STEM Reasoning and Learning via Science Modeling and Engineering Design Challenges

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Introduction

The Trends in International Mathematics and Science Study (TIMMS) and Programme for International Student Assessment (PISA) studies have shown that many countries across the world need to improve not only student content scores in science and mathematics but also their reasoning skills (Mullis, Martin, Goh, & Cotter, 2016; OECD, 2016). The OECD has recommended that these nations consider implementing authentic practices in STEM education. Two authentic practices that could be implemented by these nations include model-based science curriculum units (Gilbert, 2004; Jackson, Dukerich, & Hestenes (2008), Passmore, Stewart, & Cartier, 2009; Windschitl, Thompson & Braaten, 2008) as well as the introduction of engineering design challenges (Zeid, Chin, Duggan & Kamarthi, 2014).

Model-Based Pedagogical Techniques

Model-based pedagogies are either based on the use of existing models to make predictions or the development of models from empirical data using a modeling cycle. Model-based science is an authentic practice as it is routinely utilized by scientists. Scientists are continually developing theoretical or empirical models consisting of multiple representations (Hestenes, 2010; Kozma, 2003).

Model-based pedagogies make use of scientific models in different ways. One model-based intervention in biology was developed by Passmore and Stewart (2002). They developed a model-based curriculum that introduced students to already existing models of natural selection. Students' were asked to deploy the models while problem solving using real world data. During these deployments students could either confirm or refute the existing models they were presented.

An empirical approach, Modeling Instruction, was developed for physics education by Wells, Hestenes and Swackhamer (1995). This program scaffolded students in the development of lab activities in order to collect data pertinent to the scientific phenomena under study. The collected data was then analyzed in order to construct a scientific model along with its multiple representations. The student generated models were then deployed during problem solving activities.

The models developed within the context of this curriculum are continually revised based upon the model's ability to be predictive in multiple contexts. But, models and modeling cycles can be defined in multiple ways.

What is a Model?

In this article a scientific model is thought to be either conceptual or mental in nature (National Research Council, 2012). Mental models can only be made visible through the conceptual model representations produced by students. These conceptual model representations allow the scientific phenomena being studied to be made more understandable as well as predictable by students through the use of these multiple representations. These representations can include, graphs, algebraic equations, verbal descriptions, pictorial drawings as well computer simulations. These explicit representations produced by students allows them to better understand their implicit mental models. An example of the scientific model of constant velocity along with some of its representations can be seen in Figure 1. Expert problem solvers can easily switch between the model representations thus improving their ability to solve more complex problems (Harrison & Treagust, 2000).

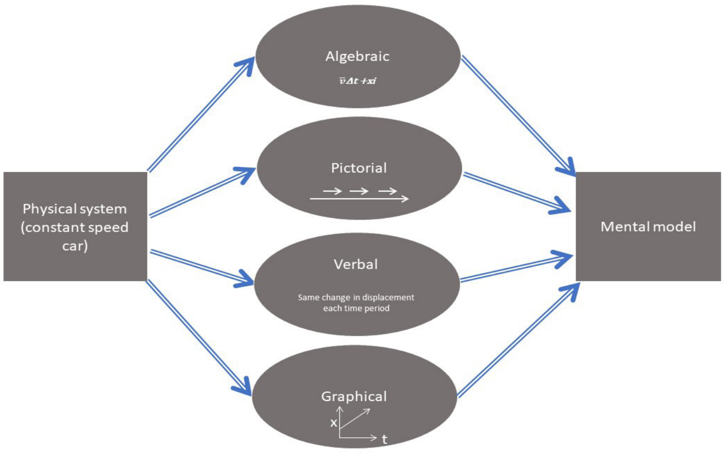

Figure 1. Constant Velocity Model and Its Representations (adapted from Dukerich, 2015)

Models and the Modeling Cycle

Scientific models and their associated representations are created within a modeling cycle. One modeling cycle that has been used extensively within the Modeling Instruction pedagogy includes model development and model deployment (Jackson et al, 2008). This simplified cycle can be expanded into a more in-depth model (see Figure 2). At the beginning of the modeling cycle students encounter scientific phenomena such as a car moving at a constant velocity. The students discuss what variables can be collected via hands-on activities. They design an experiment and collect data. Using the data collected the students can develop the scientific model along with its multiple representations. The newly developed model can then be used to predict outcomes for both the original phenomena as well as similar phenomena in different contexts. When the initial model fails students can refine the model allowing it to become more predictive in diverse situations. When the model fails to be predictive in a new situation or context the students may have to start over by developing a new model that will be predictive in this new situation. For example, this can occur when students attempt to use the constant velocity model to predict outcomes for a situation where the object is moving at a constant acceleration. In this situation the students realize after attempting to revise the constant velocity model that a new model is required. Thus they develop a model of constant acceleration.

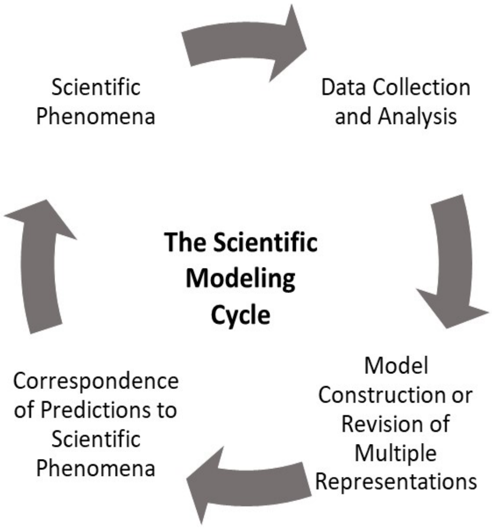

Figure 2. The Scientific Modeling Cycle

Engineering Design Challenges

Engineering design challenges have been used at many grade levels from kindergarten to university level. The challenges are developed so that they sustain student interest while making use of the engineering design process (EDP). The challenges are usually based on real-world problems for which students can construct viable solutions making use EDP and their knowledge of a variety of academic subjects. The key to a good engineering challenge is that it must be open ended enough to allow for multiple solution paths (i.e., there is no “right” answer to the problem). An example of an engineering design challenge would be to assign the problem of how to control an invasive species. This can be a complex problem that becomes even more complex when one of the constraints of the problem is that groups must have an ecologically friendly solution (Malone, Schuchardt & Schunn, 2018). Thus, engineering design challenges lead to higher order problem solving that requires the use of collaboration, communication, creativity and systems thinking. During the creation of a solution the students working on engineering design challenges discover that failure can be a positive motivator during the problem-solving process by allowing for improvements in the final prototype or process. Thus failure is an expectation of any design challenge. In addition, the challenges drive home the idea that engineers have a desire to improve the world for its inhabitants.

Engineering Design Process

The engineering design process (EDP) is an iterative process that engineers advance through when solving an engineering design challenge and producing a final solution. There is not a single process that has been approved by all engineers and EDP can range from a complicated cycle to only a few steps.

A simplified version would start with the introduction to the problem and discovering the constraints of the problem (see figure 3). This step, the asking stage, allows the team to clarify the problem as well as conduct background research into the science behind the problem. After a through understanding of the problem students can brainstorm solutions and decide on initial tentative solutions, during the imagining stage. During the planning stage, the team must propose the development of the solution by diagramming a possible solution and deciding on the materials to be utilized. After diagramming the possible solution, the team must create the prototype or process and test out the possible solution during the creating stage. Finally during the improving stage of EDP, they must determine the pros and cons of the solution based upon their testing. This leads them to understand the idea of failure which leads to improvements of the design. Thus, while improving the design they can be led to more questions and a recreation of the design moving back to the asking stage.

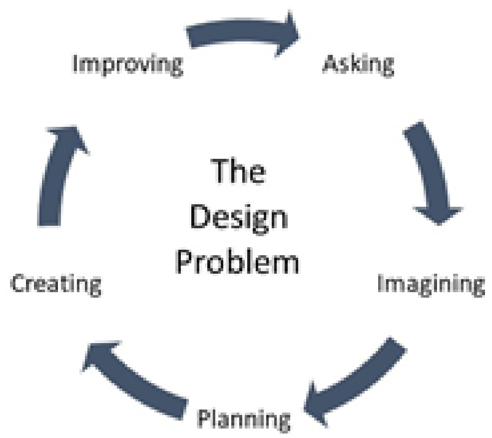

Figure 3. A Simplified Engineering Design Process

As students engage with EDP they will discover that the process can be used in multiple contexts not simply STEM fields. This new understanding of EDP gives them a problem-solving process to incorporate into their lifelong learning goals.

Adding the Arts to STEM = STEAM

The use of engineering design challenges can allow for integration of STEM concepts. However, the introduction of the arts can convert the integration from STEM to STEAM. One such STEAM integration has been attempted by the incorporation of dramatic inquiry and dance into primary school STEM curriculum units. Dramatic inquiry (DI) is a dialogic inquiry and dramatic play-based pedagogy (Edmiston, 2014) One DI approach is the "Mantle of the Expert" which positions students as expert engineers while allowing them to engage in scientific inquiry (Heathcote & Bolton, 1995). This approach allows students to take on the role of expert engineers as they attempt to solve an engineering design challenge in an authentic fashion. In addition, other components of artistic expression can also be included into the units such as interpreting the transfer of energy during a windmill engineering design challenge via interpretative dance movements. This kinesthetic approach to engineering challenges and EDP allows students to become more engaged in the STEM subjects thus heightening their interest.

The Efficacy of Authentic Practices

Several studies have shown that the use of modeling-based units and engineering design challenges at all levels of instruction have improved students' knowledge of science as well as other skills such as scientific reasoning and problem-solving.

Research Supporting Modeling Based Practices

Modeling-based practices have been shown to be effective at many different grade levels. In primary schools modeling-based practices have been used to develop students' ability to explain science concepts (Archer, Arca, & Sanmarti, 2007) as well as their use of modeling practices to reason about scientific phenomena (Zangori & Forbes,2015). Lehrer and Schauble (2005) have shown that young children can progress from modeling science ideas through the use of literal representations to more symbolic and mathematical representations during primary grades. Thus, modeling is a viable approach for students in these primary grades.

The majority of the research concerning modeling-based practices has taken place within secondary schools. In secondary schools in the United States, Modeling Instruction has been the most extensive investigated modeling-based approach to science. It has demonstrated improvements in conceptual knowledge along with declines in alternative conceptions in physics (Hestenes, Wells, & Swackhamer, 1992; Jackson et al, 2008; Malone, 2008; Liang, Fulmer, Majerich, Clevenstine, Howanski, 2012); biology (Malone, Schuchardt, & Sabree, in press) and chemistry (Malone & Schuchardt, 2016).

A similar modeling-based approach that incorporated engineering design challenges also demonstrated an increase in student conceptual knowledge over the course of a unit (Malone et al, 2018; Schuchardt & Schunn, 2016).

Multiple model-based practices in science have also demonstrated an increase in the use of multiple representations in multiple subject areas (Harrison & Treagust, 2000, Malone, 2008, Malone et al, 2018, Tsui & Treagust, 2013). Multiple representational use might be the key factor to the improved problem solving and metacognitive skills developed by Modeling Instruction physics students observed by Malone (2008). The improvement of scientific reasoning skills when modeling-based practices are deployed have been observed by several researchers (Coletta, Phillips, & Steinert, 2007; O'brien & Thompson, 2008; Schuchardt et al, 2008). These model-based practices have also demonstrated increases in students' modeling skills in chemistry (Dori & Kaberman, 2012) and in biology (Passmore & Stewart, 2000).

Research Supporting Engineering Design Challenges

Engineering design challenges have been used effectively at many different grade levels. The use of engineering design challenges has produced conceptual gains in biology and physical science at multiple levels of schooling including college (Sahin, 2010), high school (Apedoe, Reynolds, Ellefson, & Schunn, 2008; Ellefson, Brinker, Vernacchio, & Schunn, 2008; Malone, et al, 2018; Zeid et al, 2014), middle school (Mehalik, Doppelt, & Schunn, 2008) and elementary school (Lachapelle, Oh, & Cunningham, 2017). The use of engineering design challenges have also produced increases in scienctific reasoning skills in eighth grade students (Silk, Schunn & Cary, 2009), mathematical understanding of secondary schoool students (Hernandez et al, 2014; Schuchardt & Schunn, 2016), and student engagement at all levels (Doppelt, Mehalik, Schunn, & Krysinski, 2008; Lachapelle & Cunningham, 2017; Malone, et al, 2018). The integration of dramatic inquiry and other artistic endeavours with engineering design challenges has demonstarted an increase in elementary students' understanding of engineering, tehcnology and science concepts (Tiarani, Irving, Malone, Giasi, & Kajfez, 2018).

Discussion and Implications

The authentic practices of scientific modeling and engineering design challenges have been shown to improve student abilities in a multitude of areas. The incorporation of these practices within classrooms at all levels of schooling should affect the expertise of students in terms of content, problem-solving and reasoning skills. By enhancing students' abilities in these areas, we can produce competent science students ready to be lifelong learners and successful STEM college students. In fact, there is a strong correlation between higher scientific reasoning ability and success in STEM courses both in college and high school courses (Coletta & Phillips, 2005; Coletta, et al, 2007). A concerted effort to implement these authentic practices at all grade levels should allow for the production of a strong STEM pipeline ensuring the necessary STEM professionals for the future development of all countries.

Conclusion and Recommendations

The implementation of authentic practices given the knowledge that success in STEM courses is correlated to scientific reasoning ability makes their incorporation into STEM classes worldwide an equity issue. If we want all students to succeed to their utmost, then authentic practices of STEM education must be incorporated at all educational levels. The incorporation of these practices will lead to a worldwide populace that are STEM literate and ensure economic growth. However, to realize these goals research must be enacted in order to determine how best to implement modeling and engineering at all grades. In addition, longitudinal studies should be conducted to determine the effects over time on the use of authentic practices across multiple grade levels.

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