Core Concepts in Engineering as a Basis for Understanding and Improving K-12 Engineering Education in the United States

Final Draft of a Report to the National Academy of Engineering Committee on Understanding and Improving K-12 Engineering Education in the United States

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A review of empirical research related to core engineering concepts was conducted in order to inform efforts to understand and improve K-12 engineering education in the United States. An analysis of the overlap across multiple standards documents and educational reports led to a focus on the engineering concepts of *systems* and *optimization* as core, organizing concepts that are foundational to the discipline. The cognitive development and learning science literature related to each of these core concepts was reviewed in order to synthesize the empirical research and answer the following three questions: (1) What is difficult about these concepts for K-12 students? (2) How do students' understanding and capabilities for understanding develop over the course of the K-12 grade levels? (3) What experiences and interventions facilitate students in building on and extending their understanding of these concepts?

Although engineering is only rarely taught explicitly in K-12 classrooms in the United States, evidence from successful classroom interventions related to these core concepts suggest that even elementary-age students would be capable of productively engaging with these concepts. Nevertheless, challenges do exist in designing instruction for both younger and older students that take into account their limitations in knowledge and skills, especially with respect to their understanding of mathematics. The findings from this review suggest that effective incorporation of core engineering concepts in K-12 classrooms would require the following: (1) an allocation of sufficient amounts of time in the classroom to develop these core concepts through immersion in extended design activities; (2) a commitment to iterative and purposeful revision of students' designs in more than one design cycle; (3) a recognition of aspects of the core concepts that are less difficult for students and the sequencing of instruction to build from those towards aspects that are more difficult; and (4) a seamless integration of tools to minimize cognitive load, bring the important conceptual ideas to the foreground, and support increasingly sophisticated and powerful representations of those ideas. A focus on the core engineering concepts of systems and optimization in K-12 engineering education in light of these recommendations has the potential to provide a solid foundation for continued study of engineering at the undergraduate level and beyond, but the recommendations are also general and could serve as the basis for reviewing other core engineering concepts as well.

Outline

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The goal of this paper is to review and synthesize the empirical research from the cognitive development and learning sciences literatures that is relevant for understanding how K-12 students understand and learn core concepts in engineering. We will accomplish this goal by first describing what we consider to be a core concept of engineering and how we chose the particular core concepts for this review. Then, we will review relevant literature for each of the concepts in turn. This review will include a discussion of how each concept supports the work that engineers do, what we know empirically about what students (K-12) understand or find difficult about these concepts and at what grade levels, and what we know about the kinds of experiences that might allow students to overcome their difficulties and build understanding in relation to these concepts. Finally, we will summarize this work by highlighting what we believe to be the commonalities across the empirical research on these core concepts that have the potential to inform how engineering may be taught effectively in K-12 settings.

Our Approach

When considering the scope of engineering concepts to be considered for this review, there were a number of possibilities that would be relevant to the task of improving engineering education in K-12 settings in the United States. One possibility was to review empirical work on basic science and mathematics concepts (e.g., models in science, space in mathematics) that are not specifically engineering-related, but may serve as the foundation for successful engineering work. There are so many of these topics, and many have already been the subjects of extensive reviews of their cognitive development, so that will not be the focus of this review. A second possibility included concepts connected to particular engineering disciplines (e.g., statics). These domain-specific concepts are essentially science concepts very tightly connected to engineering. Although these concepts are certainly important to the work of engineers, there is not likely to be much cognitive developmental literature on those topics because there is not much exposure to those topics in K-12 settings in the United States. The third kind involves concepts that are shared across most areas of engineering, and are therefore more general concepts or big ideas in the discipline of engineering. Possible concepts of this kind are: structure-behavior-function concepts; trade-offs, constraints, and optimization concepts; and system, subsystem, and control concepts. For this review, we chose to focus on the cognitive development of those more general concepts that are shared across most areas of engineering, what we refer to as core engineering concepts.

Our criteria for such core concepts are that they are representative of the essential knowledge that distinguishes engineering from other disciplines and the knowledge that is needed for students to be able to understand and engage competently in the practice of engineering design. There are a number of literatures that are relevant for this type of review task, including literatures on the cognitive development of these concepts in domain-general or context-free tasks, the cognitive development of these concepts in domains other than engineering such as mathematics or science domains (e.g., earth sciences), the cognitive development of components of those concepts and what makes those component concepts hard, and intervention studies that explore instructional methods and classroom environments that facilitate students' increasing understanding of those concepts. We will attempt to draw from each of those literatures in this review.

Although engineering in the United States is mostly taught at the undergraduate and graduate levels, and therefore much of the research related to engineering education is conducted at that level, the student population in K-12 settings is considerably more diverse, with a much wider range of achievement levels. Wider ranges of achievements level might lead to different learning challenges. Therefore, as much as possible, we searched for and focused on empirical research in which the participants were students of K-12 age and the research activities were conducted in a K-12 classroom. Before we review this research, first we will discuss our process for choosing the core engineering concepts and identify the concepts that were chosen.

Choosing the Core Concepts in Engineering

Our first task was to choose the concepts about which to focus the review. We did this by engaging in an analysis in which we examined the overlap among national standards documents and other reviews that have sought to identify concepts that are at the core of the work that engineers do. The following sources were examined in our analysis:

- *Standards for Technological Literacy* (International Technology Education Association, 2000);
- *National Science Education Standards* (National Research Council, 1996);
- *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993)
- *Atlas of Science Literacy, Volume 1 and 2* (American Association for the Advancement of Science, 2001, 2007);
- American Society for Engineering Education (ASEE) K-12 Standards (Morrison, 2007); and
- A report from the National Center for Engineering and Technology Education (NCETE) (Merrill, Custer, Daugherty, Westrick, & Zeng, 2007).

Since there are many parallels between technology and engineering, Standard 2 of the *Standards for Technological Literacy* (International Technology Education Association, 2000), entitled "The core concepts of technology," provided an initial list of candidate core concepts, which included the following: systems, resources, requirements, optimization and trade-offs, processes, and controls. Other concepts that specifically related to engineering that we found among these documents and then considered in our analysis included predictive analysis and models.

After generating a list of engineering concepts, we then reviewed each candidate concept and each standards document a second time to determine whether that concept was represented explicitly in that document. Our results are presented in Table 1. Based on this analysis of the consistency with which each concept was mentioned across the standards documents, we identified the two concepts mentioned most often: *systems* and *optimization*. As a result of these concepts being mentioned consistently throughout many of the standards documents, we considered them to be representative of concepts that are at the core of the discipline of engineering.

Table 1: Engineering Concepts as Represented in National Standards Documents

	Standards				
Concepts	Standards for Technological Literacy	Atlas of Science Literacy, Vols. 1 & 2	National Science Education Standards	American Society of Engineering Education K-12 Standards	National Center for Engineering and Technological Literacy Standards
Systems	Yes	Yes	Yes	Yes	
Resources	Yes				
Requirements	Yes		Yes		Yes
Optimization (trade-offs)	Yes	Yes		Yes	Yes
Processes	Yes				
Controls	Yes	Yes			
Models (predictive analysis)	Yes				Yes

It is notable that these concepts can be thought of as *Big Ideas* in that they incorporate and organize many of the other engineering concepts that we identified from the different sources. Table 2 relates how these two ideas organize a number of other important concepts within the discipline of engineering into two main clusters. For instance, optimization, as a process that maximizes the functionality of a design with respect to the design requirements and the resources available, necessarily involves an understanding of resources and requirements as concepts in and of themselves.

Having identified the concepts of interest, we then set about identifying and reviewing the relevant literature from empirical studies in cognitive development and in the learning sciences. Our review of the literature provided insight into students' understanding of those concepts, how that understanding develops over time, and how that understanding may be impacted by instruction. The following is a synthesis of our findings, starting with the first core concept, systems.

Table 2: Engineering Concepts Organized Under the Big Ideas of Systems and Optimization.

Systems	Optimization
Control/feedback	Trade-offs
Processes	Requirements
Emergent properties	Resources
Boundaries	Physical laws
Subsystems	Social constraints
Structure-behavior-function	Cultural norms
Interactions	Side effects

Systems

The concept of a system relates to the way in which individual components of an object or process work together to accomplish the function of that system. Analysis and design of systems is central to the work of engineers as they seek to modify their surroundings for particular purposes. By thinking in terms of systems, engineers may choose to focus on the role and performance of individual parts, subsystems, or levels within the system, or they may highlight the boundaries between the system and its interaction with the environment. As a result, the concept of a system has many layers and can serve different purposes throughout the engineering design process.

Thinking in terms of systems involves both being able to understand how the individual parts function, as well as how they relate to each other and contribute to the functioning of the system as a whole. As related in Table 2, the concept of a system includes many other concepts, including control/feedback, processes, and boundaries. For our review here, we will concentrate on two aspects of the concept of systems that have been the subject of substantial empirical research: structure-behavior-function and emergent properties.

Structure-Behavior-Function (SBF)

Relevance to the Practice of Engineering

Structure-behavior-function is a framework for representing a system and can be used to describe both natural and designed systems. It relates the system's components (structures) to the purpose of those structures within the system (functions) and the mechanisms that enable the structures to achieve their function (behaviors). The framework has been used for explaining designed physical systems, such as electrical devices, and the specification is explicit enough to serve as the basis for knowledge-based computer programs that can effectively evaluate and adapt existing device designs (Goel, Bhatta, & Stroulia, 1997). SBF can also represent the process of design as conducted by experienced designers. In this case, some researchers have provided empirical evidence that functional considerations drive the design process for more experienced designers, and as a result label the framework as FBS (Gero & Kannengiesser, 2004). For our purposes, it is sufficient to make the distinction between the three aspects of a design without making a formal commitment about their order or importance in the process of authentic engineering design. In either case, the SBF framework is a useful framework both in analyzing designed systems and in explaining the process of design.

Based on our review of the literature, we will attempt to support the claim that for K-12 students an understanding of structures precedes an understanding of functions, which in turn precedes an understanding of behaviors. Behaviors are the most challenging to understand as they attempt to connect structures and functions through underlying causal mechanisms, which are often invisible and dynamic. Goal-directed and iterative model development from simple models that focus on structures toward more complex models that attempt to understand functions and ultimately explain behaviors appear to help students even at very young ages to build more sophisticated ideas about systems. SBF is a rich concept with which we can begin our discussion of what is challenging for students over the grade span of K-12 in understanding systems.

What is Challenging for Students and at What Grade Levels

Although we have not found many investigations into young children's interactions with designed devices, there is some evidence to suggest that young students (and possibly adults as well) do not spontaneously consider the structures of a device that make it work unless prompted to do so. In other words, people are often content to use a device for its functional purpose without carefully inspecting of what the device is made (Rozenblit & Keil, 2002). Lehrer and Schauble (1998) explored how elementary school students (second and fifth grade) explained the way designed devices work in the context of gears. They interviewed students to assess their reasoning about the mechanics of gears in situations where there was no function, using increasingly complex combinations of gears on a gearboard, and in familiar machines with a known purpose, including a handheld eggbeater and a ten-speed bicycle. They found that, even though all the aspects of the devices could be directly inspected, as they involved no hidden parts, the students' ideas about the structures within the devices and about the mechanisms that explained how those structures worked varied noticeably. The older students were more likely to form causal chains involving the relationships of three or more components in the functional devices (e.g., "When you turn the handle, it turns this big gear, which turns these [little] gears, which turn the beaters."). It was also notable that in the function-free context, the fifth graders were more likely than the second graders to mention explicitly the role of the gear teeth as the important aspect driving the gears' motion. In the functional context of the eggbeater, both groups were likely to mention the gear teeth. This improved performance of the younger students with eggbeaters may indicate the importance of context in helping younger students to reason about causal mechanisms.

Another difference between grade levels was that even though students at both grade levels were equally likely to mention that the relative gear size determines the speed of the gears, the older students were more likely to take that idea a step further and actually count and calculate the ratio of gear teeth. The fifth graders used this mathematical reasoning when analyzing more complicated combinations of gears, which may be the result of the students' strategic use of mathematics to help minimize the complexity of the task. Early elementary students may not have the mathematical skills or knowledge to utilize this strategy. When considering the bicycle, most children understood that the gears had something to do with speed, but almost none, in either grade, were able to provide sophisticated explanations about how the gear ratios would affect the difficulty of pedaling, even with considerable prompting. Taken together, these findings caution that even when the structures of a design are visible, young students may recognize the function of objects without considering how the structures are responsible for providing that function. In addition, early elementary students may have yet to develop sophisticated strategies for explicitly articulating causal mechanisms and for using mathematical representations as tools to represent more complex causal behaviors.

Further work on the differences between adults and students has elaborated how the understanding of systems in terms of SBF may change over time and with experience. Hmelo-Silver and colleagues have done research that has explicitly used the SBF framework to analyze expert and novice differences in providing explanations of systems (Hmelo-Silver, Marathe, & Liu, 2007; Hmelo-Silver & Pfeffer, 2004). They considered two systems, an aquarium ecosystem and the human respiratory system. The studies compared seventh grade students with preservice teachers and two types of experts, those whose education was geared toward practice (aquarium hobbyists and respiratory therapists) and those with more extensive, formal training (biology researchers and pulmonary physicians). They found minimal differences between experts and novices when thinking about structures, but the differences were much wider when understanding functions, and even more so with causal behaviors, which are related to the connectedness that characterize the elements within a system. The authors suggest that behaviors are the most difficult to understand because they are often dynamic and invisible, whereas functions are easier because they are focused on specific outcomes.

There were little differences observed between middle school students and preservice teachers (both novices), but preservice teachers did tend to hold more sophisticated holistic mental models of the systems. This difference suggests that an understanding of the interdependencies of systems may develop over time, even if that understanding doesn’t necessarily transfer to understanding the behaviors and functions of particular systems. There were also expert-expert differences. Hobbyists were more likely to discuss specific behaviors and practical ways to maintain the system. Biologists talked more globally, giving few concrete examples, but described and explained the underlying scientific basis for how the system worked, focusing on general issues of regulation, equilibrium, and energy. Similarly, the respiratory therapists focused their descriptions on a clinical series of events, whereas the pulmonary physicians centered their explanations on how the nervous system drives respiration (providing energy for cellular metabolism). Hmelo et al. interpreted these findings as suggesting that pragmatic expertise may be a more appropriate target for instruction, since it is grounded in concreteness and clear outcomes, and may serve as a bridge toward more abstract understanding. In summary, these studies of expert-novice differences demonstrate that functional aspects deal with outcomes that are easier for less experienced individuals to understand, whereas behaviors deal with aspects that are dynamic, invisible, and therefore require more experience in a domain to understand.

Experiences that Extend or Build Understanding

Both research groups studying student performance with SBF have gone further in examining SBF in the context of systems to design and analyze instructional situations that build on these ideas. Penner and colleagues designed two studies using the task of building functional models of an elbow to assess students' judgments of the purposes of models (Penner, Giles, Lehrer, & Schauble, 1997; Penner, Lehrer, & Schauble, 1998). In the first study (Penner et al., 1997), they conducted the design task of building a model of the elbow with a class of first and second graders and then used post-interviews to assess their ability to evaluate models based on functional characteristics rather than perceptual similarities. The first and second grade modelers were compared to two non-modeling groups: students from another second grade class and students from a fourth and fifth grade class. An interesting finding from the study was that even though the design task from the very beginning was to design a model that "works like your elbow", students' initial designs has many more perceptual similarities with the elbow than functional ones. It was only with considerable teacher prompting that helped students to identify the constraints on the movement of the elbow, and an opportunity to revise their models, that students' designs modeled the functional characteristics of the elbow. As a result of the discussion, model-building, evaluation, and revision, the modeling students were able to learn to judge the models in final interview in terms of their functional qualities at a rate similar to the non-modeling fourth and fifth graders, whereas the non-modeling second graders almost exclusively evaluated models based on perceptual characteristics (i.e., the extent to which the model "looks like" an elbow). This study provides evidence that although students may make progress throughout elementary school in learning to think of models in functional ways, with the appropriate classroom supports and opportunities to iteratively revise designed models, even young elementary students are capable of this type of understanding.

In the second study, third grade students engaged in similar model-building and revising to understand how the human elbow works, but went further with their models by exploring the mechanisms of motion (i.e., muscles) and in connecting to the general mechanics of leverage through data collection and analysis of tables and graphs (Penner et al., 1998). In this classroom, the teacher played a central role in supporting the model development of the students. The particular moves the teacher made included: (1) pointing out limitations of the class models as a whole, such as when none of the initial models included a mechanism for motion, and then asked students to consider that specific idea in their model revision; (2) provided information through telling when there was not a way for students to discover the information on their own, such as telling the students that muscles only worked in contraction and providing the mathematical concept of median as way to represent a group of data; and (3) encouraged individual teams of students to pursue specific design challenges that extended their existing models in more general ways, such as considering how the function of the shoulder and a hand with moveable fingers is similar and different from an elbow. As a result of this explicit teacher support, students were able to design functional models of the elbow of increasing complexity, including models of the mechanism of motion, and then develop data representations that supported their claims about the different performance of their designs. Despite many successes related to understanding how the structures of the systems related to the function of the models and drawing some conclusions from their data on the patterns associated with attaching the "muscles" at different points on the arm, students were not successful in developing general principles from the data related to the abstract science ideas of leverage. In sum, these elementary students needed considerable teacher support to develop their ideas over time, but with that support, were able to successfully consider many increasingly complex aspects of structures, behaviors, and functions, although understanding the causal mechanisms of the behaviors in a general way continued to be a challenge.

Similarly, Hmelo-Silver and colleagues used the SBF framework to design instruction to engage sixth grade students in a design task. They also used an instructional framework called Learning by Design (Kolodner et al., 2003) to have students learn about the human respiratory system by designing an artificial lung (Hmelo, Holton, & Kolodner, 2000). In this implementation, students spent considerable time generating questions about lungs and doing investigations of those questions before designing. As an unfortunate consequence of this long pre-design activity, though, students only created one design that only was beginning to appropriately model the function of the lung. With further iterations of the designs, students may have refined their ideas considerably. Nevertheless, looking at students' drawings of the respiratory systems from before and then after the unit, students' diagrams indicated a more system-like understanding. For example, they were more likely to connect the respiratory system to other structures in the body, such as the brain and blood vessels. At the conclusion of the unit, the majority of the students still held relatively simplistic mental models of the human respiratory system that included relevant structures, but not always the relations between the structures or the relations to other systems in the body. In general, though, the students were able to develop more sophisticated understanding of the human respiratory system by engaging in the design task. As a powerful example of what might have been done to improve this implementation, the authors related how one day an engineering professor came to talk with the class about designing. The professor viewed their list of learning ideas on the board, and found that they focused on the big ideas of the issue, but not on the details that were needed to build working models. The professor helped the students to revise those ideas to make a more specific and pragmatic set of questions and then provided explicit help in translating those questions and ideas into designs. The lack of explicit support connecting very specific goals to design decisions prior to this point was likely a major reason that students' models were not as refined at they could have been. Hmelo et al. suggest that with more revision of the models, more explicit language connecting to the SBF framework, and more focused investigations into the causal mechanisms, that students would have likely made more progress on some of the more sophisticated aspects of the system.

The findings from this study are consistent with their other work comparing experts and novices, in that understanding of the structures of the system seems to precede knowledge of the functions, and knowledge of functions seems to precede knowledge about the causal behaviors that give rise to those functions. Again, though, through iterative model development and explicit teacher supports that helps students focus purposefully on particular challenges that are aligned with understanding the causal mechanisms, elementary and middle schools students are capable of developing sophisticated understanding of structure-behavior-function.

Summary

What we can conclude from these studies is that students at a young age are unlikely to spontaneously consider the causal mechanisms that underlie a system. Students are much more likely to consider surface features, even when prompted. One primary method for advancing students' ideas about structure-behavior-function seems to be engaging in active design of models. In addition, the iteration of successively complex models may be especially beneficial, since the first models tend to focus on superficial features and structural aspects, and many constructive ideas are raised in revision and refinement of the models. Furthermore, the supports provided by the teacher appear to have a large influence in making model-building activities productive toward understanding SBF. In particular, teacher questions that help students to focus on the connections between the design and the questions that are being asked, as well as helping to make step-wise and pragmatic goals for each revision, helps students to understand SBF in a deeper way. With considerable supports by a teacher, early elementary students and older students are able to move toward a conceptual understanding that highlights functions, which is more characteristic of experienced designers. Despite this apparent opportunity, there are still many challenges that remain in understanding the behavior aspect of systems, presumably because the causal mechanisms underlying system behavior are more general and dynamic while also being less visible. The following concept is concerned with understanding some of the dynamic aspects that characterize complex systems.

Emergent Properties

Relevance to the Practice of Engineering

Not all systems are appropriately analyzed in terms of simple causal behaviors or a direct, linear sequence of events. Another prominent framework for understanding systems focuses on the behaviors that emerge from the dynamic interactions between components within the system. Emergent behaviors occur when the global, aggregate, or macro level behavior of a system emerges from the local, simple, or micro level interactions of the individual elements or components within the system. In these cases, the aggregate level behavior is not just a sum of the individual component behaviors, but is qualitatively distinct. Complex systems, and thus emergent behaviors, are a central part of many engineered systems that are commonly found today, including highways, the Internet, and the US power grid (Ottino, 2004), so understanding about these types of systems is important for engineers who intend to work in these fields.

A further reason why the concept of emergent properties in systems is central to the work that engineers do is that much of the work of engineers makes use of foundational science concepts. These foundational science ideas can often be misunderstood because they are not thought of in terms of emergent properties. For instance, basic physics concepts such as force, light, heat, and electricity are often thought of by novices as material substances rather than being more appropriately represented as emergent processes (Chi, 2005; Reiner, Slotta, Chi, & Resnick, 2000). Individuals that maintain these less appropriate conceptual models for understanding phenomena may be limited in their ability to use science ideas effectively when engaging in design. Therefore, an understanding of the concept of emerging properties both supports the work that engineers do directly with complex systems and the ideas that comprise the scientific knowledge base that is essential in all engineering work.

What is Challenging for Students and at What Grade Levels

Although the research specifically on emergent processes and behaviors has not been examined from a strictly developmental perspective, there is current learning science research available that is relevant to understand what is difficult about these ideas. All of the work that we are aware of has been with middle school students or older, which suggests that this concept may be more appropriate for older students. It also seems to be the case that these ideas are not intuitive even for adults, and therefore are not learned through everyday experiences, but instead require special kinds of support or learning experiences. Our findings about the major difficulties in understanding emergent properties are that there exists a strong (perhaps innate) tendency to ascribe central plans or single causes to resulting behavior, and that tendency impedes understanding. In addition, analyzing emergent properties is cognitively demanding as it necessarily involves thinking across levels of a system.

The classic example of students' reasoning about emergent phenomena occurred in Resnick's (1996) research with 12 high school students using a complex systems modeling program that he created, StarLogo. Resnick created StarLogo as an extended version of the Logo program, in which users could specify the behaviors of individuals, then observe how the interactions between the individuals gave rise to group-level behaviors. Mostly in pairs and with considerable help from Resnick, the students each developed an individualized project using StarLogo. One of the projects was an exploration of traffic jams on one-lane highways with the following three basic rules governing each individual car's behavior: (1) if there is a car close ahead of you, slow down; (2) if there are no cars close ahead of you, speed up until the speed limit; and (3) if you detect a radar trap, slow down. The students observed traffic jams when running their simulation, and in an attempt to explain this result, reasoned that some localizable cause must be responsible. In this case, they attributed the cause to the speed trap. When they removed the trap, effectively making this a two-rule system, surprisingly, the traffic jams still emerged. Even when the students had the cars each start at the same speed, the traffic jams still emerged. Only when the students made uniform speeds and equally spaced starting positions, did each car uniformly accelerate up to the speed limit and stay there, creating a smooth flow of traffic. In sum, it was the randomness of the cars initial spacing that gave rise to the emergent properties, the traffic jam. This result was highly counter to students' ideas, which Resnick characterizes as representative of what he calls the *centralized mindset*. In all of the high school students he worked with, their initial reaction was to explain system-level patterns in terms of being created by a leader that orchestrated the pattern (e.g., a bird at the head of a flock) or a seed that caused the pattern (e.g., a speed trap). Resnick suggests that most people prefer explanations that assume a central control, single causality, and predictability. On the other hand, those who understand about emergent properties can reason about decentralized control, multiple causes, and an understanding of stochastic and equilibration processes. As the students worked to test their simulations with different starting parameters and to refine their rules, and with Resnick continually challenging their assumptions, they were able to adopt an appreciation for decentralized thinking and emergent properties. Many people, when faced with complex artifacts, tend to assume some form of central organization that is responsible for planning, developing, and coordinating the construction of the artifact. Although this is a reasonable assumption in many cases, it is not always so. Recognizing the cases when a system is better explained by the lower level interactions is very difficult for students at all grade levels.

Penner conducted two studies with younger students, in sixth grade, to determine not just how to characterize a students' novice understanding of emergent properties, but also how students may come to develop an understanding of emergent behaviors (Penner, 2000, 2001). In the first study, Penner observed a sixth grade class of students who were studying insects and trying to explain how some termite nests in Africa are more than twenty feet tall. The students' initial ideas, consistent with the centralized mindset, were to suggest a central plan or organizer. For example, they said, "Well it's like when you build a house. You have to follow plans. Otherwise nothing will probably go together right," and "I guess [the queen termite] must tell [the worker termites] what to do somehow." After going through the example of the "wave" at a football game and how that emergent behavior is organized but not centrally planned, the teacher returned to the idea of building termite nests and suggested the following rules in which students would simulate termites: (1) A student can move either forward, turn right ninety degrees, or left ninety degrees; (2) a student picks up a chip if they run into one and not already carrying one; and (3) a student should put down their chip if they run into someone else carrying one. Again, based on their predictions, students persisted in thinking that such a simple system could not possibly build nests, “I don’t see how. Nobody is telling people where to put things down. They could put them down anywhere!” When they actually did the simulation, many students commented on the small piles beginning to appear, but still held onto ideas that the process was centrally organized, “Aren’t the rules just another way of telling us how to make piles?” Penner points out that the students’ reactions indicate their difficulty in separating what they did, from the global pattern that emerged. Through the simulation, the sixth-grade students were able to extend their understanding of systems to consider the idea that a central, explicit plan is not necessary for macro level order to be produced. Instead, that order may emerge from individuals following simple rules who interact with each other in the environment. And yet, students continued to have difficulty separating the behavior of individuals at one level of the system from the product at a different level, suggesting that thinking across levels is conceptually challenging.

An alternative explanation for why understanding emergent properties is conceptually difficult is that students are actively trying to understand these phenomena in terms of what they already know, such as direct causes or material substances, but that those prior ideas are inappropriate for understanding emergence. Through a series of studies, Chi and her colleagues have proposed that some misconceptions of science phenomena are robust because they are classified conceptually in an inappropriate ontological category (Chi, 2005; Chi & Roscoe, 2002; Reiner et al., 2000; Slotta & Chi, 2006; Slotta, Chi, & Joram, 1995). Examples of robust misconceptions in understanding electricity, heat, and light are claimed to be of this kind. The implications of this research are that in order to understand emergent properties, students must be helped to form such a category in the first place, and then to begin to associate ideas with that category that were originally miscategorized as members of a distinct class of ideas. In order to demonstrate the plausibility of this theory, Slotta and Chi developed an ontology training procedure which they tested empirically, although with undergraduate students that had no university-level science background (Slotta & Chi, 2006). The procedure included a computerized module of text and simulations that attempted to convey central aspects of emergent processes. In addition, the students learned from an electricity text, in which all references to a substance model (i.e., the water analogy) were removed. At pre-test the students used almost entirely substance models, but at post-test they used many emergent process explanations. These findings thus provide evidence that the creation of a new ontological category for emergent processes was helpful in encouraging students to correctly classify electricity problems as emergent processes rather than with substance explanations. The implications of this research then may be that students cannot simply experience emergent phenomena, even if they are actively manipulating them. They may have to be explicitly helped to form a general understanding of what emergent properties are, and then learn to interpret their experiences using that emergent category as a lens. In the next section, we will review some empirical work that addresses possibilities for teaching students about emergent properties.

Experiences that Extend or Build Understanding

Since much of what we know about what K-12 students find difficult about emergent properties is found in learning science research, that same research often includes an instructional component. For instance, Penner described a life-sized, participatory simulation of gathering wood-chips into piles and the parallels to termites building their nests (Penner, 2001). Other researchers have also considered the effect of life-sized, participatory simulations for the study of emergent properties (e.g., Colella, 2000; Resnick & Wilensky, 1998). Penner's purpose for the simulation was to understand the ways in which students develop ideas about emergent properties from such a simulation in the context of classroom instruction. An important aspect of the simulation was that is was properly motivated, in that students understood how it related to their real question of termite nests and had made clear predictions that the simulation would not result in creating organized piles. In addition, it is important to note that the results of the simulation did not fully address all of the students' ideas. On the other hand, they did provide a set of refined questions that could be answered with modifications to the simulation and continued investigation of students' evolving ideas. Thus, the simulation was best understood as being situated in a broader instructional context that supported its effective use.

Another promising feature of the work that has been shown to extend and build on students' understandings of emergent properties is software environments that help students to manipulate complex systems. The primary example is StarLogo, the object-based modeling tool described earlier that was created by Resnick to help students explore emergent properties and self-organizing systems (Resnick, 1996). Some aspects of the tool have already been described in the previous section, but a central benefit provided by the tool is in how it facilitates students' thinking about systems at multiple levels (Wilensky & Reisman, 2006; Wilensky & Resnick, 1999). This software modeling approach, often called the embodied approach, can be contrasted with a traditional approach to understanding emergent properties that uses differential equations. One drawback to the equation-based approach is that only students with advanced skills in mathematics would be able to use that approach. That would immediately exclude the exploration of emergent phenomena in all K-12 settings, except in unusual cases. A further argument is that equation-based approaches represent a pattern, but do not represent the mechanisms that underlie those patterns. Using software tools in the embodied approach allows students to consider how the individual-level rules give rise to the higher-level emergent behavior. Resnick and colleagues argue that computational tools, in general, are especially capable of providing students the ability to more easily explore, manipulate, and understand concepts that span levels of a system.

Other relevant work has considered not only the link between multiple levels, but has gone a step further to consider the importance of having one level be dynamically derived from the next (Frederiksen, White, & Gutwill, 1999). Frederiksen and colleagues studied the context of direct current electricity, and developed three levels of models that were important in understanding this content: a particle model, an aggregate model, and an algebraic model. They also developed simulations that demonstrated how successive cycles of applying the particle model to the aggregate model of a closed circuit with a battery and a resistor result in a dynamic steady state in which charge continues to flow. They hypothesized that the dynamic nature of the simulation was important in making salient the transition to the steady state. This transition would help students to make sense of difficult concepts, such as a dynamic steady state and a system with multiple constraints, since the steady state was being derived from the more fundamental and concrete particle model. In this laboratory study, 32 tenth and eleventh graders were recruited and divided into two groups, a transient group that was provided with the simulations including the transient states that resulted in the steady states, and a steady-state group that also was provided with the simulations but shown only the steady states without having access to the transient states. As expected, although both groups understood the particle model equally well, the transient group had a better understanding of the aggregate model and could more accurately solve qualitative and quantitative circuit problems. Thus, it appears that making explicit the connections between levels benefits students' understanding, and that dynamic simulations are a productive to way to make those connections salient.

Summary

The research on what students find difficult and what helps them to build their knowledge of emergent properties highlights the importance of using tools to effectively analyze situations at multiple levels. Engaging in analysis at multiple levels may make the concept of emergent properties particularly demanding for elementary-age students, but there is not enough research to support that claim right now. With effective simulations that are properly motivated in the classroom context and make salient the connections between different levels, the strong tendency to use explanations that include central plans and single causes may be effectively transitioned to a perspective more consistent with conceptions of emergent properties.

Optimization

The concept of optimization in engineering relates to the aspect of the design process in which the functionality or effectiveness of the design is maximized (International Technology Education Association, 2000). Because in real-world designs there are always multiple, conflicting requirements and constraints on a design, optimization always involves considering trade-offs in which the designer must make decisions about the improvement of one quality of the design over another (e.g., range of motion versus mechanical advantage, or additional strength versus added material cost). The types of requirements and constraints that have to be considered in optimizing a design may include understanding the resources available, the cultural and social norms that influence what qualities of the design are valued most, and, of course, the physical laws that determine how things work. Thus, the concept of optimization is a core concept that organizes many related engineering concepts, including trade-offs, requirements, resources, physical laws, social constraints, cultural norms, and side effects (as related in Table 2 above).

In the case of optimization, we were not aware of cognitive development or learning science literature that directly addressed what was difficult about these concepts for K-12 students. As a result, we chose to focus on concepts that are relevant to the idea of optimization, but may not be discussed in the same terms as they are in engineering contexts. For instance, optimization could be thought of as an understanding of how the multiple internal variables of a system or product can be manipulated to maximize the multiple external performance measures of that system or product. Therefore, understanding conceptually how to simultaneously consider the effect of multiple variables on an outcome is a central aspect of the concept of optimization and has also been researched extensively in cognitive development and learning science domains. In addition, when relevant variables interact with one another, additional conceptual knowledge is required to consider the trade-offs that must be made in the design. Trade-offs is then a second conceptual idea that is both important for understanding students' cognitive development of ideas about optimization in engineering and that also may have a solid body of empirical data on students' developing understanding of the idea across the K-12 grade span. As a result, for our review here, we will focus on these two aspects that are central to understanding the concept of optimization: multiple variables and trade-offs.

Multiple Variables

Relevance to the Practice of Engineering

As just mentioned, the goal of engineering design is primarily about designing products or processes that result in predictable outcomes, often maximizing those outcomes as outputs given constraints on resources as inputs to the design. But in all real-world products or processes in need of an engineering solution, there are almost always a large number and wide range of input variables that can be manipulated in the design of an effective solution. Knowing which of those variables have a causal effect on the outcome is thus of central importance in engineering design.

What is Challenging for Students and at What Grade Levels

People with an interest in bringing engineering to younger children may be concerned that there is a developmental trend of global cognitive processes that may constrain the ability of younger students to work on complex engineering problems that incorporate many variables and requirements simultaneously. There are global cognitive processes that gradually improve throughout childhood, which include processing speed, working memory, and executive functioning (Kail, 2004). Although those general age-dependent aspects of cognitive functioning can have a significant influence on task performance, domain-specific aspects (e.g., task strategies and prior knowledge) are also important, if not more so. Furthermore, there is considerable evidence to support cognitive load theory (CLT), which argues convincingly that the seemingly infinite intellectual capacity of humans is primarily due to modifications in our long-term memory, since our short-term memory, at all ages, is tightly constrained to considering no more than five to seven elements at a time (Sweller & Chandler, 1994). Even well-practiced adults are only able to process three or four variables simultaneously without compensating for their processing constraints using some sort of chunking strategy or linear processing (Halford, Baker, McCredden, & Bain, 2005). Thus, although students' capabilities of working memory, processing speed and executive functioning almost certainly do improve to some extent over the course of their time in K-12, many aspects of real-world engineering design are well-beyond the cognitive processing limitations of even adults. As a result, we would be wise to carefully consider the ways in which adults manage these constraints in complicated situations and evaluate whether those can be taught successfully in K-12 settings.

There are two relevant issues that have been researched in the cognitive development and learning sciences literature. First is the coordination of multiple variables in a consistent and additive way. And second, in the cases when there are interactions between variables, is the additional difficulty of understanding the conditions under which a particular variable will have a particular effect. We will postpone our discussion of the case of interacting variables till the next section on understanding trade-offs.

Kuhn and her colleagues have conducted numerous studies that have uncovered much about students' mental models underlying their understanding of scientific inquiry. Similar to how students' may have mental models of particular systems (e.g., a mental model that explains cause of the seasons or the flow of electricity in a circuit), students also have more general mental models of core concepts, such as causality itself (Kuhn, Black, Keselman, & Kaplan, 2000). Kuhn et al. consider this type of mental model to be at the metalevel, in that this conceptual understanding is not tied to a particular domain. In particular, a mental model that was consistent with a normative understanding of causality in a multivariable system based on the analysis of variance (ANOVA) model would assume that each variable in a system has both a consistent and an additive effect on the outcome variable. But work with students in their studies suggests that students at the middle school level very often have an alternative mental model of causality that is neither consistent nor additive. A further complication, though, is that even when considering multiple variables in a consistent and additive way, Kuhn and colleagues have identified that understanding the causal effect of each variable individually in a system does not imply that they can be coordinated successfully, as would be necessary to do in the design of a product or process. Using a paradigm in which fourth grade students engaged in a multivariable prediction (MVP) tasks after having successfully used the control of variables (COV) strategy to infer the causal nature of a set of variables, Kuhn found that almost all students reverted to a preference for indicating only one variable as being causal in any prediction and for choosing a different variable as the causal one across predictions (Kuhn, 2007). Both of these studies highlight that helping students to focus on the effects of individual variables may not be sufficient unless the students are also supported in reconsidering more general notions of the impact of variables in a system.

It is important to note that students' inability to effectively engage in multivariable prediction tasks may have more to do with their understanding of the task itself than of their capabilities of engaging in effective experimentation. For instance, fifth and sixth grade students are more likely to make valid inferences about the importance of a variable when they understand that the goals of the task as being scientific goals rather than engineering goals (Schauble, Klopfer, & Raghavan, 1991). Thus, helping students to be aware of what they believe is the purpose of their testing is also important in making sense of and designing multivariable systems.

These studies provide considerable evidence that students' conceptual understanding of the causality of variables is important and needs to be taught explicitly in instruction for students to be able to understand and design multivariable systems. The following section will consider some ways that this type of understanding has been facilitated for students in instructional settings.

Experiences that Extend or Build Understanding

Adults are able to increase their ability to engage in complex tasks by interacting with long-term memory, in which ideas can be reorganized into more complex ones (schemata) so that many elements can be loaded into working memory as one element, and by automating the application of those schemata so that they do not need to be consciously applied within working memory through repeated practice across a variety of situations. Thus, schema construction and schema automation are the central processes that allow an individual to engage in more complex tasks. Explicitly helping students build schemas for analyzing multivariable systems, such as an assumption of additive and consistent effects and a control of variables strategy as a logical test of the effect of variables, is one strategy for assisting students. Although these ideas could be characterized at the metalevel, evidence suggests that they can be taught to young children through explicit instruction. One method for making this possible in this case is to teach explicitly the normative understanding of multivariable causality so that students understand at a metalevel what effective experimentation is (Keselman, 2003).

Chunking is another way to overcome working memory constraints, similar to the acquisition of context-specific schemas, as it involves mental representation of a situation as one, discrete element in memory with many different aspects hidden underneath it. An example of chunking might be when one can think of a continuous, two-dimensional space as a set of discrete objects, each object with a discrete value on those two dimensions. The adaptive expertise theory (Schwartz, Bransford, & Sears, 2005) and Pasteur's Quadrant (Stokes, 1997) are recent well-known cases in which the authors support reader understanding by transforming the two-dimensional space into discrete elements and explicitly labeling each cell in a theoretical account involving the interactions between those two dimensions (see Figure 1).

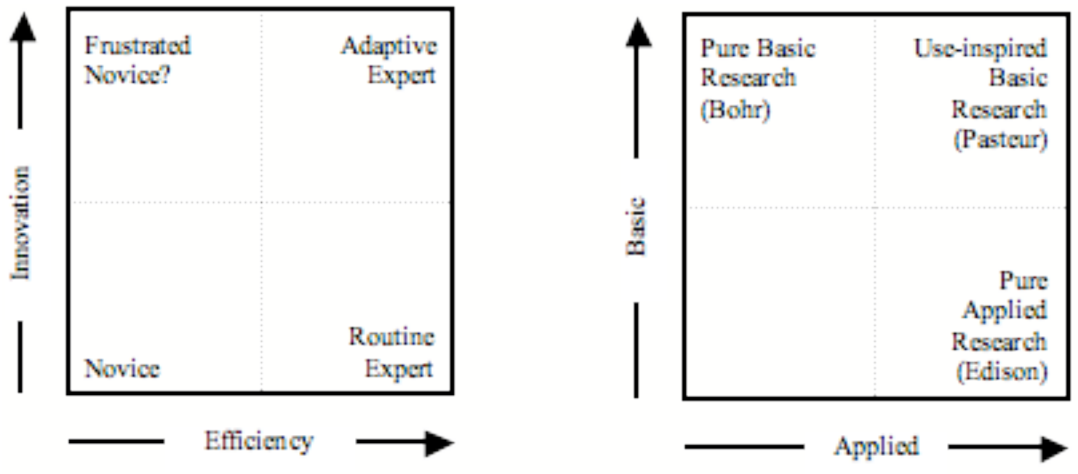

Figure 1: Examples of chunking a two-dimensional space into discrete objects: (left) Characterization of expertise in terms of both efficiency and innovation (adapted from Schwartz, Bransford et al., 2005); (right) Characterization of research goals in terms of both the extent to which the findings are intended for practical use versus increasing scientific understanding (adapted from Stokes, 1997)

In addition to learning schemata for efficient cognitive processing, there are a number of other important strategies for overcoming working memory constraints that are an important part of mature learning as well as authentic engineering practice. For instance, one strategy may be to utilize functional decomposition, which is a design-specific strategy, but an instance of a more general strategy that allows one to simplify and focus on one part of a system For example, the Wright Brothers used functional decomposition to make progress in designing their airplane, isolating the effects of different aspects for testing before building their entire system (Bradshaw, 1992). Strategies such as these can be taught to students so that they may employ them when engaging in design of complex devices or processes.

But conceptual ideas are not represented solely within an individual's mind. Physical representations of ideas also help students to understand complicated situations. As a result, another important strategy is the use of external representations. These external representations can take the form of prototypes of designs, which makes most aspects of the design concrete and visible. In this case the conceptual design is embodied in the physical object, the prototype, and by making it physical, the outcome variables are salient. Roth (2001) has documented in a fourth and fifth grade classroom students learning about simple machines, and how the artifacts that students created functioned to both open up possibilities and to provide constraints. In addition, those artifacts became the source of productive whole-class discussions, in which students were able to articulate their ideas, evaluate them with the help of others, and identify places in need of revision and other things to try.

Conceptual ideas do not necessarily need to be embodied in physical objects. A further important strategy is mathematizing, which represents conceptual ideas as mathematical relationships. In contrast to the prototyping, this strategy purposefully makes only some variables concrete, and hides others. Mathematizing has the advantage of being able to combine dimensions, such as rate or efficiency. Sometimes these variables are in a trade-off relationship. Part of mathematizing could be using an equation that represents the relationship, a unit of measure that combines variables, or a graphical representation (Yerushalmy, 1997). It would be a mistake to assume that because younger students do not have vast amounts of formal mathematics experience, that they are not capable of representing complicated situations in mathematical ways. A number of powerful examples have shown that very young children are capable of developing sophisticated mathematical representations of situations that communicate meaningful ideas and aid in problem solving. For instance, third grade students were capable of representing plant growth in increasingly sophisticated graphical representations when given the opportunity to continually edit, revise, and elaborate on their graphical inscriptions over time (Lehrer, Schauble, Carpenter, & Penner, 2000). This relates the theoretical idea of “situated abstraction” (Pratt & Noss, 2002), in which students don’t necessarily progress in their understanding toward increasingly decontextualized, but instead, create a denser connection among contexts in which the mathematical ideas have meaning and are useful for problems solving (Noss, Healy, & Hoyles, 1997). Thus, when used in the support of problem solving and are given sufficient time to develop and be elaborated, mathematical representations can be used by very young students to make sense of complicated situations.

Mathematical relationships, when they are applied successfully, can be used to make a situation cognitively tractable and thus aid problem solving in ways that are even more effective than embodied physical objects. People may use conceptual chunking to make a situation less cognitive demanding, such as when they combine a ratio into one value, a percentage. But doing so necessarily loses information. Situational factors can determine whether students are likely to apply their knowledge of mathematics to solve problems (Schwartz & Moore, 1998). Sixth-grade students are more likely to invoke mathematical representational strategies when the numbers with which they are working are easy to make proportional comparisons between (e.g., 2:1, 6:2). Whereas, when problems are presented as real, physical objects rather than as diagrams, students are more likely to appeal to knowledge from experience. As a result, instruction may have to consider ways to encourage students to use mathematics to help make sense of situations even when the situation does not lend itself to doing so.

Finally, there are also methods, such as note-taking (Garcia-Mila & Andersen, 2007) or sketching (Anning, 1997; MacDonald & Gustafson, 2004; MacDonald, Gustafson, & Gentilini, 2007) that are important in students’ success in working with multivariable systems. Sketching sits in between prototyping and mathematizing, in that it is more abstract than prototypes, more concrete than mathematical equations or graphs, and allows for hiding or de-emphasizing some possibly irrelevant variables.

Summary

The large number of variables that are involved in most engineering contexts easily overwhelm the limited cognitive resources of all individuals, including adults, even though adults have slightly more developed general cognitive resources. Metalevel knowledge about the nature of causality and the goal of testing can help students be systematic in learning about design. In addition, strategies for simplifying tasks by focusing on subproblems, and utilizing external representations (physical and mathematical) are important things that students in K-12 setting can be taught so that they can effectively construct and evaluate complicated designs in systematic ways.

Trade-offs

Relevance to the Practice of Engineering

In all optimization tasks, trade-offs occur both when considering the input variables of a system, those that can be manipulated in the system design, and the outcome variables, those that are used to judge the quality of the design. A trade-off of an input variable occurs when a choice to modify the level of one variable impacts the effect of another variable on the outcome. Thus, trade-offs refer not just to a case when multiple variables combine to influence an outcome in an additive way, but it refers to the more specific case when those variables are opposing each other. A similar case occurs when a particular variable will have a particular effect only under certain conditions. Trade-offs also occur when weighing the different outcomes of a design, such as when considering the cost of a design compared to its effectiveness. Trade-offs are an important aspect of all real-world engineering design and many tools have been developed to help engineers reason about trade-offs, such as a design matrix (Otto & Antonsson, 1991).

What is Challenging for Students and at What Grade Levels

In a normative sense, a conceptual understanding of interactions between variables is very difficult. Zohar found that when thinking through interactions between variables, community college students in a low-SES area thinking did not reflect that of experts (Zohar, 1995). In particular, she found that students had four difficulties: (1) lacking the “double set of controlled comparisons” strategy that is necessary to validly infer an interaction; (2) lack of a conceptual framework to explain the results of those comparisons; (3) a tendency to divert attention when thinking through an interaction; and (4) a difficulty in controlling the necessary variables across comparisons. Experts (a physics and a philosophy professor) did not have these difficulties. In contrast to the experts, when students did make inferences about interactions between variables (which was rare, only 10% of the time, 241 out of 2,348), they tended to make limited inferences that can be described as theory-saving or attempts to preserve a prior belief that may have been undermined by current evidence (e.g., “even though noise makes no difference in small classrooms, it may still make a difference when the class is large”). Less than 3% of the inferences about interactions (7 of 241) were valid ones. More theory-save limited inferences were made in a social domain as compared to a physical domain, presumably because the strength of the prior beliefs was stronger in the social domain. These difficulties seem to mirror those that individuals have in determining the causal inferences of single variables in multivariable systems, although the challenges appear to be magnified due to the increased processing demands of considering more than one variable at a time. Thus, in the normative sense of understanding interactions between variables, considerable formal training may be required for success.

Nevertheless, there are aspects of understanding at younger ages that may help to illuminate possible trajectories toward understanding the trade-offs when considering more than one variable simultaneously. Even in well-understood physical settings, younger students understand direct relationships before they understand indirect relationships. For instance, when considering the relationship between distance, time, and speed, fifth grade students are more likely to understand that speed is directly related to distance and that time is directly related to distance, but they are less likely to understand that speed and time are indirectly related (Acredelo, Adams, & Schmid, 1984). Many of the fifth grade students even argued that a faster object would take a longer time when distances are held constant. Although it is not clear how students transition toward understanding indirect relationships, which are more cognitively demanding, understanding direct relationships in a system may be a necessary precondition to understanding the indirect relationships.

Mathematical ideas may also be a conceptual resource for representing trade-offs and thus for helping students in considering variables that have an indirect relationship. Schwartz and colleagues have demonstrated how simply encouraging students to represent situations mathematically can be effective (Schwartz, Martin, & Pfaffman, 2005). In a series of three studies, the first two with fifth graders and the last one with fourth graders, Schwartz and colleagues used a balance scale task (Siegler, 1976) in which students considered forces over a distance by predicting the outcome of balances that varied on two dimensions, the number of weights on each side and the distance of those weights from the fulcrum. In the first study, they compared representing the weights as discrete pegs versus as beakers of water filled up to different levels. The researchers found that the students in the beaker condition were more likely to reason only about the weight dimension. They explained this finding by suggesting that these students were less likely to quantify the beakers into discrete values and that made it more difficult to consider both dimensions simultaneously. A second study tested this hypothesis further. In this study, students were given only peg problems and then asked to justify their predictions, but some were asked to justify with a general prompt to explain ("Explain you answer") and others were asked to justify with math ("Show your math"). Only 19% of the explain students considered both dimensions on at least one of the problems, compared to 68% of the math students. The explain students often switched between distance or weight as their justification, especially after receiving feedback on a problem that they predicted incorrectly, but did not often represent the dimensions simultaneously. The math students also did better on transfer problems, and of students who did consider both dimensions, the math students were more likely to consider both dimensions on these more challenging transfer problems. The third study was very similar to the second one, but did not provide example justifications or examples of how to count, and used slightly younger students (fourth grade) who were less likely to achieve the multiplicative rule for predicting the balance scale outcome. Again, the math students did better on the transfer problems in terms of being more likely to use both dimensions in predicting outcomes. Schwartz et al. also places these results in the context of extensive developmental research on the balance scale task (Siegler, 1981), showing that the fifth grade students' reasoning about the task was similar to kindergarten-age students when given a problem with hard-to-measure, continuous quantities in the form of a beaker, but the students were at the level of their peers when the problem used discrete, easy-to-quantify pegs. When given explicit instructions, feedback on their predictions, and encouragement to justify their answers using math, the fifth grade students reasoned about the problem at levels similar to adults. These studies provide compelling evidence that students, when encouraged to use mathematics, are able to better represent physical situations and reason about them, even ones that involve variables that are related indirectly.

Problems that are less well-defined are also important contexts for considering trade-offs between variables and are just as common in engineering practice. Seethaler and Linn used the Scaffolded Knowledge Integration (SKI) Framework to explore students' ability to use evidence and reasoning in science controversies. In the context of the Genetically Modified Food (GMF) controversy, they designed instruction to help eighth grade students' make arguments that took into account trade-offs (Seethaler & Linn, 2004). In the curriculum, groups of students presented evidence for and against GMF in a jigsaw format. After conclusion of the unit, students wrote position papers to argue for or against the use of GMF with the aid of a web-based tool to help them organize their arguments and evidence. Despite prior evidence to suggest that students are less likely to consider evidence that is inconsistent with their position, the students in this study used evidence both for and against their position when writing their papers. Although the students did incorporate these two sides of the argument, students were generally not explicit about the trade-offs associated with the different sides. They were also unlikely to mention the alternative position in most cases. Thus, although students were able to recognize evidence that supports and evidence that undermines a position that they personally held, the extent to which they incorporated reasoning about trade-offs in their decision-making was not clear. Further work is needed in identifying the developmental trajectories of students' understanding of trade-offs both in well-defined and ill-defined contexts.

Experiences that Extend or Build Understanding

Many of the interventions that may be effective at helping students to understand trade-offs are similar to those that help students to understand systems of multiple variables. Nevertheless, there has been some work in K-12 settings that has elaborated on interventions specific to reasoning about trade-offs. Sadler and colleagues have described their experience developing and implementing a set of design challenges for the middle school grades and the lessons they have learned from those experiences (Sadler, Coyle, & Schwartz, 2000). In one of their design tasks, middle school students are asked to build a wind turbine after being given an initial prototype model with poor performance. The wind turbines can be optimized in a variety of ways, and Sadler et al. use this feature of the design to implement successive challenges where the measurement criteria change but the materials do not. Maximizing lift, turbine speed, or power requires the manipulation of different parameters of the system to improve performance. In particular, long, fat blades produce lots of torque at low speeds, whereas the small, thin blades with a shallow pitch result in high speeds. Maximum power is achieved as a compromise between these two extremes. When engaging in this design task, the students proceed through three design challenges, as they first optimize lift (measured in nails), and then they optimize speed (measured in cm/sec) second. When these two measures are mastered, the third challenge employs both, as students work to optimize power output (measured in nails*cm/sec). As a result of this sequencing of the design goals, students proceed from thinking about simple quantities when they first manipulate the materials, and then to examining a ratio measurement as the performance measure after becoming familiar with the materials. Sadler et al. attribute the success of their middle school design challenges to a number of features of their implementation. One includes having clear tests against nature that the students can use objectively to evaluate the success of their designs. Another important aspect is their use of a number of iterations, beginning with an easy-to-build, but poor-performing prototype design. In the case of the wind turbine, they also vary the test to increasingly address more sophisticated concepts. The combination of many design iterations, and considering increasingly sophisticated performance measures that take into account more variables over time are important in helping students' to think about trade-offs between variables.

Research on problem-based learning has also identified how working on complex mathematical problems requires students to consider multiple solution paths and solution options in attempting to design an optimal solution. *The Adventures of Jasper Woodbury* series, developed by researchers at the Cognition and Technology Group at Vanderbilt, involves mathematical problem solving in complex tasks. In using a particular task from the *Jasper* series, *The Big Splash*, high-achieving sixth grade students and college undergraduates were asked to develop individually a business plan for a dunking booth at a school fair (Vye, Goldman, Voss, Hmelo, & Williams, 1997). In this task, there were constraints on time, risk and conservation, as well as motivation for minimizing both the filling and emptying expenses, all of which the students are asked to consider. When considering their solutions, the college undergraduates were much more likely to consider more than one plan and select among those, but neither group was likely to test their solution against all of the initial constraints from the problem. A follow-up study with pairs of fifth graders was conducted to build off the findings form the first study. In this study, the students were provided an example solution for the revenue aspect of the problem and then asked to do design a solution for the expenses aspect in their pairs. In this case, the pairs of fifth graders were just as likely as the undergraduate students to consider multiple solutions and were also likely to consider one or both of the problem constraints on their expenses. Successful problem solving was predicted not by the number of goals generated by the pairs, but by appropriate reasoning and sound execution of the goals that were set. Pairs that engaged in explanatory reasoning and counterarguments were able to search more of the solution space by monitoring each other, thus increasing the success of their problem solving. This provides some evidence that young students are capable of considering very complex mathematical problems that involve searching for optimal solutions. In this case, students seemed to benefit from having a partner that challenged them to justify their ideas and to monitor their ongoing solutions.

Summary

Conceptual understanding of trade-offs is cognitively demanding, and K-12 students are unlikely to have a normative understanding of interactions between variables in a general sense. Despite this, students can consider trade-offs by utilizing mathematical representations that make the relationships between variables more explicit and by engaging in successive iterations of design activities in which they are able to first consider variables in isolation and then together.

General Lessons Learned

In cognitive development, researchers worry about the distinction between general developmental constraints, those that are a function of the nature of the mind's architecture, and knowledge constraints, which are a function of an individual's experiences and how they process them. There is still disagreement about to what extent each of these constraints exists at all and which have a greater impact in different domains (Kuhn, 1997; Metz, 1995, 1997). Regardless of the generality of particular cognitive developmental trends or their origin (architecture versus experience), it is clear from the success of a number of the interventions reviewed here with students even in the early elementary grades that certain experiences can support more sophisticated understanding and use of engineering concepts than others. We think the important ideas to take away from the research are that a number of related, but complementary aspects influence students' understanding these engineering core concepts in K-12. We will review each in turn in order to summarize our recommendations.

Sufficient Amounts of Time for Extended Design Activities

In all the successful intervention studies that we reviewed, significant learning resulted only after an extended time exploring a meaningful context. Core engineering ideas cannot be developed in any meaningful way in just one class period, and instead must be developed and elaborated on through extended investigations. Design activities have been a productive context for considering these core ideas, as they are capable of sustaining interest over extended periods of time, and inviting increasingly sophisticated ways of understanding with multiple solution paths.

Iterative and Purposeful Revision of Designs, Ideas, and Models

The second aspect is that iterative, purposeful modeling appears to be a central aspect of the experiences that successfully help students to build more sophisticated knowledge. Modeling can take the form of physical designs, but also of conceptual, graphical, mathematical, and diagrammatic models. The more important aspects of this idea are that the models are used to answer particular questions that result from analysis of previous designs. The questions that result will be increasingly specific and operationally defined, and are thus purposeful. In addition, the models are developed over time, revised and refined to help understand ideas in successively deeper ways. It is unfortunate that much of design in K-12 settings supports only a single iteration of the design task. A single iteration of the design of a model to help understand an idea only begins to make salient the relevant conceptual difficulties and design challenges that need to be investigated.

An important thing to consider in thinking about iterative and purposeful revision is the role of the teacher in shaping students questions and the direction of their revisions. It might be tempting to suggest that students be responsible for determining the direction entirely on their own, but the successful interventions reviewed here highlight important roles of the teacher in providing explicit guidance in helping students to progress toward increasingly sophisticated representations and ideas. Another aspect of the revisions as being purposeful is that the iteration of cycles are targeted towards the core ideas, and the teacher often explicitly shapes this discussion through their questions of students' ideas and their introduction of possible resources for students to consider.

Sequencing Within Instructional Sequences from Easier to More Difficult Ideas

The third aspect is that knowledge builds on itself such that simpler understanding is likely to precede more complex understanding in predictable ways. Although this may seem obvious, taking this stance encourages a productive focus on the specification of cognitive developmental trajectories of particular concepts. Thus, within a domain, there are common trajectories that people may take in developing expertise, that, when specified, allow for a coherent set of experiences to build knowledge over time. For instance, in our review, we found that structure was often easier for students to understand than behaviors or functions. Therefore, beginning an activity at the structural level may be appropriate as it can provide the basis for moving toward more sophisticated understanding. That being said, although we certainly advocate for the articulation of learning progressions that recommend the types of ideas and the depth of exploration of those ideas that students should experience at different grade levels (National Research Council, 2007), we do not think that the literature on the core engineering concepts is sufficiently mature to make specific recommendations at this time. In general, much of the findings have suggested that within an instructional sequence, if students are given sufficient amounts of time and support, they are often able to make transitions from conceptual understanding typical of novices toward more sophisticated understanding. This is true even for elementary-age students.

Seamless Integration of Tools to Highlight and Represent Important Ideas

The final aspect is that tools may be used to foreground some aspects of a problem while making others less central. This strategy provides individuals with access to more complex ideas and use of those ideas when they would not have had access under normal conditions. Computer software is one clear example of a tool that can be used in this way as it is designed to support particular types of instruction. But other artifacts given to or produced by students may also serve to highlight particular aspects of a problem and thus drive further investigations. This may include suggestions by the teacher to utilize particular mathematical strategies or may be students' own creations, such as graphs to represent situations or design prototypes. These representations not only capture students' current thinking, but also shape future ideas that are considered.

Conclusion

These aspects are common across the empirical work that we have reviewed and are therefore central in understanding how lessons learned from the cognitive development and learning science literature can help to shape engineering education in K-12 settings. Taken together, we think they provide a productive basis for thinking about how students may understand and use core concepts in engineering to increasingly participate in the practices of authentic engineering.

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