A Cognitive Perspective on Integrated STEM Learning

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December 16, 2011

Author Note

A commissioned report for the National Academy of Engineering and National Research Council's committee on determining the value—in terms of student achievement, motivation, career aspirations, and other factors—of integrated K-12 STEM (iSTEM) education in the United States.

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Abstract / Summary

This paper consists of a review of cognitive science literature relevant for understanding the cognitive processes involved in integrated science, technology, engineering, and mathematics (iSTEM) learning environments. The primary objective of this paper is to introduce a set of ideas for thinking about (and associated language for discussing) the cognitive processes that are likely to be involved in iSTEM learning. Those ideas about cognitive processes are likely to help identify opportunities and challenges for iSTEM learning environments, understand why those opportunities and challenges exist, and guide effective redesign of those iSTEM learning environments.

Two noteworthy iSTEM education findings were identified to set the context for connecting cognitive science theories to iSTEM education. The first finding was that students have difficulties connecting general disciplinary knowledge to other-discipline problem solving. The second finding was an apparent asymmetry between the effects of integration on math achievement compared to science achievement. Given these findings, two cognitive science ideas were reviewed: the knowledge integration perspective and structure mapping theory.

The knowledge integration perspective sees knowledge as a repertoire of ideas. This perspective highlights how it is relatively easy to add ideas to students' repertoires but difficult to have those ideas take on connected and central roles. In the context of iSTEM education, the knowledge integration perspective explains the difficulties that students have with connecting other-discipline knowledge in the context of design for science by suggesting that students likely think of the design experiences as generating contextualized knowledge. As a result, students don't tend to use those experiences to build more coherent understandings. Consistent with the knowledge integration perspective, design for science instruction that helps students cue their

experience-based ideas within the design tasks but then also connect those experiences to general science has shown more positive results.

Structure mapping theory sees knowledge as attending to relational structure between learning experiences and new problem solving experiences. This theory highlights the difficulties students have with interference from perceptually rich experiences that compete with (and often hide) the deep structure that is useful for transferring to new problem situations. Structure mapping theory explains why few positive results exist that demonstrate how integration of math with other disciplines benefits math achievement specifically, as it is difficult to attend to the general mathematical structure within the context of perceptually rich science, engineering, and technology problems. Understanding how students can learn about the deep structure of math ideas within rich iSTEM experiences would be a productive focus for future research that both advances research in iSTEM education and in cognitive science.

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Part 1 – Introduction

The goal of this paper is to connect prominent, contemporary ideas in cognitive science with issues in integrated Science, Technology, Engineering, and Mathematics (iSTEM) education. We begin by reviewing selected iSTEM education studies that highlight particular issues in student learning that are common in iSTEM environments. These issues in learning help set the context for understanding how two particularly relevant theories in cognitive science may be useful for understanding and improving iSTEM education environments. We then consider each of these two cognitive science theories in turn by reviewing ideas from the theory that provide descriptions for thinking about how knowledge is organized and the mechanisms involved in learning. For each cognitive science theory, we then also suggest ways in which the theories may explain the noteworthy empirical findings from the iSTEM education literature. Finally, we conclude by reflecting on the process of connecting cognitive science theories of knowledge and learning to iSTEM education and suggest possible future directions for deepening those connections.

Part 2 – Noteworthy Empirical Findings from iSTEM Education

Ultimately, a theory should be able to both explain and predict. In our case, the goal is to be able to explain and predict both opportunities and challenges to the success of iSTEM education efforts. By looking back at empirical results from the iSTEM literature and attempting to explain those results using the lens of particular cognitive science theories, it may be possible to better understand the learning mechanisms involved in iSTEM learning as well as how those learning mechanisms may come into play in predicting outcomes in future iSTEM education efforts. We searched for empirical findings on “integrated STEM”, looking for empirical review articles, common patterns in empirical studies of student learning outcomes, and papers which showed the fine-grained details of student learning processes in integrated STEM contexts. We then synthesized those findings into two particularly noteworthy findings that appeared across many studies and that present interesting issues for the iSTEM education community to try to understand. The following two subsections describe these noteworthy findings and the iSTEM literature upon which they are based. In line with the objective of the paper, we do not systematically review all of the literature on evaluating the effectiveness of iSTEM programs. The other commissioned papers include reviews of that sort covering iSTEM programs in both informal and formal settings. Instead, we focus our review of the iSTEM education literature on a small number of noteworthy findings on learning in those settings that we feel could be informed by cognitive science ideas.

Difficulty Connecting Discipline Ideas in Other-Discipline Problem Solving

Although studies comparing effects of iSTEM programs on student achievement are common, to our knowledge there are fewer examples of empirical studies that delve deeply into students' progression of ideas while engaging in iSTEM problem solving. However, the studies that do exist (e.g., Crismond, 2001) suggest that students are unlikely to spontaneously make connections between the abstract, canonical forms of disciplinary ideas when problem solving in another discipline. A good example of this is Venville, Rennie, and Wallace's studies documenting the problem solving of student teams engaging in an iSTEM experience to build a solar-powered boat (Venville, Rennie, & Wallace, 2004, 2005). Venville et al. documented how the students drew on a number of different knowledge sources in their iSTEM tasks, and if they connected to the canonical science disciplinary knowledge at all, then they did so early on in their designing (Venville et al., 2004). Figure 1 illustrates how two of the teams didn't consider

Archimedes' Principle at all when designing the hull of their boat, despite all having learned it previously and the teacher explicitly encouraging the students to use that science idea when he set up the task. In the two other major design decisions for their boat—the electrical circuit design and the orientation of their solar cell—the student groups did draw on disciplinary knowledge, but in all the observed cases the students only drew on that disciplinary knowledge at the very beginning of their decision-making for the design. When the disciplinary knowledge was not sufficient, they moved to other sources of knowledge. Furthermore, the teams didn't explicitly reflect back upon that disciplinary knowledge at later points in the design either to reconsider how that knowledge could be usefully applied to other design problems or to revise their understanding of that knowledge. In this iSTEM activity, if the science was used at all by the students, it was used less in an integrated, sustained, and back-and-forth relationship with the engineering and technological design, and more as an initial, brief, and one-way starting point for the rest of the activity.

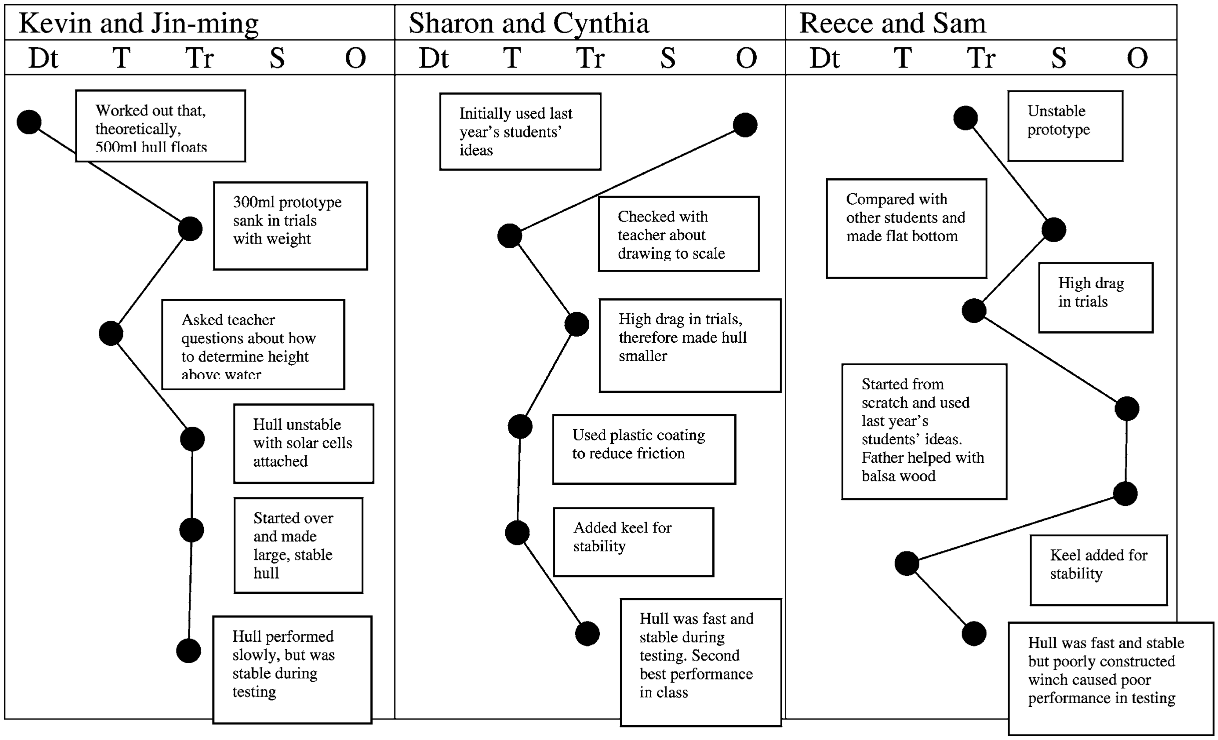

Figure 1. Sources of knowledge used by students when designing a boat hull. Key to sources of knowledge: Dt – discipline theory; T – teacher; Tr – trials and testing; S – other students in same class; O – outside students/parents. (Source: Venville et al., 2004, p. 124)

More problematic than which knowledge sources student teams drew on in their iSTEM activities is what they ultimately learn as a result of the experience. From this same dataset, Venville et al. (2005) observed that the students engaged in solving iSTEM tasks were likely to learn “how” knowledge related to the technological design (e.g., how to build a circuit), but less likely to make progress on the abstract scientific knowledge (e.g., the conservation of current in a circuit). In post-interviews, most of the students in their study continued to hold strongly a consumption view of current rather than the more canonical science model (Venville et al., 2005). The students maintained this problematic view of the science despite gaining usable knowledge about how to build circuits successfully within the solar-powered boat task. Their iSTEM experience included explicit connections between the STEM disciplines made both by their teachers in instruction and on their own in their designing, but that didn't lead to the sort of deep disciplinary understanding that would be expected of a more targeted disciplinary science program.

Similar results concerning the difficulty of using and deepening other-discipline ideas have been observed in other studies, especially ones that involved engineering or technological design as a way to learn science. For example, Penner, Lehrer, and Schauble (1998) documented third grade students designing models of the biomechanics of an elbow that helped the students understand the constraints on the mechanics of the elbow as well as to see patterns to use in optimizing the strength of the elbow. The students developed increasingly useful models of the elbow in a variety of representations, including the use of graphing. However, even with considerable scaffolding the students were not able to successfully develop the more general scientific principles of leverage. Other research focused on how students learn science in the context of engineering design suggests that even though some basic learning of both science and design does occur, it is difficult to get students to abstract general scientific mechanisms that explain their designs (Kolodner et al., 2003). Taken together, this noteworthy finding from the design for science literature generates a number of questions about the kinds of experiences that lead students to recognize the value of knowledge from other disciplines in aiding their current problem solving, to connect that other-discipline knowledge productively, and to have the experience of doing so deepen their understanding of that other-discipline knowledge. Is the most appropriate role of engineering or technological design in learning science simply to serve as a context for applying that science? What sorts of design experiences help students move beyond use of science ideas and actually encourage deepening understanding of those ideas?

Asymmetrical Effects of Integration on Math versus Science

Moving up to the grain size of overall achievement as a result of participation in iSTEM education programs, the most well studied iSTEM education pairing is between the disciplines of mathematics and science. A number of reviews of this literature have been conducted (Berlin & Lee, 2003, 2005; Czerniak, Weber, Sandmann, & Ahern, 1999; Hurley, 2001; Pang & Good, 2000). Even within this pairing, the number of studies that report the effects of integration on student learning separately for the different disciplines is considerably less. Still, enough studies exist to support meta-analyses of the effects. Hurley (2001) conducted a meta-analysis of 31 studies that involved mathematics and science integration compared to a non-integrated control group and reported mathematics and/or science achievement measures. Overall, Hurley reported positive effects for integration in both math (ES = .27) and science (ES = .37), which is consistent with other meta-analyses that report small to medium positive effects of integration (Hartzler, 2000). So at the overall level there does not seem to be a large difference between the effects of math-science integration on students' learning of math compared to their learning of science. Interestingly, however, the effects reported by Hurley (2001) varied both over time and according to the level of integration between math and science. The lowest overall effect size for math achievement (ES = .07) was observed in the 10 most recent studies reviewed (1980s-1990s), and that effect size was lower than all of the time periods for science achievement. This low effect size on math achievement raises questions about the overall effectiveness of iSTEM on math specifically. Although it is not clear why the effect sizes for the most recent results of math-science integration on math achievement were so small, Hurley also separated the achievement results by the level of integration used in the program. The effect size for math achievement was large when using a *sequenced* integration model in which math and science are taught sequentially, one preceding the other. But the effect size was much lower for all other models of integration (see Figure 2). In contrast, science achievement appeared to have increasing benefits from increasing levels of integration, with the greatest benefits observed for *enhanced* or *total* integration. This noteworthy finding that mathematics achievement does not seem to have the same level of benefit from deeper levels of integration that is present in terms of science achievement suggests that there may exist some asymmetries between the disciplines.

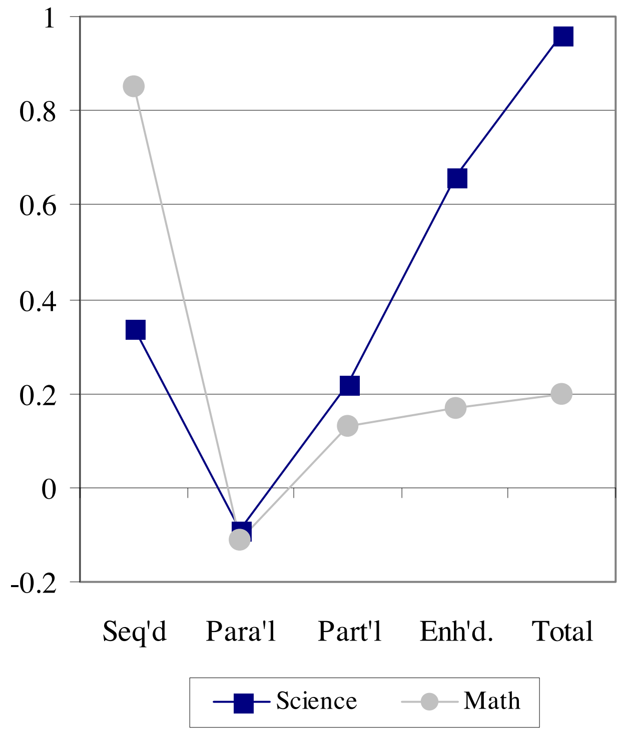

Figure 2. Effect sizes on math and science achievement by level of integration (Source: Hurley, 2001, p. 264).

Other meta-analyses of math and science integration have reported similar findings of less positive benefits of integration for math compared to science (Hartzler, 2000). Relatedly, other research has separately studied the beneficial effect of mathematics on science and the difficulty of positively effecting mathematics achievement by integrating the math into another disciplinary context. For example, Tran and Nathan (2010) provided evidence that there can be a negative effect on math achievement from participation in a pre-college engineering program even when that program specifically targets integration with mathematics. Their work establishes that enhancing math achievement through integration with other disciplines is difficult to do, and there may even be adverse effects. Tran and Nathan did not consider whether increasing levels of math integration within the engineering curriculum or even increasing levels of math outside of the curriculum would predict increasing levels of engineering-related achievement. On the other side of the equation, Sadler and Tai (2007) provided evidence that more math courses in high school do predict better performance in college science courses across all three fields of science studied (biology, chemistry, and physics). That is, math does seem to benefit science. At the same time, only prior high school courses from the same field (biology, chemistry, or physics) predict better grades in the college level course of that science field rather than courses from the other science fields. Sadler and Tai didn't specifically test whether the number of prior high school science courses would predict better college math performance.

Although these studies documented this asymmetry to some extent, to our knowledge no studies of iSTEM integration programs have attempted to explain this finding in terms of differences between the nature of knowledge in those disciplines and how those disciplines are learned. Pang and Good (2000) observed what they termed a "science focus" in the design of the majority of integrated curricular programs. That is, designers of integrated curricula tended to choose science as the primary instructional focus with related mathematics concepts connected in a secondary way. Correspondingly, the evaluations of those programs were more likely to assess improvements in students' science understanding rather than improvements in math. But Pang and Good conclude with calls for more research into this tendency for science-focused integration rather than proposing possible explanations. Is there an explanation in terms of cognitive science theories of learning that would suggest why there are benefits to integrating math into a science class on students understanding of the science, but the benefits to integrating science in a math class may have comparably less benefit to math understanding? Do those cognitive theories help predict possible asymmetries with other discipline pairings (e.g., engineering in math compared to math in engineering)? Do those cognitive theories suggest particular ways to enhance integration so that students' mathematics understanding can have increasingly positive benefits?

In the next section, we begin to consider how cognitive science ideas may help explain these two noteworthy findings from the iSTEM education literature and the questions about iSTEM learning that they raise.

Part 3 – Choosing the Cognitive Science Ideas

One of the primary contributions of cognitive science on understanding human learning is the recognition that all individuals are subject to constraints of the architecture of the human mind. The architectural constraints include strong limitations on short-term memory but seemingly unlimited capacity in long-term memory. This recognition led to basic findings that what separated novices from experts was less about the parameters of the architecture or the quantity of knowledge stored in long-term memory, and much more about the structure and organization of that knowledge for problem solving within narrow domains of expertise (Chi, Feltovich, & Glaser, 1981; Simon & Chase, 1973). Historically, the ascendancy of the cognitive perspective influenced a shift in educational research away from a focus on acquiring domain-general expertise and toward a focus on learning and instruction situated within content disciplines (Stevens, Wineburg, Herrenkohl, & Bell, 2005). However, as Stevens et al. (2005) suggest, it now seems possible to build off the wealth of discipline-specific cognitive research and shift again toward understanding how students develop knowledge that crosses disciplinary boundaries (and crosses in- and out-of-school boundaries as well).

The cognitive science literature is large and varied. In order to provide an informative review for thinking about the opportunities and challenges for learning in an iSTEM education environment, we chose to focus on theories that suggest ways of thinking about how knowledge is represented and the mechanisms involved in reorganizing and restructuring that knowledge during learning. There have been many attempts to connect theories about knowledge representations and learning mechanisms to issues in education, and we identified two such reviews that provided succinct lists of principles gleaned from the cognitive science literature (Pashler et al., 2007; Schneider & Stern, 2010). We believe that each of the findings and recommendations would be informative for the effective design of any learning environment, including iSTEM education environments. However, instead of reviewing how all of these findings might apply to iSTEM education, we narrowed the scope of the review by choosing to highlight aspects of the cognitive perspective that may be particularly relevant for understanding how students *integrate* ideas. Integration of knowledge across disciplines for solving problems that are not framed strictly within disciplinary boundaries is at the core of what students will need to be able to do in iSTEM education environments. Table 1 lists the principles of learning identified in each of the two reviews and highlights the particular finding or recommendation from each list that most closely aligns with integration. The two principles that we will focus on for this review are: (1) the finding that learning requires the integration of knowledge structures, and (2) the recommendation to connect and integrate abstract and concrete representations of concepts.

Table 1. Principles to inform education from cognitive science literature reviews. Principles that involve "integrating" knowledge are in bold.

Findings from the cognitive perspective on learning (Schneider & Stern, 2010)	Empirically-grounded recommendations for educational practice (Pashler et al., 2007)
F1. It is the learner who learns	R1. Space learning over time
F2. Optimal learning builds on prior knowledge	R2. Interleave worked example solutions and problem-solving exercises
F3. Learning requires the integration of knowledge structures	R3. Combine graphics with verbal descriptions
F4. Optimal learning is about acquiring concepts, skills and metacognitive competence in a balanced way	**R4. Connect and integrate abstract and concrete representations of concepts**
F5. Optimal learning builds complex knowledge structures through the hierarchical organization of more basic pieces of knowledge	R5. Use quizzing to promote learning R5a. Use pre-questions to introduce a new topic R5b. Use quizzes to re-expose students to information
F6. Optimally, learning uses structures in the external world to organize knowledge structures in the mind	R6. Help students allocate study time efficiently
F7. Learning is constrained by capacity limitations of the human information-processing architecture	R6a. Teach students how to use delayed judgment of learning techniques to identify concepts that need further study
F8. Learning results from the dynamic interplay of emotion, motivation and cognition	R6b. Use tests and quizzes to identify content that needs to be learned
F9. Optimal learning builds up transferrable knowledge structures	R7. Help students build explanations by asking and answering deep questions
F10. Learning requires time and effort	

We elaborate on these principles by reviewing for each one a particular cognitive science theory that aligns with the principle. After identifying the two principles that were most closely aligned with how students *integrate* ideas, we selected the cognitive science theories by reviewing the articles cited within the particular review paper from which the principle was gleaned. In reading the papers referenced from within the review articles, we sought to identify a theoretical model that was present across those papers and provided a foundation for the ideas that formed the basis for that principle. We sought a theoretical model for each principle that was well established with a broad base of empirical support, and that was useful for understanding the opportunities and challenges present in iSTEM learning environments. By useful, we suggest that the cognitive science theory serves as a scientific model that constrains its focus to particular aspects of the larger phenomena. In doing so, the model necessarily simplifies and ignores some aspects in order to make sense of other aspects. An overview of all learning theories would be too complex to draw any conclusions, and would not highlight which elements of human learning are most salient to the integrated STEM learning challenge.

It is reasonable to suggest that beginning with different review papers connecting cognitive science to principles of learning would have led to identifying other useful theoretical models to apply to iSTEM education. Nevertheless, we suggest that the appropriate criteria for judging this review is not whether it summarizes all possible connections between cognitive science and iSTEM education, but rather, whether it makes some particularly useful connections. As a result, we selected models that were useful in both a theoretical and a practical sense. In a theoretical sense, we selected models from cognitive science that predicted and explained patterns in the data. In particular, we chose theoretical models that helped to explain either or both of the two noteworthy empirical findings from the iSTEM education literature that we identified earlier. Future iSTEM research that identifies other noteworthy empirical findings may find that the theoretical models we identified here are not sufficient to explain those other findings, and so it would make sense in those cases to seek out alternative models. And second, we selected theoretical models that in a practical sense enabled action in terms of having implications for the design of effective iSTEM learning environments and for making suggestions about productive frameworks for guiding future iSTEM education research.

Reviewing the studies referenced in the first principle—that learning requires the integration of knowledge structures (Schneider & Stern, 2010)—led us to the knowledge integration perspective as a model of knowledge and learning that had both theoretical and practical implications for iSTEM education. The following section reviews the knowledge integration perspective and its connections to iSTEM learning. After reviewing the knowledge integration perspective, we then consider structure mapping theory as an alternative model that emerged from our reading of the studies referenced in the second principle—that educational practice should connect and integrate abstract and concrete representations of concepts (Pashler et al., 2007). For each of the two cognitive science theoretical model, we begin with a short overview that cites a foundational piece for that theory and cites connections to current and past research areas. We then describe how that model represents knowledge and learning by reviewing key studies that are illustrative of the central ideas in that model. These studies help introduce the language used in the model and provide rich examples of the model's central ideas. We then connect those central ideas of the model concerning knowledge and learning to iSTEM education by reviewing studies that involve some integration and that illustrate how the model functions in iSTEM learning environments. In both cases of describing the central ideas of the model and connecting the model to iSTEM education, the studies were selected to be illustrative rather than exhaustive.

Part 4 – Knowledge Integration Perspective

The knowledge integration perspective (Linn, 2006) was developed mostly in the context of science education research. The perspective arose from a recognition that it was relatively easy for instruction to introduce students to normative science ideas within classroom instruction, but much more difficult to help students resolve those classroom-instructed science ideas with their personal, experientially-based ideas about the physical world. The knowledge integration perspective is connected with iSTEM education because it provides a perspective on how students progress from having many ideas that they think about as only being relevant in specific, isolated contexts to seeking coherence among ideas in ways that apply across a wide range of contexts.

The knowledge integration perspective connects with other strands of cognitive research on knowledge integration, such as diSessa's knowledge-in-pieces framework (diSessa & Wagner, 2005; Smith, diSessa, & Roschelle, 1993; Wagner, 2010), Hammer et al.'s resources framework (Hammer, Elby, Scherr, & Redish, 2005), and other past research bases, such as Hunt and Minstrell's facets research (Hunt & Minstrell, 1994), and research on students' conceptual ecologies (Posner, Strike, Hewson, & Gertzog, 1982). In common across all of these research bases is a view of students' ideas—especially early on in instruction—as not being stable, strongly held beliefs that the students apply broadly. Instead, this view highlights how students tend to apply different ideas in different contexts, and that those ideas are likely to be sensible within that local context, but less coherent more globally across contexts. The knowledge integration perspective considers knowledge as a complex system of ideas and the connections between ideas, and learning as a process of resorting those ideas through the strengthening and weakening of the connections between them so as to emphasize less isolated and more coherent ideas and connections.

Knowledge as a Repertoire of Ideas

The knowledge integration perspective has been used in a variety of studies to explain how students apply their ideas in science classrooms (Clark & Linn, 2003; Linn, 2006; Linn & Hsi, 2000) and to design instruction that facilitates students in connecting their contextualized, personally-experienced ideas to normative, classroom-instructed ideas (Linn, Clark, & Slotta, 2003). A key aspect of the knowledge integration perspective is the view of knowledge as a system of ideas with varying levels of connections between ideas, called a *repertoire of ideas*. In this repertoire of ideas, students hold multiple ideas about phenomena that the student may or may not connect even when a canonical view would see those ideas as subsumed within one more general idea or differentiated into two distinct ideas. Integration is defined as the process by which the strength of a connection between ideas is created or increased (Clark, 2006). Students often integrate ideas in spontaneous ways based on particular contexts, and many times those connections are nonnormative. But more sophisticated integration involves promoting ideas through strengthening connections to those ideas when they prove productive over a variety of contexts and increasing the centrality of those ideas as being pivotal focal points for organizing other ideas.

Empirical research based in the knowledge integration framework illustrates how knowledge can be represented as a repertoire of ideas. Clark and Linn (2003) collected a longitudinal dataset on the implementation of an eighth grade thermodynamics curriculum that was developed using the knowledge integration framework. They interviewed 50 students who participated in the full curriculum on five occasions (at 3 week intervals from the beginning to the end of the 12 week unit), and then conducted additional interviews of the students prior to their tenth and twelfth grade years to assess continued development. In the assessments of the interviews, they coded not only whether the majority of the ideas that a student expresses are nonnormative, mixed/transitional, or normative, but also whether a student had a more nuanced normative understanding in which they explicitly draw valid connections between two or more normative ideas. One important finding was that students readily added normative ideas to their repertoire after being introduced to those ideas in instruction, as the majority of students expressed either transitional or normative understanding of a topic at the interview immediately following when the topic was covered in class. The majority of students didn't immediately develop a nuanced understanding in which they were connecting normative ideas. However, the percentage of students that did reach that more connected and integrated level continues to increase over the course of the 12-week unit. Since typical instruction in thermodynamics lasts only three weeks in total, Clark and Linn see the slow and effortful progression of the connectedness of the normative ideas as evidence that more typical-length instruction would consider it sufficient to introduce the normative ideas and them move on to other topics. This would have the effect of adding those ideas to students' repertoire without providing the students with the time and explicit scaffolding necessary for promoting those normative ideas into more central and connected roles within their repertoire.

To illustrate the range of students' ideas, and how they are added and resorted over time, Clark and Linn (2003) described a case study of one average-level student from the interview sample. During the second interview—after three of the twelve weeks of instruction, the more typical time frame for treating the topic of thermodynamics in traditional instruction—the student expressed multiple conflicting ideas, such as (1) the normative idea learned from classroom activities that “objects in the same room should be the same temperature,” (2) a normative idea presumably developed through experience that “some objects feel colder than others in the same room,” and (3) a nonnormative idea presumably developed in an unsuccessful attempt to connect the two previous ideas that “objects that are the same temperature should feel the same” (Clark & Linn, 2003, p. 475). The range of ideas that the student expressed during this interview illustrates how it was relatively easy for instruction to introduce normative ideas into the student’s repertoire that he could use to explain particular examples of heat exchange, but that that instruction wasn’t yet sufficient to help him integrate some of his other experience-based ideas. By simply attempting to resolve the different ideas of feeling and temperature, this student was moving toward a more integrated, connected, and globally coherent understanding, but at that point he had not yet achieved a nuanced level of normative understanding. Figure 3 illustrates the progression of the level of integration of this student’s ideas over the course of the study. It was only toward the end of the 12-week program that the student began making valid connections between multiple normative ideas in his explanations. He continued to progress after instruction, as it wasn’t until his interviews two and four years following instruction that he no longer expressed nonnormative ideas in his explanations. The knowledge integration perspective uses the repertoire of ideas construct to capture the multitude of ideas that students draw on, the connections that they make between ideas, and how those ideas are added and resorted over time.

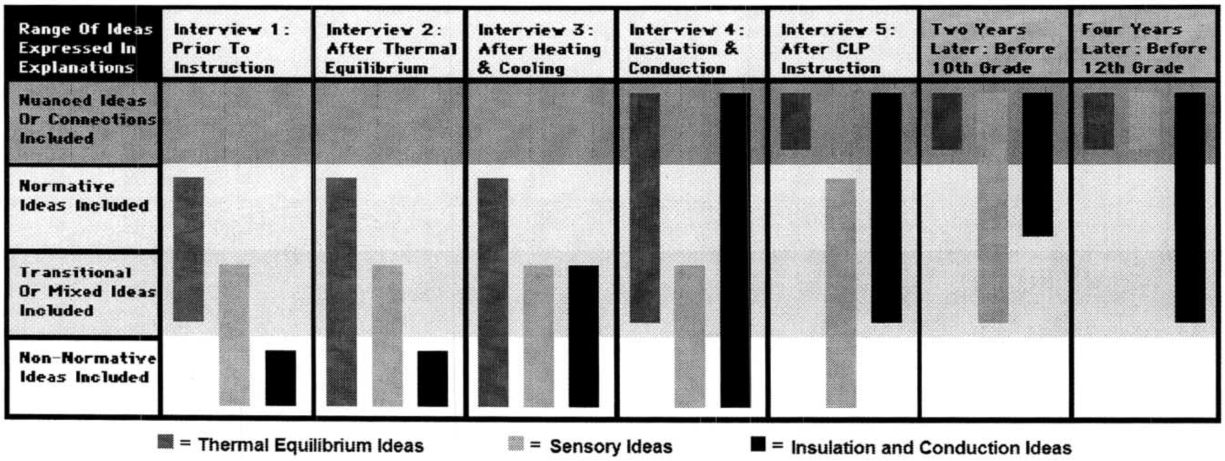

Figure 3. The progression of the case study student's ideas about thermodynamics (Source: Clark & Linn, 2003, p. 473).

Learning as Sorting Context-Dependent Ideas into Coherent Understandings

In addition to viewing the organization of knowledge as a repertoire of ideas, the knowledge integration perspective views learning as a process of increasing the strength of connections between ideas that are productively related and promoting the most productive ideas to more central, connected roles. This has led to the formulation of four processes of knowledge integration that typically need to be present in instruction to help students develop more integrated understanding: (1) eliciting ideas, (2) adding normative ideas, (3) developing criteria, and (4) sorting out ideas (Linn, 2006). Related to this, research from the knowledge integration perspective has documented typical trajectories that students follow when attempting to reorganize their repertoire of ideas in light of their instructional experiences (Lewis, 1996; Linn, 2006; Linn & Hsi, 2000). All students are limited in considering only a subset of ideas at one time, but vary greatly in how they attempt to resolve conflicting ideas. Some students respond by regularly reprioritizing their ideas and favoring normative ideas, while others seek out contextual differences between situations to preserve the distinctions between ideas. Following from the trajectory profiles, the knowledge integration perspective has led to instructional design patterns that target the integration processes by leveraging the tendencies of the different trajectory profiles. In common with all of these instructional design patterns is that if learning proceeds through the modification of the strength of connections between ideas and reprioritizing around the most productive ideas, then it is not sufficient simply to inform students about normative ideas without also helping them to sort out and reprioritize the connections between those normative ideas and their own experience-driven ideas.

Focusing specifically on knowledge restructuring, in a related study Clark (2006) analyzed the same 50-student interview dataset, but focused on case studies of four additional students. Two of the students were more successful in moving toward a more nuanced understanding of the thermodynamics concepts and two were less successful. Clark observed commonalities across the case studies. For example, all of the students expressed multiple, contradictory ideas in their repertoire across multiple interviews. This situation persisted throughout for the less successful students, while the more successful students were eventually able to progress to an integrated, normative understanding. Interestingly, the students mastered different subsets of the ideas and integrated their understanding around different pivotal ideas, suggesting that their repertoires were not identical and that they reorganized in different ways. The different progressions of learning lend further support to the claim that learning is not a matter of simple addition of the normative ideas to an individual’s repertoire. Another key finding was that students all held experientially supported ideas (e.g., “if it feels colder, it must be colder”) that disrupted their ability to reorganize their understanding around a normative idea. When a disruptive idea was cued, students dismissed, distorted, or differentiated the normative ideas unless encouraged to reconcile their normative and nonnormative ideas. These disruptive ideas were only cued in limited contexts, but the cueing of those ideas was necessary for the successful students to reconcile them with their other acquired normative ideas. This suggests that in order to engage in knowledge reorganization, students need numerous opportunities to contrast their normative and nonnormative understandings in contexts that specifically cue their nonnormative understandings. Indeed, Clark developed an effective intervention specifically to elicit disruptive experientially-supported ideas and to re-explain the connections between the two (Clark & Jorde, 2004). Thus, it is precisely these disruptive experientially supported ideas that need to be explicitly connected and resorted around the classroom-instructed normative ideas in order for students to develop an integrated understanding that they then are able to apply broadly.

Connecting to iSTEM Education

How does the knowledge integration perspective apply to iSTEM education? The implications of the knowledge integration perspective for iSTEM may be especially suited to explaining why one common finding from the iSTEM education literature is that students have difficulty drawing on (Venville et al., 2004) and deepening their understanding (Venville et al., 2005) of disciplinary concepts in other-discipline problem solving. Instructional designers need to be very careful about understanding students' ideas and how they connect them even within a discipline (Nordine, Krajcik, & Fortus, 2010), and so connecting ideas across disciplines (Stevens et al., 2005) may be especially challenging as students are unlikely to cue their normative disciplinary ideas in such a disparate context.

The knowledge integration perspective predicts that when students engage in an engineering design task that they are likely to develop contextually dependent ideas about designing (e.g., "rules of thumb" and "how-to" knowledge). At least initially, those design ideas are unlikely to connect to or be coherent with normative science ideas that could potentially inform their designs in those same contexts. Crismond (2001) documented how experts recognize opportunities to connect with science ideas, but nonexpert designers readily miss those opportunities. Even after lots of experience in given design contexts, individuals can reach an expert level but connect very different ideas to the context depending upon their own conceptual organizations. For example, aquarium hobbyists are likely to refer to practical considerations about maintaining the health of an aquarium in very concrete terms as compared to academic biologists whose ideas are more likely to be organized around very general notions about how energy exchanges drive the system (Hmelo-Silver, Marathe, & Liu, 2007). The knowledge integration perspective suggests that students will need explicit support eliciting those science ideas in an engineering or technological design context, connecting those ideas productively, and reorganizing around those ideas.

A number of integrated design-for-science programs have developed substantial scaffolding supports to help students connect normative science ideas to their designs (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner et al., 2003). However, even though some design for science interventions may have positive effects on learning of science concepts (Mehalik, Doppelt, & Schunn, 2008) and even on science reasoning (Silk, Schunn, & Strand Cary, 2009), those same programs may be less effective in terms of effecting deeper conceptual reorganization around the more normative ideas as the pivotal, central ones (Venville et al., 2005). Additional supports may be necessary. For instance, Puntambekar and Kolodner (Puntambekar & Kolodner, 2005) used more explicit prompts in design diaries and whole class pin-up sessions and presentations to encourage students to justify and articulate the science behind their own design ideas as well as to hear other ideas. Schnittka and Bell (2011) supplemented a design-for-science curriculum with demonstrations that specifically targeted alternative conceptions. This was in place of more typical demonstrations, which simply illustrated the normative idea, effectively adding that idea to students' repertoires without targeting the connection of those ideas to nonnormative ones. In the language of the knowledge integration perspective, the targeted demonstrations likely cued students' disruptive experientially-supported ideas so that they could be reconciled with normative, classroom-supported ideas (Clark & Jorde, 2004). Typical design-for-science activities need additional, targeted scaffolding for students to more explicitly connect and sort through their science ideas in the context of their designing.

So far we have considered integrating science in design activities as a challenge for iSTEM education because of the difficulty in connecting to and deepening understanding of the normative science ideas. However, there also may be opportunities for more effective learning in design-science integration that are explained by the knowledge integration perspective. Chiu and Linn (2011) recently described how the knowledge integration perspective could be used to integrate engineering design projects within science inquiry tasks so that students learn engineering skills and concepts. They describe how two different science units—the *Airbags* and *Chemical Reactions* units—helped students learn about core engineering concepts of systems and optimization. It was not clear from the data reported the extent to which participating students specifically acquired those engineering concepts or progressed toward more integrated understandings that crossed the boundaries of engineering and science. However, the authors did provide evidence of students overall learning and progression toward more complex linkages among valid scientific ideas. And they make a strong case that the knowledge integration framework can be applied to engineering concept learning (Streveler, Litzinger, Miller, & Steif, 2008) as well as it can be to science concept learning.

Another opportunity for iSTEM integration may be in the possibilities for using engineering design as a context for learning science. Sadler et al. (2000) suggest that a key element of effective design activities are “tests against nature”. According to Sadler et al., tests against nature provide students with well-understood goals and clear ways to monitor their progress. We would go further to suggest that tests against nature provide additional cognitive advantages as they are an opportunity not just to test the design, but also to externalize a student’s idea in a concrete representation. This has advantages for eliciting and attending to student ideas since the concrete design frees cognitive resources so an individual may more easily analyze her own ideas, forces an individual to consider real-world physical constraints that may not be represented in their mental images, and makes the ideas of an individual accessible so that others may provide meaningful critiques (Roth, 2001). Connected to the knowledge integration perspective, the concrete designs may cue disruptive, experientially supported ideas that only arise in real-world problem solving. When not testing against nature, students may be able to safely ignore contradictions between ideas in their repertoire.

Most likely, though, tests against nature are only an opportunity for more effective iSTEM education when they are conducted within very carefully planned instructional designs. The knowledge integration perspective implies that that even though science instructors may see design failures as being connected to students’ underlying understanding of the normative science ideas, students may not make those connections. Design curricula need to take great care in making sure that abstract knowledge is both motivated from the design and then applied to the design (Kanter, 2010). However, students are also likely to need explicit support in projecting backward to reflect on the process of connecting the normative science idea to their design, and such reflections are rare in design activities (Walkington, Nathan, Wolfgram, Alibali, &

Srisurichan, in press). And yet, those reflections backward are likely the primary mechanism for students' updating the strength and centrality of the normative science ideas.

Although core aspects of the knowledge integration perspective have been applied to mathematics (Schneider & Stern, 2009; Wagner, 2010), we are not aware of any fundamental distinctions that the knowledge integration perspective draws between knowledge of mathematics as compared to knowledge of other disciplines. On the contrary, Wagner (Wagner, 2006, 2010) argues persuasively that viewing mathematics understanding in terms of a repertoire of context-cued knowledge elements is more appropriate than considering math ideas as abstract, context-independent knowledge structures. Given this interpretation of the knowledge integration perspective, it is difficult to explain the other noteworthy iSTEM education finding concerning the asymmetries between math and science integration. Fortunately, the next cognitive science idea that we review provides an alternative perspective that may be more informative for understanding this math-science integration asymmetry.

Part 5 – Structure Mapping Theory

As a second productive connection to cognitive science theory, we review relevant literature of structure mapping theory. Structure mapping theory (Gentner, 1983) is based on the idea that individuals perceive similarity between objects not only at a literal level between particular features that the objects have in common, but also at a relational level. That is, individuals perceive relations between features of an object and then can assess whether similar relations are present in some other object. More sophisticated understanding will likely lead to using the deeper relational structure between past learning experiences and current problem solving situations to come up with a solution rather than relying on superficial or more literal similarities. There is a thriving current strand of research in the cognitive sciences about the role of abstract and concrete experiences in learning (de Vega, Glenberg, & Graesser, 2008; McNeil & Uttal, 2009). Underlying this debate are elements of structure mapping theory in the sense that the main issue is whether either concrete (perceptually rich) or abstract (perceptually sparse) learning experiences help students to understand and attend to the deep relational structure that would be most useful for later problem solving. Of course, the debate is not likely to end with a simple answer advocating for either abstract or concrete experiences alone, and so the issues currently being explored are under what conditions each type is more beneficial, in what relative amount, and in what order, sequence, or combination. We review some of the current research in this area using structure mapping theory as a framework and then explore possible connections to iSTEM education.

Knowledge as Relational Structure

A key aspect of structure mapping theory is thinking about knowledge in memory as not just a collection of ideas as whole units, but also being able to break those ideas down into a set of features that an individual recognizes as being characteristic of the idea. Structure mapping theory suggests that those features are of two different types: the literal or superficial kind focused on attributes of a specific situation, and the relational or deep kind that are focused on more abstract ideas about the situation. For example, if a student was learning about light bulbs in a circuit, they may notice aspects of the light bulb that are perceptually salient, such as that it is encased in glass and that the bottom part is threaded. However, these features of the light bulb aren't the ones that would help the student light the bulb when given only one wire and a battery. Instead, they would need to attend to some of the deeper features of how components are added into a complete circuit, such as how the light bulb has two separate contacts through which current may flow.

Research comparing experts versus novices in domains suggest that novices tend to focus on the literal features of problems rather than the features that correspond to deep structural relations between problems (Chi et al., 1981). In the current research, there is evidence that the more perceptual richness that there is in an example that a student is learning from, then the more those literal features will compete with relational features for students attention. Uttal, DeLoache, et al. have demonstrated this through many experiments in which they show young children a scale model of a room, put a small toy at some location within the scale model, then ask the children to find a larger version of the toy placed in the same relative location in a full scale room (Uttal, Liu, & DeLoache, 2006; Uttal, O'Doherty, Newland, Hand, & DeLoache, 2009). When they conducted manipulations that increased the salience of the scale model as an object in and of itself, the children were less successful in using it as a representation of the larger room. For example, and somewhat counterintuitive, when they allow students to play with the scale model first, the children are less successful finding the object in the full-scale room. In contrast, when the model was placed behind a window so the children couldn't physically interact with it, the students were more successful in finding the object in the larger room, presumably because they were better able to attend to the scale model as representing the larger model rather than as an object in and of itself. Adding perceptual richness to other sorts of instructional experiences may then make the particular experience salient to students rather than the more general idea that is the real objective to be learned. So it is in this sense that there is a competition between concrete and abstract features of a situation, such that making one feature type more salient will make that feature type more likely to be used later.

Learning as Attending to Relational Structure within Rich Details

There is evidence in current cognitive science literature that when students have learning experiences that make use of concrete instances that include too much in terms of realistic features that they are unable to identify the abstract structural aspects that are needed to transfer their experiences to other settings. In studies by both Goldstone and Sakamoto (2003) and Sloutsky, Kaminsky, and Heckler (Sloutsky, Kaminski, & Heckler, 2005), perceptually rich forms of learning are compared with perceptually sparse forms. Both studies found disadvantages to increasing levels of perceptual richness, especially when the features added in the perceptually rich conditions were irrelevant to the to-be-learned structural features. For example, simply adding color or designs on objects hinders learning compared to all black objects (Sloutsky et al., 2005). Further, (Goldstone & Sakamoto, 2003) found that the negative effect of perceptual richness (concrete) may be different for different levels of students and when assessing learning of the particular situation versus transfer. Students that are likely to encode the abstract features of a situation initially are unlikely to be influenced by learning from abstract or concrete materials. Students that are unlikely to encode the abstract information (lower level learners) are more likely to be distracted by superficial features, so they benefit from more idealized learning materials. Related to this, the lower level learners may benefit from concreteness in initial learning about that particular situation. However, when those lower level learners are assessed in a transfer situation they do better if they had learned the initial situation in a more abstract version. Overall, these studies suggest that students have difficulty perceiving the deep relational structure within situations that have increasing amounts of perceptual richness.

It may be that concreteness that encourages students to attend to the critical features of the situation (as opposed to irrelevant features) does have benefits both for learning and transfer. Kaminski, Sloutsky, and Heckler (2009) tested this idea by having students learn a mathematical rule either with materials that are entirely generic and so the rule's connection to the symbols was entirely arbitrary, or with materials in a familiar context that follows the rule (in this case beakers of liquid combined with some left over). They found again that the relevant concreteness had advantages for learning of that particular rule, but that the generic materials resulted in better transfer to another context that followed the same rule but in which the objects didn't compel the rule as they had in the relevant concrete learning materials. This was true even when the participants were explicitly told that both the learning and transfer situations followed the same rule. This seems to suggest that even with relevant concreteness, more generic and abstract forms are better for transfer. However, an alternative explanation of the role of concreteness and abstractness in learning and transfer does exist.

For example, Greeno (2009) suggests that the distinction between abstract and concrete may be less relevant than the issue of epistemological framing. That is, if students are helped to see the task as being about attending to the general conceptual structure rather than the solving of a particular problem then they likely will learn different things from the experience. When a concrete situation embeds a certain feature as given in the materials, even when that feature is a critical one, then students may not attend to that feature. In the Kaminski et al. (2009) materials, the remainder when the two liquid beakers are combined is grounded in the materials and so students don't need to generate a more general version of that mathematical rule themselves. In those cases, the perceptual richness may discourage students from learning the key aspects in a transferrable way as they depend on the structure of the materials in their problem solving.

Whereas, if the concrete aspects of the material help focus students thinking on the key critical aspects without generating the solution for students, then students may develop more general ideas about the relevant structure. For example, work by Schwartz (Schwartz, Martin, & Pfaffman, 2005; Schwartz & Moore, 1998) suggests that adding relevant concreteness that cues mathematical representations of the relational structure helps students develop deeper knowledge of the situation (e.g., by modifying hard-to-measure continuous quantities into easily-measured discrete quantities). With this alternative perspective, the ideal set of learning materials and instructional supports for learning with those materials should likely help students to focus on the function of relevant features across varied situations by both minimizing the salience of irrelevant, distracting features and by increasing students representation of and activity with those relevant features.

Connecting to iSTEM Education

How does the structure mapping theory and the research on concreteness and abstractness in learning and transfer apply to iSTEM education? One obvious connection would be in explaining the asymmetry between integration effects on science compared to math. A classic study of the asymmetry between math and science from the structure mapping perspective was conducted by Bassok and Holyoak (1989). In this study, students who learned about arithmetic progressions in algebra were able to apply their knowledge to another context much more readily than students who learned the equivalent math idea in the context of constant-acceleration problems in physics. It seemed as though the students who learned about arithmetic-progressions in the context of physics attended to particular features of the physics context that were not necessary within the more general structure of arithmetic progressions. Similarly, it may be very difficult for students to learn general math ideas within very rich scientific contexts since the number of critical features to the math idea itself may be much smaller than those that connect that math idea to the particular science context.

Other research on design for science learning suggests that it is difficult to help students to attend to the deep structure of problems. For example, when helping grade 1-2 students learn about modeling through the design of an elbow, Penner et al. (Penner, Giles, Lehrer, & Schauble, 1997) needed multiple iterations of design, evaluation, and revision to get students to move beyond perceptual qualities in their models to more functional qualities. However, the success of the intervention suggests that students, even young students, can attend to deeper structural features given enough scaffolding that helps them filter out the surface-level features and explore how the deeper level features work.

What about learning math within iSTEM education? To our knowledge there are not many examples in the literature that have demonstrated this and the structure mapping theory and associated research suggest that the competition between deep and surface features is one explanation for why. That is, it is difficult for students to learn about abstract and general mathematical ideas when they are embedded in richly contextualized science, technology, and engineering problems. One exceptional example that does exist is the work of Stone and colleagues who enhanced career and technical education with mathematics (Stone, Alfeld, & Pearson, 2008). Stone et al. demonstrated that students in their math-enhanced technical education courses did better on measures of more general math ability compared to regular technical education courses while performing at similar levels in terms of technical skills. Stone et al. suggest that a fundamental distinction of their program compared to other programs that integrate math with other disciplines was that their lesson sequence always moved from specific contextualized technical applications to general mathematical principles. Furthermore, at every step of the process explicit connections are made between the current level of abstraction and the previous ones to help make the interdisciplinary transitions smooth. This emphasis is stated clearly in one of the key components of their math-enhanced lessons, “The transition from CTE to math vocabulary should be gradual throughout the lesson, being sure never to abandon completely either set of vocabulary once it is introduced” (Stone et al., 2008, p. 774). Consistent with structure mapping theory, one explanation for the success of this iSTEM program may be its focus on making explicit connections between the concrete problems within the technical context and the more abstract mathematical ideas. Research within the structure mapping theory suggests that indeed switching between concrete and abstract elements is more beneficial than learning from either concrete or abstract problems alone (Goldstone & Son, 2005). Further, Goldstone and Son found that the particular sequence of starting with concrete and then successively moving toward a more idealized or abstract version—called concreteness fading—had the most benefits both for learning and for transfer. The role of abstractness and concreteness in learning continues today to be a productive area for research in cognitive science, and it is likely that there are many additional aspects that we must be taken into account when considering how that research may inform the more complex situations involved in iSTEM education. Studies of the different ways in which iSTEM learning environments help students make connections and transition back and forth between problem-solving in rich, detailed contexts and understanding of more general disciplinary ideas are likely to advance our understanding of how students learn powerful, integrated ideas. In particular, even though there may be some studies that do show a benefit to math achievement in an iSTEM learning environment, the small number of such studies highlights this area as one that should be explored further.

Part 6 – Discussion

In this section, we will summarize the key ideas that are common across the two theories and their connections with iSTEM education, as well as identify areas for further research that would help strengthen the connections. Strengthened connections between cognitive science and iSTEM education would help research in iSTEM education to be better grounded and informed by theories and models of cognition and would in turn motivate the cognitive science research community to better address the unique issues that are raised in iSTEM educational environments.

A Productive Set of Ideas for Thinking About iSTEM Learning

This paper has set out to provide a set of ideas that are likely to be helpful in considering the cognitive processes involved when students are engaging in iSTEM learning environments. For example, acknowledging that students have a repertoire of ideas may help iSTEM educators to be more explicit about not only introducing new ideas to students in the course of their iSTEM problem solving, but also how they intend to help them connect those new ideas to other previously-held ideas that students may have developed through other experiences. The language of “repertoire of ideas” and the associated actions of eliciting and sorting may help focus iSTEM experiences so that the activities don’t simply make it possible for students to connect ideas from one discipline to another on their own, but rather more explicitly and actively encourage those connections within the structure of the iSTEM learning environment.

Similarly, the language associated with structure mapping theory helps to focus on identifying the essential structural features that students will need to recognize in order to transfer their knowledge across varied problem solving situations. The research on abstractness and concreteness in learning helps clarify the importance of attending to general structure even within very rich situations. That way, when iSTEM educators are considering adding richness to their tasks, they are simultaneously considering ways to orient students to attend to the deep features of the problems that activate powerful, abstract disciplinary ideas. Table 2 summarizes the key points from these two cognitive science theoretical models.

Table 2. Key points of the cognitive science theoretical models.

	Knowledge Integration Perspective	Structure Mapping Theory
Knowledge	Repertoire of ideas	Objects, (deep and surface) features, and relations
Learning	Connecting, sorting, and reprioritizing	Attending to deep structural features
Challenge	Easy to add normative ideas, hard to reorganize around them	Surface features compete with deep features
Connection to iSTEM	Difficulties connecting normative disciplinary knowledge in design contexts can be explained in that students likely think of the design experiences as generating contextualized knowledge	Difficulties of learning math in iSTEM can be explained by rich details of science, technology, or engineering problem contexts making the deep mathematical structures difficult to attend to
Implications for iSTEM	Use inter-disciplinary problem contexts to cue experience-based ideas, while providing explicit supports to reinterpret those experience-based ideas using normative, disciplinary ideas	Use sequencing that moves from richly contextualized problems to idealized representations, while explicitly moving back and forth and maintaining connections between them

Implications of Connecting Cognitive Science Theories to iSTEM Education

Although we have highlighted some iSTEM programs that have successfully overcome some of the challenges that are predicted and explained by the knowledge integration perspective (e.g., Puntambekar & Kolodner, 2005; Schnittka & Bell, 2011) and structure mapping theory (e.g., Penner et al., 1997; Stone et al., 2008), the most compelling implications of this review may not be about the identification of particular instructional approaches that are likely to be successful in iSTEM learning environments. A more compelling finding may be found in the implications for how future empirical research, literature reviews, and meta-analyses may be conducted. Just as in other areas of educational research where the field has advanced when research moved beyond asking just whether one type of instruction is better than another (e.g., Kirschner, Sweller, & Clark, 2006), and began to ask more nuanced questions about what form of those instructional types work best and under what conditions (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011). iSTEM education research may be better served by moving beyond the question of whether integrated STEM is more effective than non-integrated STEM, and begin to assess the variation in types of implementation for iSTEM programs.

Although Hurley (2001) began this process by assessing different levels of math-science integration (from sequenced to total integration), our review of the cognitive science literature suggests that other organizations may better explain the variation in program success. For example, the knowledge integration perspective suggests that paying attention to the particular ways in which instructional designs connect disciplinary ideas with experience-based ideas is likely to be critical. Some iSTEM education programs may focus exclusively on introducing the normative ideas within interdisciplinary contexts (e.g., formal, academic-focused programs, such as a standards-based classroom curricula). Other programs may use similar interdisciplinary contexts, but may focus exclusively on getting students to draw on their experience-based ideas in those contexts (e.g., informal experienced-based programs, such as robot competitions). The knowledge integration perspective would predict that those programs that have scaffolds in place for explicitly evoking and reinterpreting experience-based ideas using normative, disciplinary ideas are likely to be more effective than doing either alone.

Similarly, structure mapping theory suggests that the role of concrete problems and abstract ideas in the instructional design may be critical. Some programs begin with abstract disciplinary ideas and then simply have students move onto concrete problems from another discipline in which presumably they can apply those abstract ideas. Other programs may immerse students in richly contextualized interdisciplinary problems with lots of concrete details from which the students may draw on any number of ideas. Structure mapping theory would predict that programs that help students transition from rich problems to more idealized forms or to move back and forth between concrete problems and abstract representations may be more effective.

However, to assess any of these different forms of integration the data must exist over a broad range of studies. It is important for researchers and designers to be explicit about the types of scaffolds and instructional designs that they used when writing about their programs so that the programs can be classified in these suggested ways. Further, to truly assess what forms of iSTEM are most effective compared to other non-integrated forms of STEM education, studies ought to pay more attention to the types of outcome measures that are collected. Because the learning that results may be asymmetrical across the different disciplines (math vs. the other disciplines), it would be useful for researchers to more consistently include separate measures of learning for each discipline that is integrated. Similarly, the differences between programs may be apparent not simply in measures of basic knowledge, such as recall of normative ideas or very contextualized problem solutions, but may be more apparent in measures of deep, connected conceptual understanding and transfer. Building on the research base of iSTEM education programs with rich descriptions of the scaffolds and instructional design choices as well as careful measures of outcomes is likely to make future reviews of the this type even more productive.

Although beyond the scope of this paper, we recognize that alternative theoretical models of cognition and learning would likely explain other findings from the iSTEM education literature as well as inform the design of more effective iSTEM learning environments. Research on cognition and learning from a social perspective or a situated perspective would likely better be able to explain aspects of iSTEM learning environments related to the collaboration between learners with each other and with more knowledgeable others. These areas of research may also help to understand the complex interactions within iSTEM learning environments such as the trajectories of individual and shared ideas, and the interplay of understandings with conceptual tools and created artifacts.

A particularly important line of related research may be to focus on how students in iSTEM learning environments not only acquire deep, transferrable conceptual knowledge, but also how they learn the practices and epistemology of the different STEM disciplines. For example, in their suggestion to pursue comparative studies of students' understandings across school subjects and across in- and out-of-school contexts, Stevens et al. (2005) suggest that one productive line of research would investigate how students' understanding of "proof" is integrated (or disconnected) across the math and science classrooms. Although we are aware of some studies in higher education settings that focus on how interdisciplinary programs help students connect disciplines at the level of participatory practices (Boix Mansilla & Duraising, 2007; Nikitina, 2005), a review of the literature to inform iSTEM learning of disciplinary practices in K-12 settings would be very valuable. Further, understanding the impact of iSTEM education on learners' affect with respect to the STEM disciplines would be important and would help test whether iSTEM environments have the potential to be more interesting and motivated for students than traditional non-integrated STEM education.

However, in the all the different theoretical frames, the approach that we have taken in this paper—to begin by identifying noteworthy iSTEM findings and then draw on theoretical models to help explain those findings and predict useful ways of classifying future programs—would still be appropriate and would help advance understanding of iSTEM education. In turn, as the iSTEM education community expands with better-articulated program designs and hones in on particular phenomena that are in need of explanation, that may open up new areas of research for cognitive science to pursue that will enhance our basic understanding of the nature of knowledge and the mechanisms of learning.

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