulb to light, a bell to ring or both at the end of the series of energy transfers.

The learning environments should be organized around driving questions (Krajcik & Czerniak, 2013; Delen & Krajcik, 2016) that motivate students to apply the science that they learn. The classroom resources center around experiencing phenomena, conducting investigations, using technology tools, and reading materials that extend students' first-hand experiences of phenomena and support science literacy. An associated driving question or driving problem might be: How can I get a light bulb to light using the flowing of water or the blowing of wind?

Often in our work, we start by having students experience an engaging or anchoring phenomenon (Krajcik & Czerniak, 2013). One possible anchoring activity related to the above learning performance and driving question might be observing a complex Rube Goldberg machine. The challenge or driving question for the students is to build their own Rube Goldberg. The following YouTube video could serve as an engaging anchoring phenomena: http://www.wired.com/gadgetlab/2010/03/ok-go-rube-goldberg. The YouTube video not only shows an engaging Rube Goldberg, but a popular rock band is also involved in the video and the production. The blending of students' own culture can go a long way to developing meaningful learning activities.

Finally, our work also engages students in the building of artifacts that provide a physical representation of the design solution and meet the characteristics specified by the teacher and elaborated by the group. To build artifacts, students work together in collaborative teams. In our example, the artifact would include building the apparatus to accomplish the task (i.e., lighting a light bulb or ringing a bell as the result of a series of energy transfers). The building of external artifacts can lead to deeper knowledge; just as important, it can also lead to a sense of personal ownership as students become the designers (Fortus, Dershimer. Krajcik & Marx, 2004). Throughout STEM units the focus on designing solutions to problems requires students to create, modify, and improve their artifacts (design solution), building deeper and more sophisticated science knowledge. Engaging learners in building artifacts that represent their design solution promotes not only deeper knowledge but also important motivational goals such as ownership and efficacy (Fortus & Krajcik, 2015).

To design longer units to meet specific learning goals, we often develop storylines (Krajcik, Codere, Dahsah, Bayer & Mun, 2014; Reiser, Novak & Fumagalli, 2015). Storylines show how the disciplinary core ideas, crosscutting concepts and scientific and engineering practices develop over time in the unit and what problems and phenomena the students will explore in the process of responding to the driving question. What do students need to be introduced to first? How would the ideas and practices develop over time? What are students figuring out during each lesson and experience that leads to a solution to the problem?

Design is a Key Idea in STEM

The process of engaging students in STEM, like the example of designing an apparatus to light a bulb, sound a bell or both, includes involving learners in the design process. Design is integral to student thinking in the STEM world. Fortus and colleagues (2004) present a model of a design process that can be implemented within schools. Design is a unique way of thinking and is critical for students in this society. Design engages learners in finding solutions to problems. The figure below is modified from Fortus and colleagues (2004) and provides one visualization of the design process that can be used in schools.

Critical to this design process is students clearly articulating and identifying the design problem, researching what is known to about the problem, generating potential solutions, developing prototype designs (artifacts) to demonstrate their solutions and sharing and receiving feedback from their classmates and other knowledgeable others on their solutions. (see Fortus and colleagues, 2004 for greater elaboration of each of these steps).

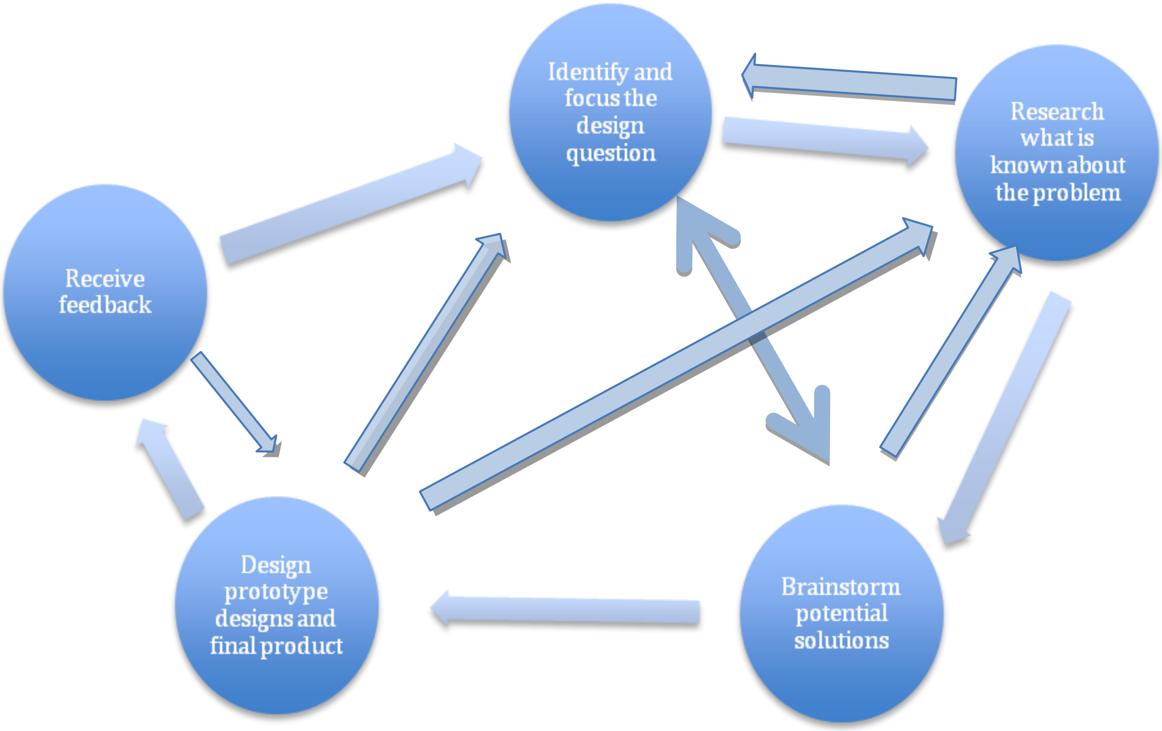

Figure 1. The design-based science learning cycle modified from Fortus and colleagues (2004)

A Focus on Disciplinary Core Ideas

STEM experiences that emphasis design often focus on connecting students' scientific ideas across different disciplines. As noted by Honey, Pearson and Schweingruber (NRC, 2014a), when implementing STEM, students "need support to elicit the relevant scientific or mathematical ideas in an engineering or technological design context, to connect those ideas productively, and to reorganize their own ideas in ways that come to reflect normative, scientific ideas and practices" (p. 5).

All STEM based design projects need to have a specific focus on supporting students in developing deep understanding of big ideas that can be used as thinking tools to find solutions to other problems or in making sense of phenomena. Articulating the learning performance as described above can support students in meeting several disciplinary core ideas (big ideas) from the Framework for K-12 Science Education (NRC, 2012). We list these disciplinary core ideas below.

PS3.A: Definitions of Energy (Physical Science core idea 3, component A)

- Motion energy is properly called kinetic energy; it is proportional to the mass of the moving object and grows with the square of its speed.
- A system of objects may also contain stored (potential) energy, depending on the relative positions of the objects in the system.

PS3.B: Conservation of Energy and Energy Transfer (Physical Science core idea 3, component B)

- When the motion energy of an object changes, there is inevitably some other change in energy at the same time.

PS3.C: Relationship Between Energy and Forces (Physical Science core idea 3, component C)

- When two objects interact, each one exerts a force on the other that can cause energy to be transferred to or from an object.

A unit designed to explore these big ideas in physical science might also help students meet the following big ideas (core disciplinary ideas of engineering) from the Framework for K-12 Science Education (NRC, 2012) related to engineering, technology and applications of science.

ETS1.B: Developing Possible Solutions (Engineering, Technology and Applications of Science core idea 1, component B)

- A solution needs to be tested, and then modified on the basis of the test results, in order to improve it.
- There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem.
- Sometimes parts of different solutions can be combined to create a solution that is better than any of its predecessors. http://www.nap.edu/openbook.php?record_id=13165&page=206

ETS1.C: Optimizing the Design Solution (Engineering, Technology and Applications of Science core idea 1, component B) http://www.nap.edu/openbook.php?record_id=13165&page=208

- The iterative process of testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution.
- Although one design may not perform the best across all tests, identifying the characteristics of the design that performed the best in each test can provide useful information for the redesign process—that is, some of those characteristics may be incorporated into the new design.

Additional STEM Examples

In a previous study, we focused on supporting middle school students' learning about energy ideas and the transfer of energy by asking students to construct models discussing how they might generate electricity to charge their mobile devices using different types of energy transfers that they observed in a museum (Delen & Krajcik, 2016). In this process, students focused on defining energy and energy transfers, and then developed potential solutions. One of the student groups developed the following design solution: the group created a poster that used the idea of a pulley by drawing foot pedals working like an exercise bike in a gym. Later in their poster, the group focused on transferring electrical energy by including a generator. Another poster used mechanical energy coming from a windmill, and transferred it to turbines to create electrical energy. Final products created in this study presented energy transfers clearly; however, they lacked a focus on how different types of energy can be converted to electrical energy. This lack of understanding can be linked to middle school students' limited understanding of electricity. Another possible explanation could be related to a lack of exhibits discussing how this transfer process occurs.

Since we tested this question with seventh grade students, we only focused on design and finding an optimal solution. In higher grades, teachers can also create a platform to find the best design by asking students to consider the relationship between energy and forces. Another example unit can focus on students searching for ways to reduce energy bills with an emphasis on insulation. This would support students in designing energy efficient houses by considering the transfer of energy by thermal conductivity through different materials.

We would like to note here that design in STEM education does not always require students to construct models; it can also refer to technological designs (NRC, 2014b). No matter how we define it, many teachers are not familiar with design thinking where the focus is on using disciplinary core ideas, practices and crosscutting concepts to find solutions to problems. This lack of familiarity could be linked to low numbers of certified STEM teachers (Hutchison, 2012), lack of teachers' experience in the design process and the relative absence of addressing STEM and design in teacher education (NRC, 2014b). What we know for sure is that, to make STEM and design an integral component of science teaching, we need to engage teachers in sustained professional learning opportunities and provide them access to good curriculum resources (Guskey, 2002; National Academies of Sciences, Engineering, and Medicine, 2015).

Challenges of Incorporating STEM Education

Although having more science teachers who know how to teach and engage students through STEM is a global need, adding engineering design to science education is not a new idea. One of the earlier studies in this area described the components of this process as "the design and building of devices that satisfy constraints" (Sadler, Coyle & Schwartz, 2000, p. 299). Sadler and colleagues emphasized that student products should focus on "the connections between science concepts and solutions to real world problems" (Sadler, Coyle & Schwartz, 2000, p. 303). Sadler and colleagues (2000) noted that moving engineering design to middle school levels would support students' interest in careers in science and technology. Recently, we started shifting our focus from inquiry to incorporating design in developing curriculum resources.

To address the challenges teachers might face in implementing the process, we expand on the elements of successful design addressed by Sadler and colleagues (2000):

1. Define clear and specific learning goals expressed as learning performances to ensure students develop disciplinary core ideas, practices and crosscutting concepts.
2. Express the design challenge that students need to accomplish in clear and concise language. Clarity of the design challenge will support learners in accomplishing both the design goal and the learning outcomes.
3. Create motivating and engaging design challenges for students.
4. Develop prototype designs that students can improve upon to help develop students' construction skills and confidence in the design process. As students build new iterations of their devices, they become more sophisticated and show improved performance.
5. Allow for multiple iterations that will allow students to modify and test their devices.
6. Incorporate scaffolds to support students in becoming familiar with design procedure.
7. Support the acceptance of design failures by providing students opportunities to perform multiple iterations.
8. Increase the design performance of students by connecting the design process with the science underlying it.
9. Construct observation protocols to formatively assess students as they engage in the design process.
10. Assure the opportunity for all students to present and receive feedback on their designs.

Conclusions

All students need to experience the joy of discovery and innovation. STEM education focuses on design and provides students with these opportunities. Learning environments that focus on STEM questions and engage students in design have the potential to help students learn core ideas related to STEM as well as to increase student engagement. STEM learning environments that focus on design can engage learners in the critical thinking process of design, promote their integrated thinking across the disciplines and allow them to experience the wonder and joy of discovery and innovations.

The design process described above has the potential to support students in learning disciplinary core ideas in science and engineering, important scientific practices and crosscutting concepts. It can also improve important motivational outcomes such as ownership and efficacy. In addition, students will be engaged in developing important 21st century capabilities such as problem solving, communication and collaboration. K-12 classrooms need to support students in STEM and design based education to help them meet important learning goals essential to world in which they live. Engaging K-12 STEM will require shifts in teaching practices and new ways of thinking, but the benefits of meeting these challenges will help to ensure that K-12 learners have the knowledge-in-use they need to live and help this world prosper. Such experiences will help prepare the learners of today to invent the solutions of tomorrow, perhaps helping quadriplegics do even more with the arms, hands and legs than stirring a drink with a straw.

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