AC 2010-722: MODELING IN SUPPORT OF THE ENGINEERING DESIGN PROCESS: EXPERIENCES IN THE ELEMENTARY CLASSROOM

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Modeling in support of engineering design process: Experiences in the elementary classroom

Abstract

Increasingly students of all ages should be engaged in science, engineering and computational activities as it is used across an increasing amount of subject areas. Inquiry-based elementary science education provides students with some opportunities to engage in authentic science but the subject area expertise required by teachers can be daunting and time consuming. Currently engineering education professionals are looking for opportunities to positively influence elementary (STEM) experience but the school curriculum demands limit their opportunity to expose students to the benefits of engineering problem solving. Through professional development we have instituted some graphic-based modeling techniques that support and extend current inquiry science curriculum activities and leverage the engineering design cycle. Research and findings done as part of a two-year NSF-supported project in elementary education will be presented, demonstrating how modeling activities in the form of student-produced drawings and notebook entries have been used to help explore scientific and mathematical concepts underlying engineering problems. Specifically, kit-based science and technology education activities that actively support engineering problem-based learning are used as a context for exploring the potential of these graphic-based modeling activities.

Introduction

In recent years K-12 education was to provide a strong foundation in science and mathematics prior to formal engineering education in college. Increasingly, however, “pre-engineering” curricula have been developed as either stand-alone courses or supplemental experiences [1]. To this end, a full or modified version of the engineering design cycle is employed as part of the context and process orientation of the activities [2]. At the same time, kit-based elementary science education has become a prominent strategy among many school districts. An ongoing challenge for both science and engineering education is to provide rich and meaningful context based instruction that is connected to student’s real world experience by moving students beyond process skills to more problem based learning [3]. The National Science Education Standards [4] advocates technology and design as central features to a strong inquiry-based science education. Whereas science helps learners to understand the natural world, the goal of technology is to extend human capabilities and make modifications in the world. Technology design involves the application of knowledge to new situations or goals, resulting in the development of new knowledge [5]. However, recent research has demonstrated that difficulties of effectively bringing substantive math and science content to bear in middle and high school pre-engineering curricula [6]. These challenges for relevant math and science integration are even greater at the elementary level [7]. With little room for new curriculum, there is a need to develop innovative instructional strategies that leverage existing inquiry-based science curriculum to support engineering education goals. We suggest graphic-based modeling as a mediating process between inquiry science and engineering design, providing students with a robust way of using and developing scientific abilities while engaging in engineering problem solving.

Over the years several engineering education research initiatives have developed engineering design cycles appropriate for elementary engineering education [8 7, 9]. Burghart & Hacker's [10] Informed Design framework is an equally suitable heuristic. It relies on students leveraging math and science in order to facilitate design-engineering challenges. From the teacher's perspective, Informed Design engages students with a small set of design steps that are integrated within a scaffolded instructional framework supporting students throughout their design challenge. Briefly, students clarify design specifications and constraints; research and investigate the problem; generate alternative designs, choose and justify optimal design; develop a prototype; test and evaluate the design solution; redesign the solution with modifications; and communicate findings. With few exceptions there are many features within the Informed Design cycle that mirror inquiry-based science.

The National Science Education Standards [4] has provided extensive discussion on the importance and role of inquiry in science. As with Informed Design it is an iterative process, and provides a way of studying the natural world and a means for students to develop scientific ideas. Inquiry science includes science process skills (measuring and creating devices), science content knowledge and the practice of scientific inquiry. For the purposes of this study we are interested in how the inquiry process is used in a similar fashion to the engineering design cycle (as defined by Informed Design) to investigate phenomena, answer questions and solve engineering problems. This is not unlike other initiatives that take a design-science approach to explore engineering problems [9]. Inquiry involves posing questions and making predictions, background research, planning investigations, making observations, gathering evidence, proposing explanations and communicating findings [4]. There are opportunities to use inquiry-based science kits to engage in engineering problem-based learning but the challenge remains identifying the appropriate pedagogical strategies that will expose students to important science concepts—ones that are often abstract and invisible—and use these ideas to help resolve engineering-based design challenges. The introduction of a modeling pedagogy can support students' science and engineering reasoning. For students it provides a framework to engage in personal ideas while testing them against theoretical understanding that impact actual phenomena related to the problem under investigation.

Recent research findings on the role of modeling in science education may provide a useful approach to both respect the desire to provide students with experiences that incorporate the engineering design process but also effectively integrate modeling as a means of substantively incorporating scientific and mathematical ideas into the engineering problems [11]. Modeling as a vehicle for representing simplified yet robust conceptual understandings of natural and man-made systems provides a vehicle for rendering visible abstract ideas and invisible (e.g., too fast or too small) phenomena that underlie decision-making in engineering problem-solving [12, 13] suggest involving learners in modeling practices can help them build subject matter expertise, epistemological understanding, and expertise in the practices of building and evaluating scientific knowledge. As with engineering design and inquiry science, modeling is best practiced as part of an iterative process that occurs throughout the lifecycle of a science investigation or engineering problem [14, 15]. Modeling can be used to illustrate, explain or predict an engineering problem outcome or phenomena, and/or used as an evaluative tool for future redesign and testing of ideas [16]. Graphic-based modeling is a cognitive tool that supports meaning making throughout various aspects of the engineering design cycle and scientific investigation. Modeling helps explain why phenomena occurs rather than simply being a process to capture an event. In order to simplify when and how graphic-based modeling can be used to engage investigations that combine the engineering design cycle and inquiry science we collapsed the three heuristics into 3 phases: planning, observation and testing, and reflection and communication while highlighting where modeling is most useful in supporting student meaning making.

In the *planning phase* of inquiry-based science, it is not apparent predictions can be represented in a preliminary model or that initial questions can be tested prior to conducting an investigation or solution. In the case of the engineering design cycle and graphic-based modeling, the representation and testing of preliminary ideas is encouraged. In the *observation and testing* phase the science investigation encourages recording of events and phenomena. The Informed Design and graphic-based modeling approach encourages recording of events along with testing and redesign to help students uncover the science and math (instantiated in models) needed to understand the event. The graphic-based modeling makes thinking visible and thus suggests students begin the process of developing consensus models—coming to preliminary agreement on what and why an event is occurring, encouraging a reflective practice important in meaning making [11]. Consensus models helps students focus on how science and math concepts need to be deployed to solve the engineering problem and what metrics can be used to evaluate design solutions. In the *reflection and communication* phase inquiry-based science and graphic-based modeling highlight the need to answer and explain findings. Modeling extends this phase to encourage students to generalize their understanding of the event or phenomena across a variety of design scenarios (Table 1).

Table 1: Comparing and contrasting inquiry science, engineering design (Informed Design) and modeling

Inquiry-based Science	Informed Design	Graphic-based modeling
	Planning	
• Pre-Investigation: Asking questions, making predictions, explaining predictions	• Clarify design specifications: Describe the problem • Research the problem: Identify related problems and issues and complete skill building activities • Generate alternative designs: Develop new ways to design a solution • Justify optimal design: Rate and rank the alternative designs and the specifications and constraints • Develop a prototype: Make a model of the solution	• Anchoring phenomena: Introduce a driving question • Construct a model: Determine key elements to represent and their underlying behavior • Empirically test the model: Investigate the phenomena
	Observation and Testing	
• During Investigation: Describe materials and methods and record observations	• Test and evaluate the design: Collect and analyze performance data • Redesign solution with modifications: Identify variables that affect performance and determine which science concepts and mathematical models are most appropriate in the redesign	• Test the model: Against initial assumptions and other ideas/theories • Revise the model: Compare competing models and construct a consensus model
	Reflection and communication	
• Post Investigation: Answering questions and, explaining, comparing and presenting findings	• Communicate findings: Complete design portfolio or report	• Use models to predict and explain: Generalize models to other phenomena

Based on the following sources[10, 13 17]

Modeling in the form of structured drawing activities can easily be brought in as part of this process in the elementary classroom as a way of moving ideation drawings beyond simply representing macro-scale proposed or as-built designs, to linking outcomes to the underlying (invisible/abstract) scientific or mathematical ideas that ultimately drive the design [9]. To do this, however, strategies for integration of engineering design into existing science and math instruction that reflects the realities of classroom instructional constraints and student capabilities. This study provided a ground-truthing of how science is currently conducted, what role graphic-based modeling currently plays, and what are the opportunities for engineering design experiences.

Methods

Over the past two years student notebooks from six area elementary schools grades 2-5 were collected, photographed, coded and analyzed to establish the types of graphics being used and in what context. We requested a random sample of 8-12 notebooks per teacher at the end of each 9 week unit. In order to further our understanding of the notebook entries the research team participated in extensive classroom observations. The "science and graphic" observation protocol captured the classroom culture, the nature and objectives of the investigation, instructional pedagogies, how modeling was implemented and a host of classroom interactions. Teacher semi-structured interviews were conducted to further the researchers understanding of how models were used during classroom investigations, what explanations and reflections were the students able to achieve as a result of working with graphic models, and how student-generated models aided teacher formative assessment. Student interviews were performed to help indentify student scientific thinking and new learning as a result of modeling during inquiry and problem solving investigations. In conjunction with this work, the research team had implemented a series of teacher professional development training on the use of graphic-based modeling techniques. As a result of these ongoing efforts the research team had amassed a database of several thousand images covering eight science units. This research will present findings from activities from the Sound, Landforms, and Motion and Design kits developed by Insights™, FOSS™ and STC™ , respectively.

Results and Discussion

Sound Kit: Exploring Pitch and Vibration

This kit provides students with opportunities to think about sound from a variety of perspectives. They identify the various sounds recorded on CD, compare and contrast indoor sounds to outdoor sounds, remaining attentive to high versus low sounds, how yelling is different from whispering, and how sounds are created by their own bodies distinguishing vibration from buzzing and flat sounds. Using a variety of materials and instruments (tuning fork, kazoo, peg board and drum) the students explore and test differences in sound associated with changes in material properties and size. These notebook entries tell a story of a student's exploration of sound.

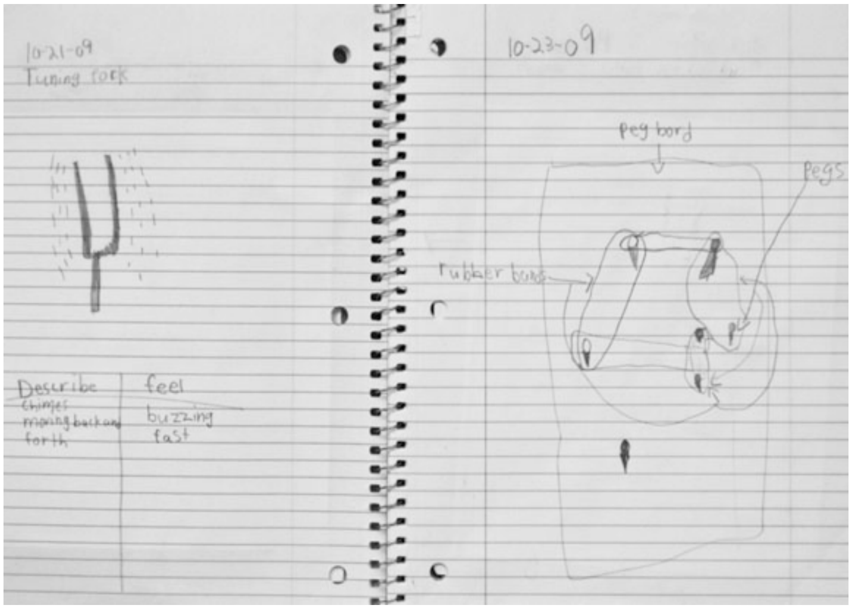

Figure 1: Modeling the invisible, exploring vibration and pitch

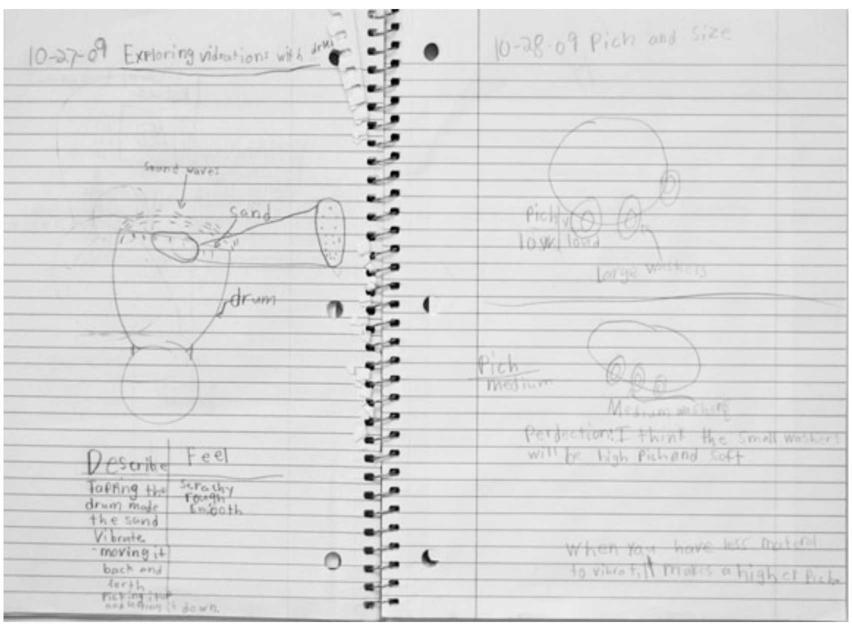

Figure 2: Exploring vibration and pitch due to changes in size and materials

Figures 1/2: Testing and Modeling Phase (Table 1)
In this sequence of entries students are being asked to explore and model characteristics of sound. In Figure 1, (left side) students explore the vibration created by striking a tuning fork and utilize a graphic representation of waves (curved dotted lines) to illustrate their propagation. The use of the curved line is a modeling technique introduced to the students prior to this lesson to support student meaning making about invisible and/or very small phenomena. A follow up to this entry was to have students place the tuning fork in water. In Figure 2, (left side) students further their understanding of wave propagation by observing the interaction between the

movement of the drum and the reaction of the sand. In this instance students isolate the sand motion by using a magnifier tool. The magnifier is another graphic tool (scale tool) students were provided to support their observation and thinking about things that are very small. In this case students were reasoning abstractly about waves coming from different apparatus.

As Hester and Cunningham [7] suggest, students have a natural inclination to design and build things. The next entry Figure 1, (right side) illustrates the students design of a peg board apparatus to further explore differences in sound. In this instance the spacing and size of the elastic band around the peg board create changes in volume and pitch. The movement of the elastic band is similar to their graphic representation of the waves coming from the tuning fork. These relationships are an important feature in modeling as Hsin-Kai [8] suggests, modeling provides opportunity to understand complex relationship and interactions. Lastly, Figure 2 (right side) students tested changes in pitch using different size washers attached to a string. Students use annotations near and around the washers to indicate the differences they heard. The use of annotations is an important aspect in reasoning with models and sketches [18]. Both the peg board and washer activities could be aligned to serve Informed Design goals by asking students to establish goals, in terms of pitch, for their designed devices. They would then use their knowledge of material characteristics (and how they can be manipulated by stretching or weighting them) to model different design alternatives.

Motion and Design: Vehicle with a Sail Investigation
A scenario or design challenge introduces students to each major investigation in the motion and design kit. Students explore, design and test a variety of science and engineering related concepts tied to Newtonian physics (e.g., friction and gravity) that are integrated with ideas associated with form, function, and performance.

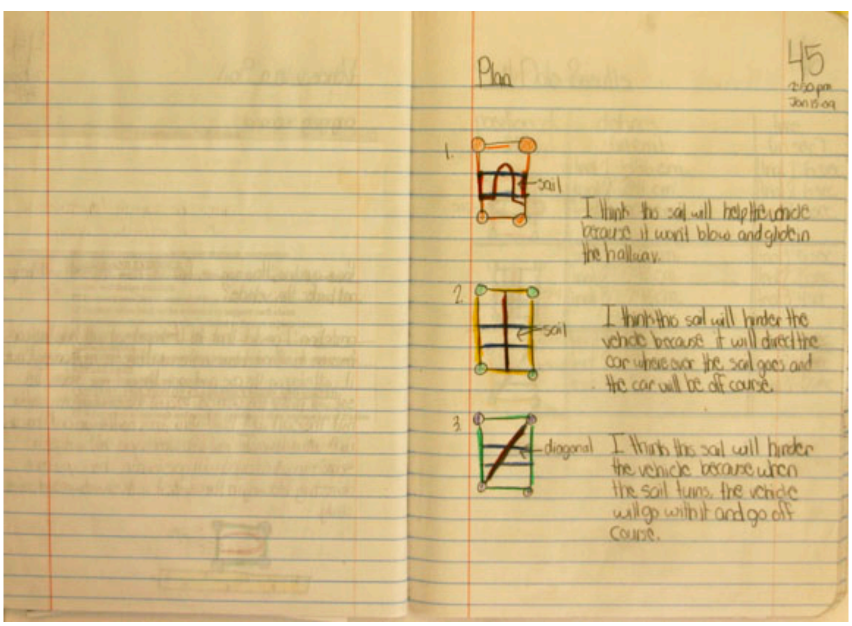

Figure 3: Predicting and designing alternative sail designs to measure differences in vehicle travel

Figure 3: Testing and Modeling Phase (Table 1)
Prior to the student observations they are given a scenario to help contextualize the investigation. This is in keeping with the work by Etheredge [3] and Genalo et al. [19] who suggest the importance of offering students authentic experiences that reflect how engineers think and approach problems. Once the class is able to develop their own predictions they can work in teams and plan their designs (Figure 3). This is an important step in the early stages of modeling—providing students with opportunities to clarify the problem and express initial ideas using graphic models [13].

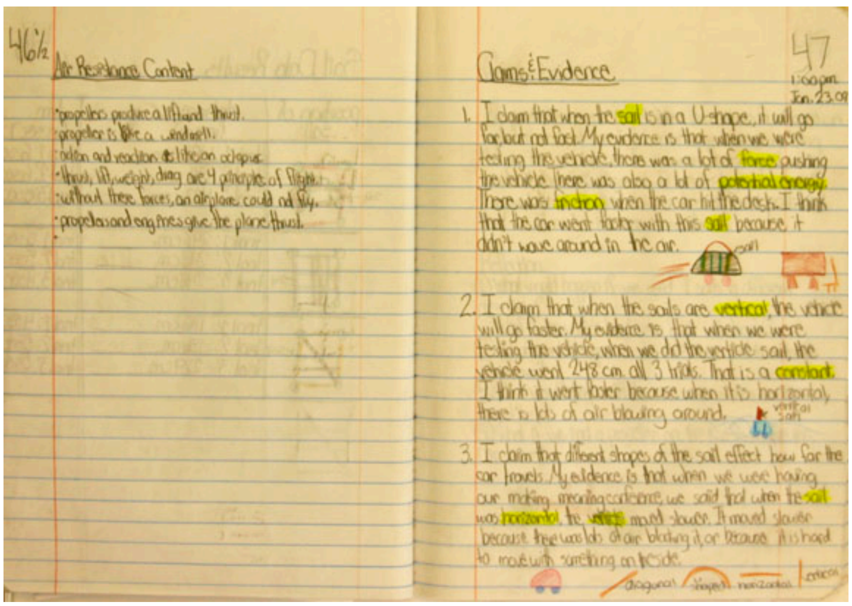
Figure 4: Claims and evidence entry

Figure 4: Reflection and Communication Phase (Table 1)
In Figure 4 students are given the task of stating their claims and evidence. This provides them with an opportunity to revisit their previous entries and models to determine whether or not they were able to answer the question at hand. In answering their prediction they must incorporate the science and design knowledge used throughout the process. As student B states "…when we were testing the vehicle there was a lot of force pushing the vehicle, there was a lot of potential energy. There was a lot of friction when the car hit the desk." Along with this quote the student provided thumbnail representations of the car moving. The student was combining process knowledge with critical thinking, important science and engineering skills [3] [6]. This stage is synonymous with the stage in modeling where students reflect and communicate their findings as a means of trying to generalize their scientific understanding [13]. An opportunity to tie their knowledge about friction and potential energy back to a scenario where students were being asked to solve a particular transportation problem would provide an opportunity to develop an activity that incorporated Informed Design more explicitly.

Landforms: Stream Tables

The Grade 5 Landforms kit provides students with several opportunities to work with physical models as they explore the science behind landforms. They have opportunities to model their local surroundings, translate these models into maps, and test concepts of erosion, deposition and stream flow in the making of new landforms. Ideas of scale, for instance how the Grand Canyon was created, and why and how rivers work, are tested using stream tables. Each investigation is introduced with a scenario with ample time for reflection and scaffolding throughout the instruction was observed.

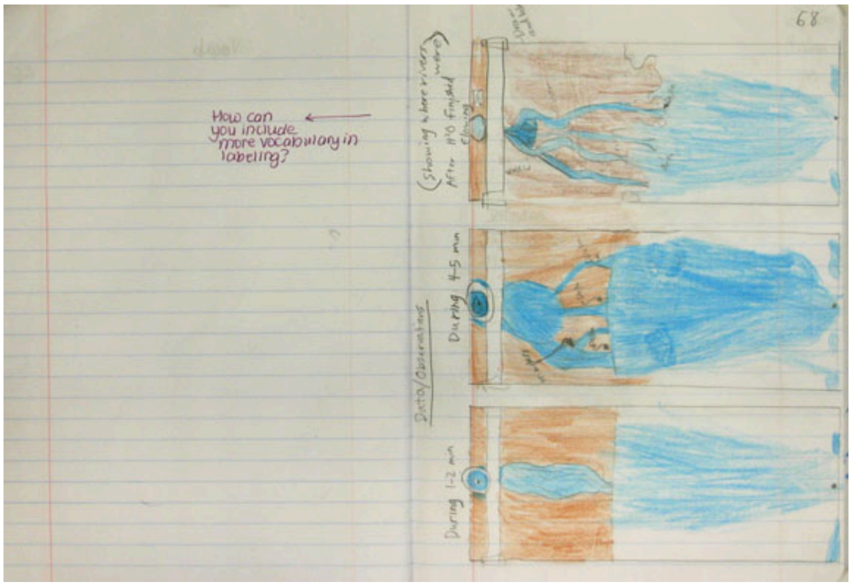

Figure 5: Modeling change over time of how landforms are created

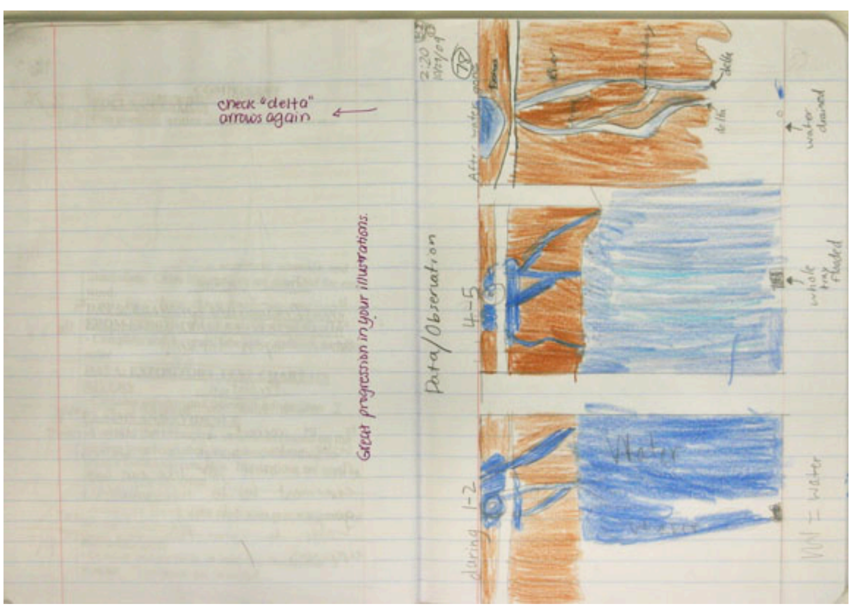

Figure 6: Modeling change over time

Figures 5/6: Testing and Modeling Phase (Table 1)
Prior to testing and documenting their observations students are given the opportunity to develop a list of vocabulary words they can use to annotate their models and include as part of their written observations. The importance of this sequence is two-fold: one they are interpreting the impact water has on creating landforms in this case rivers, deltas and floods. As they are testing the rate at which they pour the water, they are comparing their simulations against photorealistic images provided by the teacher and having to consolidate their ideas into these graphic models. In Figure 5 the student is given feedback by the teacher "You can include more vocabulary in labeling." In Figure 6 the student is given another opportunity to test their ideas on how landforms are created and does a better job of annotating their graphic model. This is akin to the iterative process discussed across the engineering design cycle and modeling literature [10, 13]—something that is not always explicit even though encouraged in scientific inquiry. However, as was seen in the other activities, data collection around iterations of the model were a means for exploring science concepts rather than refining engineered designs.

Conclusion

Within these elementary kit based science activity examples, there was opportunity to incorporate engineering problem based learning using graphic modeling as a mediating process. We are concerned with helping students deepen their understanding of the causes and effect associated with the phenomena under investigation. For instance, how students use an abstract graphical concept such a wave to discuss sound vibration. Or how can modeling support student thinking as they move through various phases of the engineering problem. The mediation is between the graphic model and the exploration of the initial question, the testing of their hypothesis, the testing of actual solutions and how they distill and generalize their findings. Modeling is a graphic vocabulary that can help students reason the multiple aspects of their investigation. As per Table 1, inquiry science, engineering design cycle (Informed Design) and graphic based modeling share many commonalities. Figures 1, 2, 5 and 6 demonstrate the students are provided with several opportunities to explore science concepts in an iterative manner. Revisiting their models and annotations provides them with opportunities to incorporate additional science content and gives the teachers a chance to provide feedback, helping students refine their testing and observations. Another feature these heuristics share is the importance of clarifying the problem through probing designs and prediction. In Figure 3, the student is explicit in detailing the three designs they want to test. An opportunity to plan their investigation using graphic models (representations) helps them think about and isolate certain variables such as the angle, shape and location of the sail on the vehicle. This form of planning might instill mini thought experiments, causing students to create mental models of their ideas, a seminal feature of the graphic modeling process [13, 16]. Finally, Figure 4 illustrates the student's reflective practice through the use of claims and evidence. The student is required to assimilate various perspectives from peers, science and engineering content knowledge and reason the various interactions that exist between the sail and vehicle (e.g., friction, sail angle and shape). This can only be accomplished if the student is given the time to assess and, in some instances, re-evaluate their ideas.

Contribution to engineering education

The three examples given here all make use of modeling in the context of science. To that end, natural and man-made phenomena are modeled and iteratively explored as a means for better understanding science concepts. The opportunity that seems to have been missed is to then place this modeling activity in the context of a engineering problem to be solved. In such a context, the focal science content can then be used, with modeling as the primary tool, to drive informed design decision-making.

The use of modeling has the potential to pull together best practices in inquiry science and engineering design. A common challenge with teachers is time. They are being asked to teach an increasing amount of science content within an inquiry-based framework. If anything, modeling and engineering problem solving require more time to properly execute. In order to strike a balance between elementary teachers' time constraints and the needs for students to experience contextualized science and engineering learning, there needs to be an acknowledgement that teachers need assistance in identifying the important and appropriate science content that best prepares student for future STEM disciplines or more generally provides a foundation for scientific literacy. Incorporating modeling and the engineering problem cycle helps to expose the important science concepts teachers and students need to be working through. Modeling helps to identify the important phenomenological interactions between materials and invisible forces. Modeling can be a fun but rigorous process, forcing students to test their competing ideas or, at minimum, explore various perspectives. Finally, modeling and more broadly the interactive process it demands helps students to develop generalized scientific explanations that can be leveraged in other investigations of similar or different context.

The engineering education community should work with the kit based science publishing community to exploit the opportunities inherent in these kits and at the same time add value by suggesting the incorporation of engineering problem solving and modeling throughout students science investigations. It will help expose and deepen the science content knowledge mentioned in the science kits that are never truly tackled within science instruction classroom experience.

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