STEM Thinking in Informal Environments:
Integration and Recommendations for Formal Settings

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Abstract

Learning in informal environments often takes the shape of authentic learning experiences that lend themselves to integrated perspectives. In addition, learning in informal environments typically does not silo understanding into distinct disciplines as often encountered in formal education. As engineering education researchers begin conducting research on learning in informal environments, understanding how engineering thinking occurs in informal environments can inform meaningful learning experiences in both informal and formal settings. Furthermore, learning in informal environments can be viewed as low-risk venues for educational experimentation that may inform STEM (science, technology, engineering, and mathematics) integration designed for formal learning environments. Identifying boundaries that separate science thinking, technology thinking, engineering thinking, and mathematical thinking in informal environments can be difficult since significant overlap exists in the various learning spaces. Instead of trying to dissect these boundaries, it may be useful to identify examples of each and understand how these seemingly independent ways of thinking can be integrated in a holistic concept of STEM thinking in informal settings. This paper will provide a synthesis of previous research focused on learning in informal environments with concrete examples of activities that can foster STEM thinking and recommendations for integrating aspects of STEM thinking.

Introduction

Learning can occur in a variety of environments and contexts which includes but is not limited to everyday learning, family learning, learning in designed spaces, learning from media or learning in out-of-school time[1]. Within the diverse ways that learning in informal environment occurs, there are different themes of integration, which include integrating previous knowledge with new experience, integrating multiple goals with contextual limitations, and integrating diverse perspectives within a single activity. We chose to examine how STEM thinking is integrated in learning in informal environments with the purpose of informing formal learning practices. STEM thinking may be defined as purposeful thinking and learning that incorporates concepts, methods, and attitudes from science, technology, engineering, and mathematics; and includes critical thinking, modeling, systems thinking, creativity, collaboration, communication among other modes of cognition[2].

Understanding how integrated STEM thinking may occur is crucial to engineering education as engineering instruction and curricula are increasingly focused on how students can integrate knowledge across domains to address engineering problems[3]. In addition, integrative activities can promote more meaningful learning, motivation, and retention[3]. This paper intends to serve as a resource for engineering educators by presenting a synthesis of STEM thinking in informal environments through a discussion of its facets and integrative nature, as well as recommendations for integrating STEM thinking for engineering education. Additionally, we hope to encourage research in engineering education in informal environments for better understanding of how learning in informal environments occurs and to what extent it informs practices in formal environments.

Formal and Informal Learning

The model of learning in informal environments used to situate this synthetic study is one that encompasses environments or activities that provide entrance to and sustained engagement in STEM thinking, as well as purposeful informal education with identified learning goals. The boundary between informal and formal learning environments is blurry at best, but characteristics of each can be useful in understanding the distinction between modes of learning. In a recent conference paper, *FILE: A Taxonomy of Formal and Informal Learning Environments,* Dorie et al.[4] developed and discussed the various dimensions of formal and informal learning environments. A schema was developed to distinguish formal and informal environments because the boundaries are not clear in all cases[4]. While there are activities and environments which may be purely formal or informal, Dorie et al.[4] presented an innovative model to examine the formality of learning environments. According to them, all learning activities and environments fall within a continuum between formal and informal. For example, instruction in the classroom may be considered a formal environment; however, if the instructor takes the class to an exhibit, the formal environment has now entered an informal space.

The taxonomy presented by Dorie et al[4] does not make clear distinctions between learning activities but rather shows how diverse learning environments can be used to complement each other. The authors state that at times constraints of a formal environment can restrict what can be learned by the student. When this occurs, instructors should be aware of additional informal learning environments to re-engage the learning opportunity. Although the taxonomy as described was primarily concerned with only science learning in informal environments. The source literature used to create the taxonomy includes examples of learning and environments across STEM fields. This suggests that this framework may be appropriate for understanding the integrated nature of STEM thinking in informal environments.

Examples of STEM Thinking

An understanding of engineering relates concepts from science, mathematics and technology. This section provides examples of STEM thinking segmented by content area as a means to organize our review of current literature. The discussion begins with science thinking, which is where the most work on learning in informal environments has been done followed by mathematics, engineering and technology. The individual strands are integrative by nature and can lead to better conceptual understanding, to increased collaboration and to a greater awareness of different cultural perspectives in STEM thinking.

Science Thinking

Science thinking revolves around the "dynamic refinement of scientific understanding of the natural world[1]." When engaged in science thinking, individuals ask and answer questions through the process of evaluating evidence. Museums are one of the most common informal settings for disseminating science concepts. Other sources of learning in informal environments include everyday experiences such as nature hikes, designed experiences such as science centers or zoos, and informal school programs such as science clubs. Student outcomes associated specifically with informal science learning have been developed to include "experience excitement, interest and motivation to learn about phenomena in the natural and physical world," and "think about themselves as science learners and develop an identity as someone who knows about, uses, and sometimes contributes to science[1]."

Dierking and Falk[5] found that when families participate in learning within the setting of museums, they attempt to connect their experience to their prior knowledge, which likely comes from formal environments. In fact, it has been found that when exposed to engineering education, most students do not "understand the distinction between science and design[6]." An opportunity for connection between formal and informal environments could exist through field trips or classroom outings. Making connections between formal and informal environments can help students to make their learning whole. The desire to make the connection between science and engineering more explicit is represented formally through the inclusion of engineering standards within the new national science standards[7]. STEM thinking in informal environments is not only limited to science; it also includes technology, engineering, and mathematics.

Mathematical Thinking

Science, technology, and engineering thinking all include aspects of what may be considered mathematical thinking. It may further be characterized by Schoenfeld's[8] five aspects of mathematical thinking: content knowledge, problem solving strategies, the use of available resources to solve problems, beliefs about the utility of mathematics and mathematical practices.

The following study is an example of students' use of mathematics thinking in an robotics competition. The discussion in this section will explore ways the student utilize mathematical thinking in design contexts as well as the means by which students may acquire mathematical knowledge, beliefs and skills through interaction with their peers and their family. Silk et al.[9] performed an exploratory study of middle and elementary school students to investigate whether the use of mathematics in terms of proportional reasoning contributed to the success in their design solutions. They based their results on the data gathered from two surveys and structured interviews with sixteen teams participating in a robotic competition. The two surveys were focused on the use of mathematics in problem solving and in robotics, and the interviews aimed to explore the design strategy chosen by each team. The results showed that although there was a wide range of design strategies used by each team, most of the teams did not use extensive mathematics in their design process, which showed a varying relationship between use of mathematics and success in the competition. However, all the teams, successful and unsuccessful, which used mathematics in their design process exhibited improved performance on transfer test of robot problem solving and acknowledged a boost in their interest in mathematics after participating in the competition. Mathematical thinking can also include optimization of more real-world contextual problems.

Goldman et al.[10] point out that children learn from observing and engaging in various mathematical activities in diverse contexts within their families, but these rich sources of socially distributed mathematical activities are not duly recognized in mathematical learning and teaching. They based their findings by interviewing twenty families with middle school aged children. The aim of these interviews was to build a bridge between classroom and everyday mathematics by identifying opportunities for mathematical learning for kids in social, cultural, and material contexts within their families while exploring the resources used within families for problem solving. Four prominent features of mathematical activities within family life emerged from this study. Firstly, mathematics itself follows everyday problems from very complex and occasionally occurring problem like designing a bathroom to very simple and everyday problem like paying bills. Secondly, family values and preferences guide problem solving and mathematical activities within homes, for example, family members choosing between the option of renovating kitchen themselves or hiring someone for it. Thirdly, unlike mathematical teaching at schools where mathematical problems are designed to facilitate understanding single mathematical concepts, problem solving at home gives way to choice and use of range of mathematical concepts within similar situations. Lastly, all mathematical activities at home ranging from playing games to managing debt are embedded and distributed in social, historical, and cultural situations. Many ways of thinking that can be considered mathematical are represented throughout other STEM areas. In fact, mathematical thinking can provide the base upon which other STEM thinking and activity can be built. This leads to examples of engineering thinking, which is commonly recognized as the application of math and science.

Engineering Thinking

Within STEM learning spaces there is boundary overlap; however, a distinction between engineering and the other three disciplines can be made due to its unique focus on design. Through informal engagement in engineering design, students may begin to experience a paradigm shift in thinking about the engineering design process. Traditionally, students are taught that they will solve engineering problems by exercising linear processes, including the following: asking questions, translating the problem into models, developing an equation to find unknown values, and confirming that the calculated values satisfies the condition of the problem[11-13]. This way of solving design problems does not allow the student to develop the ability to deal with the uncertainty and iterations which characterize real engineering design problems. Furthermore, the current methods of teaching engineering design provide too much information to the students. Too many of the parameters are either already given or are easily accessible. However, in authentic engineering design the path to a solution may not be so linear[14]. Therefore, through learning experiences --both formal and informal--students should become comfortable with constraint-rich, ill-defined problems.

P-12 Informal engineering learning spaces include museums, outreach programs, robotics competitions and afterschool programs. Aspects of engineering thinking that students learn from these informal settings are optimization and tradeoff, mathematical modeling in engineering contexts and iteration. In addition, students' mathematical thinking can also be elicited from these engineering focused activities[9]. For example, the robot design contest offered students an informal learning environment to apply mathematical modeling in order to optimize control of the robot. These students developed a mathematical model that related motor rotations to distance traveled.

Gainsburg[15] conducted an ethnographic study of five junior-level and four senior-level structural engineers working in their offices to capture their mathematical behavior and modeling in practice. She intended to observe engineers' mathematical behavior at work to see how school mathematics relates to the mathematics in practice. She observed that the engineers in practice engage in many aspects of modeling like selecting, applying, adapting, and creating models and engineers in practice are sometimes required to devise mathematical models and strategies to analyze the structures and their behavior. From observing modeling activity of these engineers, she proposed two particular challenges for K-12 school mathematics. One challenge is to prepare students to understand the inaccessible phenomena through modeling as compared to the well-structured modeling currently taught to the students in school. The second challenge is to prepare students to keep mental track of multiple, elusive and abstract models simultaneously as compared to working with a single concrete model at a time. These challenges should be considered while designing informal learning spaces and activities for students. For example, the integration of mathematical thinking through modeling is a critical aspect of the aforementioned informal learning spaces like robotic competitions and afterschool programs.

Technical Thinking

In comparison to mathematical, scientific, and engineering thinking, "technological thinking" is perhaps the least developed and least studied. This is partially due to a push from within the technology education community to align technology education with the engineering design process, where the engineering design process is the core competency and way of thinking that is taught[16]. Some scholars have defined technological thinking more explicitly. For example, Fanta-Vagenshtein and Chen[17] define technological thinking as:

> "The ability to solve technological problems using cognitive skills such as system thinking, problem solving, planning and preparation, decision-making, application and evaluation (Chen & Stroup, 1993; Simon, 1985). This is a person's ability to overcome his physical limitations aimed at addressing human needs (Chen, 1996, 1998; Mioduser, 1998) using the following cognitive skills: future-oriented thinking, system thinking, problem-solving, planning and preparation, decision-making, application and evaluation (Chen & Stroup, 1993; Simon, 1985)."

Even in this definition of technological thinking, however, there are many similarities to engineering thinking and engineering design thinking; terms such as "systems thinking," "problem solving," "decision-making" and "addressing human needs" are often used to describe engineering. Fanta-Vagenshtein and Chen[17] also describe technological thinking in terms of having a sense of knowing how things fit together and in terms of having a sense of how things work.

Recent research on the development of technological thinking in informal learning environments mainly has focused on children's development of technological thinking, or technological fluency, in everyday settings with parents. Barron and her colleagues[18] interviewed eight middle school students and their families to identify different roles that parents adopt as they help children develop technological fluency: teacher, collaborator, learning broker, resource provider, nontechnical consultant, employer and learner[18]. Their findings suggest that the parents of the students participating in the study played significant and varied roles in supporting their children as they engaged in creative technological activities.

Projects such as the Robot Diaries[19] show that learners also develop technological thinking through programs. The Robot Diaries project builds on other programs that have been designed to help pre-college students gain interest in and understanding of STEM concepts through the design of robots, often in competitive environments. The Robot Diaries departs from these other programs in the shift away from competitions, an explicit focus on engaging girls, and a social context prompting the creation of the robots (girls were prompted to create a customizable robot that could serve as a means of expression for its creator). The specific technological knowledge assessed in this study was participants' understanding of the different components of the robots (e.g. sensors, motors), including an ability to name and describe each component, and an ability to describe how things work (in this case how a particular robot works). The authors developed their assessment strategy based on the American Association for the Advancement of Science (AAAS)'s[20] benchmark for students in 6th through 8th grade's understanding of technical systems. This standard states that students should be able to:

> "Analyze simple mechanical devices and describe what the various parts are for; estimate what the effect of making a change in one part of a device would have on the device as a whole[20]."

While Hamner and her colleagues'[19] focus on naming components and describing their function and how their work helps to set technological thinking apart from engineering, the AAAS[20] benchmark re-emphasizes the interrelatedness of technology, engineering, mathematics and science as there are aspects of the benchmark that resonate with each of the strands of STEM thinking.

Recommendations for Integration in Formal Settings

A key monograph in this field[1] focuses on the *people*, *places* and *pursuits* of learning in informal environments. Similarly, we opted to present recommendations for integrating STEM thinking through targeted discussion on the people, places and pursuits involved. The following sections address *who* benefits from integrated STEM thinking, both through individual cognition and culturally among peoples. An additional section describing opportunities for collaboration describes *where* integration may occur as approaches to learning in informal environments is carried into learning in formal environments. Finally, we focus on *why* and integrated approach to STEM thinking may be beneficial for learning engineering in formal environments.

Conceptual Argument for Integration

We encourage educators to consider integrating lessons from informal learning experiences into more formal settings. Conceptual change theorists[21-22] argue strongly that students need learning experiences anchored in the real world. Ties to the real world often help students apply abstract concepts that are especially present in STEM disciplines.

Vosniadou[22] suggests focusing on identifying micro-concepts from informal settings that undergird students' cognitive models and hinder conceptual learning in formal settings. An example of such micro-concepts is the concept of numbers and counting. This seemingly simple mathematical concept can cause confusion in learning other scientific concepts like density[22]. Vosniadou[22], therefore, emphasizes an intentional integration of STEM concepts in formal and informal settings to support strong conceptual understanding in students.

DiSessa[21, 23-24] presents a constructivist use of learning from informal environments to support conceptual learning in informal environments. According to him, the knowledge gained from informal environments often seem to contradict with expert's knowledge, but it is not a misconception as advocated by many conceptual understanding experts like Kuhn[25]. He calls this knowledge structure a phenomenological primitive or p-prim. P-prims are phenomenological as they originate automatically from interpretations of some experienced reality in informal settings and primitive because they are assumed to be self-evident. Any situation within their span of applicability can activate these p-prims. In formal learning environments these p-prims give way to stronger conceptual understanding when activated in an appropriate context, however, inappropriate contextual activation of these p-prims leads to misconceptions[24, 26-27]. diSessa[21, 23] emphasizes on constructing knowledge in formal settings by identifying and re-contextualizing p-prims from informal environments. According to him, coordinated contextual changes of p-prims learned from informal learning settings create normative scientific concepts.

For example, in a study, when students were asked why weather is hot in summer, most of them replied that it is because earth is closer to sun in summer. This misconception of students is clearly based on an inappropriate activation of the p-prim connecting proximity and intensity (closer means stronger). However, the knowledge, 'closer means stronger' learned in informal environments is not a misconception and will help in knowledge empowerment when activated appropriately in many contextually appropriate formal learning situations[28].

Creating a Culture that Promotes Integration

Creating a culture that promotes integration is vital to successful STEM learning. Considering various aspects of integration may also lead to more robust learning experiences and promote engagement. Classroom discourse may be considered an aspect of STEM learning, as integrated thinking requires understanding concepts from multiple perspectives. It is advised that teachers check with students to make sure that the mathematical terms and mathematical language they use to explain math problems align with student perceptions[29]. Moschkovich[29] provided an example where a teacher asked students to explain what the definitions of different types of quadrilaterals. It was obvious in the students' definitions of the quadrilaterals, that the students assumed a different meaning for some of the mathematical terms than the instructor intended. Determining any disconnect between terms and language early in instruction may allow teachers and students to correct any wrong assumptions. This may also expand upon students' mathematical knowledge when a related topic is discussed or introduced.

Teachers should also consider that students of different cultural backgrounds may assign different meanings and associated feelings with specific terms and phrases and that checking with students may help exposing cultural differences. Cultural differences among students should also be a consideration when creating an inviting learning environment. This does not mean that the material provided to the students needs to be culturally relevant or changed for the students to understand it or find value within it. Rochelle Gutierrez indicates that "the goal is not to replace traditional mathematics with a predefined 'culturally relevant mathematics' in an essentialist way, but rather to strike a balance between opportunities to reflect on oneself and others as part of the mathematics learning experience[30]." Also regarding the effect of culture on learning, "it has been argued that the classroom experiences of minority populations are different from those of nonminority populations[31]." Teachers should respect that students may come from different cultural backgrounds and that language and culture differences may present themselves in the classroom. However, this does not have to be a stumbling block to overcome but can serve as a learning experience.

It has been discovered that a teacher's low or high expectations can affect a student's motivation accordingly[32]. Two studies were considered that looked at how students perceived their teachers' expectations of them and whether this compared to their perceptions of themselves[32]. Both studies indicated that that there was a correlate between the teachers' expectations with the students' own perceptions[32]. It was found in one of the studies that the end outcomes for the classroom expected by the teachers contributed more to the students' own perceptions[32]. This suggests that teachers should consider having high expectations for all of its students, regardless of cultural, gender, and economic background, so that students will therefore have higher expectations for themselves. Another study done by Madden[33] looked at polling teachers and found that teachers utilized the goal-setting method while others utilized the academic expectation method to motivate their students. It was found that the goal-setting method worked more effectively[33]. This indicates that there is material available for teachers to consider to help students employ high expectation motivational methods.

Another example of this looked at math classrooms with a high percentage of Native American students[30]. One teacher explained that she did not require her students to complete math homework because she was told by other teachers that the students would not complete it. But a different teacher explained she required her students to complete math homework. The math performance of the students who were required to complete homework far outshined those that were not. This is another indication that if teachers have "high expectations" and "expected accountability" that so will the students for themselves[30]. The teacher that required homework said she did so because it's "just like we have in the real world" and they "just have to do it[30]."

Formal and Informal Collaboration

Collaboration between formal and informal learning environments is an area of STEM education that is of continued interest to researchers. Studies conducted by Dori and Tal[34] and Wager[35] have sought to directly connect what students learn in formal and informal settings. They believe that there should be tangible connections between what activities students engage in outside of the classroom with what they learn in the formal structured learning environment. Wager[35] discusses that teaching for understanding has been missing one crucial aspect, which is linking school mathematics to student experiences outside of the context of school. She believed that if these two were not in unison, then students learning would be restricted to specific areas of their life. Consequently, the student would only be able to solve mathematical problems within context instead of applying various approaches to the same problem. Dori and Tal[34] argued that informal learning environments, though thought of as the creation of a new learning environment but with fewer restrictions than the formal learning environment, can have lasting effects on the student. As such, students should be engaged in activities that afford them the opportunity to bridge the gap between what they learn in school as well as these external environments.

In the study by Dori and Tal[34] students were given projects to work on that involved addressing practical needs. These projects required the full participation of students, teachers, parents and other community volunteers. Students worked in groups both inside the classroom and at other areas outside the classroom. The project they selected had to be of the nature that would solve some need in their immediate environment. Collectively, the students were expected to incorporate issues that were discussed in the classroom into their final project design. In both instances, formal and informal, the teacher played a key role. The teacher's responsibility in the classroom was to provide the students with all the necessary information they would need to be able to complete the project. The teacher was also involved in the meeting of the groups outside of the classroom. Their role was to ensure that any disconnect being experienced by the student was addressed when next they met in their formal learning environment.

Similarly, Wager[35] recommended four areas that school teachers can incorporate the mathematics students learn in formal and informal settings. Three of these are in direct relation to the student while the fourth is more on the part of the teacher. These areas are:

- using students prior experiences as a context for problems
- linking their prior experiences to school mathematics
- identifying the prominent mathematical practices which are embedded in these experiences
- teacher initiated situated settings, this is the use of shared perspectives in the classroom as a site of culture

This, she discussed, was a main cause for concern since it was apparent that even though the teachers knew the importance of having a connection between formal and informal learning environments, they were challenged in the area of implementing these strategies or even what strategies to use to create this collaboration. Through the use of the workshop teachers were able to have specific examples of how they could include and use these four areas to enrich students learning in the classroom.

Collaboration between formal and informal settings is still a rich area of study for engineering educators. According to Adams and Felder[36], research on the activities students engage in has taken on a new life of its own to push the boundaries of the formal learning environment to informal spaces. The new emerging belief is that informal learning environments provide the student with a wealth of experiences that can be used to inform formal learning environments. In STEM education, students need to be motivated to learn difficult concepts and to be able to transfer them from one context to the next. In order for this to be effective, students must be able to see the relation between the formal and informal learning environments, why it is important that they engage in both areas and what life-long advantages they can gain from the formal and informal activities they participate in.

Providing Students with Opportunities for Integrated Thinking

Many engineering activities require students practice integrated forms of thinking. Mousoulides and English[37] describe how elementary students approach engineering design activities known as Model Eliciting Activities. When using Model Eliciting Activities, instructors present students a complicated situation that requires students develop a mathematical model to predict likely scenarios. The situation described below can be used as a Model Eliciting Activity because students need to formulate some quantitative model in order to offer advice:

"In 1993 the worldwide reserves of natural gas were estimated to be 141.8 billion cubic metres. Since then 2.5 billion cubic metres have been used every year on average. The Ministry of Communications and Works is thinking on placing a large investment on building natural gas and oil refinery stations. Calculate when the reserves of natural gas will be exhausted, so as to advise them whether they should proceed with the investment or not[37]."

This problem is an open-ended problem[38] where students can approach the problem from many different angles. Informal learning environments generally afford students with more space to explore these different angles and frequently provide students space to practice more forms of exploration. Recognizing that Model Eliciting Activities are open-ended problems, formal educators have many options to give students opportunities to explore these problems. Most commonly, educators using Model Eliciting Activities will allow students to conduct further research on the internet to propose several models[37]. Alternately, educators provide space for different forms of thinking by changing the instructions to differentiate how student teams approach this problem[39]. Educators may consider hosting a debate where students argue for or against investing in natural gas and oil refinery stations, ask students to explain how governments could calculate the amount of natural gas used every year, or write letters to the editor about the wisdom of using natural gas. Even formal educators can look for opportunistic opportunities to engage the interests of their students[1].

Conclusion

From the examples provided, it should be clear that aspects of science inquiry, design, mathematical modeling and methods of computation can be integrated to support engineering education[2]. It is not new to claim that engineering education requires integration of knowledge and skills in science, mathematics and technology; however, by understanding how aspects of scientific, mathematical, engineering and technological thinking are activated through learning in informal environments, we may be better equipped to incorporate integrated STEM thinking in formal engineering education. Additionally, in describing recommendations for integration in formal environments, we hope to have shown that considerations should be made regarding the people, places and pursuits of any educational endeavor. We hope that this synthesis may serve as a jumping off point for further engineering education research exploring learning engineering in informal environments, as well as how further understanding in this area may inform engineering education in formal environments.

References

1. National Research Council, *Learning science in informal environments: People, places, and pursuits*, ed. P. Bell, et al. 2009, Washington, D.C.: National Academies Press.
2. National Research Council, *Engineering in K-12 education: Understanding the status and improving the prospects*, ed. L. Katehi, G. Pearson, and M.A. Feder. 2009, Washington, D.C.: National Academy Press.
3. Everett, L.J., P.K. Imbrie, and J. Morgan, *Integrated curricula: Purpose and design.* Journal of Engineering Education, 2000. **89**(2): p. 167-175.

4. Dorie, B.L., et al., *FILE: A taxonomy of formal and informal learning environments*, in *ASEE 2012 IL/IN Sectional Conference*. 2012, American Society for Engineering Education: Valparaiso, Indiana.
5. Dierking, L.D. and J.H. Falk, *Family behavior and learning in informal science settings: A review of the research.* Science Education, 2006. **78**(1): p. 57-72.
6. Downey, G.L. and J. Lucena, *When students resist: Ethnography of a senior design experience in engineering education.* International Journal of Engineering Education, 2003. **19**(1): p. 168-176.
7. National Research Council, *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*, ed. Q. Helen, S. Heidi, and K. Thomas. 2012, Washington, D.C.: National Academies Press.
8. Schoenfeld, A.H., *Learning to think mathematically: Problem solving, metacognition, and sense making in mathematics*, in *Handbook of research on mathematics teaching and learning*, D.A. Grouws, Editor. 1992, Macmillan: New York. p. 334-370.
9. Silk, E.M., R. Higashi, and C.D. Schunn, *Resources for robot competition success: Assessing math use in grade-school-level engineering design*, in *2011 ASEE Annual Conference and Exposition*. 2011, American Society for Engineering Education: Vancouver, B.C. Canada.
10. Goldman, S., et al. *Math engaged problem solving in families*. in *Proceedings of the 9th International Conference of the Learning Sciences-Volume 1*. 2010: International Society of the Learning Sciences.
11. Atman, C.J., et al., *Engineering design processes: A comparison of students and expert practitioners.* Journal of Engineering Education, 2007. **96**(4): p. 359.
12. Dym, C.L., et al., *Engineering design thinking, teaching, and learning.* Journal of Engineering Education, 2005. **94**(1): p. 103-120.
13. Jonassen, D., J. Strobel, and C.B. Lee, *Everyday problem solving in engineering: Lessons for engineering educators.* Journal of Engineering Education, 2006. **95**(2): p. 139.
14. Hjalmarson, M.A., M.E. Cardella, and R. Adams, *Uncertainty and iteration in design tasks for engineering students*, in *Foundations for the Future in Mathematics Curriculum*, R.A. Lesh, E. Hamilton, and J.J. Kaput, Editors. 2007, Lawrence Erlbaum Associates: Mahwah, NJ.
15. Gainsburg, J., *The mathematical modeling of structural engineers.* Mathematical Thinking and Learning, 2006. **8**(1): p. 3-36.
16. Wicklein, R.C., *Five good reasons for engineering as the focus for technology education.* The Technology Teacher, 2006. **65**(7): p. 25.
17. Fanta-Vagenshtein, Y. and D. Chen, *Technological knowledge among non-literate Ethiopian adults in Israel.* Knowledge, Technology & Policy, 2009. **22**(4): p. 287-302.

18. Barron, B., et al., *Parents as learning partners in the development of technological fluency.* International Journal of Learning and Media, 2009. **1**(2): p. 55-77.
19. Hamner, E., et al., *Robot diaries: Broadening participation in the computer science pipeline through social technical exploration*, in *AAAI Spring Symposium on Using AI to Motivate Greater Participation in Computer Science*. 2008, Association for the Advancement of Artificial Intelligence: Palo Alto, CA.
20. AAAS, *Atlas of science literacy*. Vol. 2. 2007, Washington, DC: American Association for the Advancement of Science and National Science Teachers Association.
21. diSessa, A.A., *A bird's-eye view of the "pieces" vs. "coherence" controversy*, in *International handbook of research on conceptual change*, S. Vosniadou, Editor. 2008, Routledge: New York. p. 35-60.
22. Vosniadou, S. and X. Vamvakoussi, *Examining mathematics learning from a conceptual change point of view: Implications for the design of learning environments*, in *Instructional psychology: Past, present and future trends. Sixteen essays in honour of Erik De Corte*, L. Verschaffel, et al., Editors. 2006, Elsevier p. 55-70.
23. diSessa, A.A., *Unlearning Aristotelian physics: A study of knowledge-based learning.* Cognitive Science, 1982. **6**(1): p. 37-75.
24. diSessa, A.A., *Toward an epistemology of physics.* Cognition and Instruction, 1993. **10**(2/3): p. 105-225.
25. Kuhn, T.S., *The structure of scientific revolutions*. 1970, Chicago: University of Chicago Press.
26. diSessa, A.A., *Why "conceptual ecology" is a good idea*, in *Reconsidering conceptual change: Issues in theory and practice*, M. Limón and L. Mason, Editors. 2002, Springer. p. 28-60.
27. diSessa, A.A. and B.L. Sherin, *What changes in conceptual change?* International Journal of Science Education, 1998. **20**(10): p. 1155-1191.
28. Hammer, D., *Student resources for learning introductory physics.* American Journal of Physics, Physics Education Research Supplement, 2000. **68**(S1): p. S52-S59.
29. Moschkovich, J., *Examining mathematical discourse practices.* For the Learning of Mathematics, 2007. **27**(1): p. 24-30.
30. Stone, J. and E.T. Hamann, *Improving elementary American Indian students' math achievement with inquiry-based mathematics and games.* Journal of American Indian Education, 2012. **51**(1): p. 45-66.
31. Franke, M.L. and D.A. Carey, *Young children's perceptions of mathematics in problem-solving environments.* Journal for Research in Mathematics Education, 1997. **28**(1): p. 8-25.

32. Brattesani, K.A., R.S. Weinstein, and H.H. Marshall, *Student perceptions of differential teacher treatment as moderators of teacher expectation effects.* Journal of Educational Psychology, 1984. **76**(2): p. 236.

33. Madden, L.E., *Motivating students to learn better through own goal-setting.* Education, 1997. **117**(3): p. 368,411-414.

34. Dori, Y.J. and R.T. Tal, *Formal and informal collaborative projects: Engaging in industry with environmental awareness.* Science Education, 2000. **84**(1): p. 95-113.

35. Wager, A.A., *Incorporating out-of-school mathematics: From cultural context to embedded practice.* Journal of Mathematics Teacher Education, 2012. **15**: p. 9-23.

36. Adams, R.S. and R.M. Felder, *Reframing professional development: A systems approach to preparing engineering educators to educate tomorrow's engineers.* Journal of Engineering Education, 2008. **97**(3): p. 239-240.

37. Mousoulides, N.G. and L.D. English, *Engineering model eliciting activities for elementary school students*, in *Trends in Teaching and Learning of Mathematical Modelling*, G. Kaiser, et al., Editors. 2011, Springer Netherlands. p. 221-230.

38. Renzulli, J.S., *What makes a problem real: Stalking the illusive meaning of qualitative differences in gifted education.* Gifted Child Quarterly, 1982. **26**(4): p. 147-156.

39. Hertzog, N.B., *Open-ended activities: Differentiation through learner responses.* Gifted Child Quarterly, 1998. **42**(4): p. 212-227.