Contributions of Cognitive Engineering Methods to Engineering Education

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Introduction

Cognitive engineering is the inter-disciplinary study of the design and improvement of socio-technical systems through better training of personnel, through procedures and through the introduction of technologies to support human performance. This field builds upon insights into human performance provided by cognitive science and psychology, as well as knowledge of technology design from engineering and computer science. This paper will review important potential contributions of cognitive engineering to several ‘hot topics’ in the study of engineering education research methods.

These contributions are of several different types. First, cognitive science and engineering has its own established vernacular; for example, terms such as ‘mental model’ and ‘representation’ have specific meanings. Second, a variety of methods and methodologies for research have been developed, such as using system models to establish the meaning of data. Finally, ‘design guidance’ for forms of instruction and for educational technology can be found from cognitive science and engineering; for example, some aspects of education have been studied in domains outside academic instruction – e.g. computer-based instruction – and lessons learned from those domains can be shown here. Throughout this paper, fundamental references to the field are noted.

Summary of Cognitive Science Insights Into Learning

Cognitive science provides insights relevant to education into individual learning. The main focus of cognitive science is to understand the human mind, building on several diverse disciplines including psychology, neuroscience, linguistics, philosophy, anthropology, and artificial intelligence. Often going beyond purely psychological explanations of how the mind functions, cognitive science also centers on understanding cognition in real-world contexts. Thus, education serves as a meaningful domain in which cognitive science insights can be both researched and applied.

One major subject of study in cognitive science examines the nature of mental representations. A mental representation is defined as the internal representation of information used in a mental process (e.g., perception, language, thinking, reasoning, and other cognitive activities). The term
mental model specifically refers to mental representations employed in thinking and reasoning processes. Mental representations are analogous to external representations, such as maps, pictures, and words, but mental representations cannot be observed directly. Thus, an external representation is a physical object with semantic properties, whereas a mental representation is a mental object with semantic properties. Mental representations are not rigid structures, but rather evolve fluidly as experiences accumulate. Learning is a complex mental process that involves the incremental development and reorganization of mental representations over time. One area of study from cognitive science important to education is how people form mental representations of concepts.

The knowledge and skills already acquired by the learner play an important role when forming mental representations of new concepts. Rather than viewing the mind as a tabula rasa, a blank tablet upon which knowledge can be written, research on cognition supports the notion of knowledge as an internal construct that cannot be transmitted directly. Thus, instructors cannot “give” students knowledge directly. These notions form the basis of constructivism, the dominant theory of learning in modern cognitive science, derived from Piaget’s work on child development. According to this theory, learners must actively incorporate new conceptual information into an existing set of beliefs.

Furthermore, learning requires the learner’s engagement and a cognitive effort to restructure previous knowledge. Using their own language and experience as a base, students will naturally form hypotheses and explanations as they explore new concepts. In doing so, a student may develop misconceptions that must be identified and corrected for proper learning to occur. Unfortunately, once formed these misconceptions can be difficult to overcome, as learners tend to look for confirming evidence of their hypotheses (confirmation bias) and may not “frame” their understanding in a manner desired by the instructor. Some recent engineering education research on the misconceptions of engineering students may be explained by problems associated with confirmation bias (e.g., ). Since students come into the classroom with preconceived expectations about course concepts, it is important to recognize that classroom activities may very well create new misconceptions or reinforce old ones. For example, although analogies can be powerful aids to learning, their misuse can lead to serious misconceptions if the learner generalizes the analogy to situations that do not apply.

Likewise, some knowledge and skills, when acquired, are context-specific while other knowledge and skills may be more readily transferred to a new domain. A significant finding relevant to education is the encoding specificity principle. The encoding specificity principle provides a general theoretical framework for understanding how contextual information affects memory. This principle states that in order to remember, specific encoding operations are performed that determine in what form the knowledge is stored in memory. In turn, what is stored in memory determines what cues will be effective in helping to retrieve the specific memory trace. For example, the encoding specificity principle would predict that recall for information would be better if subjects were tested in the same room they had studied instead of having studied in one room and tested in a different room.

The task of instructors, therefore, is to explain their own mental representation of concepts to students. This task can be difficult because, as stated above, mental representations cannot be
observed or explained directly. Educators can best invite learning by having their students engage and reflect upon their own knowledge, guiding the early explanations that will form. Learning can also be supported by better organizing information to match the background and developmental stage of the learner. Providing organized instruction to make the structure and relations of the material evident to learners, such as through concept maps or other graphic representations, will improve learning. Educators should also link new material with what students currently know, providing a scaffolding of the new material. Overall, cognitive theory considers learning to be an individualized, active, and strategic process, which instruction should reflect.

Similarly, human memory research has shown that memory is active, strategic, and constructive. This research supports several findings in engineering education research. For example, Bloom’s research showed that students who receive one-on-one instruction perform better than students who receive traditional instruction. One possible interpretation of Bloom’s findings is that one-on-one instruction provides students with opportunities to form more specified memory traces that are in turn easier to recall.

One aspect of cognitive science that has not yet been mirrored in education is a focus on the effects of information distribution and presentation on cognitive processes. Studies from linguistics, for example, focus on both message givers’ and receivers’ understanding of language (e.g., studies of the impact of non-verbal language on comprehension). Studies of perception focus on the effect of variability of information in the environment upon recognition and interpretation (e.g., studies of optical illusions). However, little work has been done that explicitly conceptualizes teachers as cognitive agents whose job is to distribute and present information to students. From this perspective, teaching is a domain with novices and experts. Specific areas of study suggested by a cognitive science approach include the development of teaching expertise, determination of the skills required for teaching, and the structure of professional development environments to support the development of teaching expertise.

Engineering education researchers should look toward cognitive science for an interpretation of the cognitive bases of the results. This section has briefly reviewed the role of mental representations and memory in individual learning. Additional findings relevant to education include research on problem solving and decision making (e.g.,), and metacognition (e.g., ).

**Summary of Cognitive Engineering Research Into Computer-Based Instruction and Intelligent Tutoring**

Beyond studies of individual learning, cognitive scientists and engineers have also examined the development of computer-based training systems for several decades. An alternative to the traditional human instruction model of teaching and training is computer-based instruction (CBI). The specific term refers to the role the computer plays in instruction, although teaching with computers has been called by a number of names, based on the degree of computer control over instructional tasks. At the lowest level of computer control, computer-managed instruction, the computer performs rote tasks for the instructor, such as record keeping, grading, and registration, as increasingly used in university education by web-based course management tools. At a somewhat higher level, computer-assisted instruction, the computer assumes more of
the instructor’s role of information presenter. Instructional material may be presented via a computer medium or in a traditional classroom setting coordinated by an instructor. Unfortunately, initial implementations of these forms of CBI were either extremely dull or wholly dependent upon the presence of a human instructor to guide instruction. At the highest level of computer control are intelligent tutoring systems (ITSs), where the computer assumes the instructor’s role of tailoring instruction to each student’s background and current performance.\(^\text{13,14}\)

The primary components of ITSs are the expert model, the student model, and the pedagogy. The expert model contains the normative content for instruction, i.e., what the student should know after completing the tutor. The student model represents an individual student’s knowledge, often as a subset of the expert model. The pedagogy tailors instructional content and a teaching style to the individual student, based on training goals and student progress. These components work together to teach novice students the knowledge and skills they will need to become experts.

The expert model is an organized database of declarative and procedural knowledge in a specific domain. Most often in ITS research, the expert model is a set of rules that represent the expert’s knowledge in the domain.\(^\text{15}\) Production rules are two-part formal representations of knowledge wherein the first part (i.e., “if”) specifies the applicability conditions and the second part (i.e., “then”) specifies the actions to execute if the rule is applied.\(^\text{16}\) In this framework, an expert is defined as one who, in a certain circumstance, will apply the appropriate rules. According to Anderson,\(^\text{17}\) “a typical course involves on the order of 500 such rules,” suggesting the amount of material educators can realistically aim to cover in a course. Knowledge elicitation techniques are used to define the rules contained in the expert model. Thus, the development of an expert model is also beneficial in learning about and specifying the content of a domain. One of the successes of ITS research has been to define domain knowledge to a degree that is both understood by those outside the domain and codified in a generalized structure.

Results of several independent studies on the impact of ITS use show substantial improvements in learning diverse subjects including algebra, geometry, writing, and problem solving. ITSs that have been successfully implemented and evaluated have produced learning gains of about one standard deviation over traditional classroom learning.\(^\text{18}\) Although use of these tutors has not generally been extended to the university level, their potential for use in engineering education remains.

Despite their successes, ITSs have neither solved the inadequacies involved in lecturing students nor advanced to the point to fully replace human instruction. One reason is that expert knowledge is typically not structured in a manner that facilitates the generation of an expert model to teach novice learners. The task of reformatting knowledge is a difficult task for experts; studies of knowledge elicitation have shown that experts are often not aware of the particular complexities that define their own expertise. These concerns compound an additional reason for the limited application of ITS: the cost of development and amount of time involved in creating full-scale ITSs can be very high. Despite the availability of general architectures for implementing ITSs, the development of sufficiently detailed expert models remains costly.
ITSs also rely on the analysis of observable behaviors in assessing student knowledge. As described earlier, the mental representations that individual students form in understanding new concepts are internal and not directly observable. Thus, an ITS must infer student cognitive processes from their behaviors. In production rule-based ITSs this process is referred to as *model tracing*, wherein the tutor matches a sequence of productions to behaviors exhibited by the student. The process of inferring changes in student knowledge over time has implications on the development of the student model. Consistent testing is required to establish which rules the student has acquired and whether they keep those rules, since higher order cognitive functions are not directly accessible.

By considering how educational technology might be used in context, rather than as an independent teaching device, cognitive engineering methods have had significant results. For example, in aviation, pilot training has been converted from a strict curriculum to a process tailored to individuals, judged successful once all required skills and knowledge are demonstrated, extensively evaluated, and lower in cost. The skills covered by the new training methodologies include a number of skills beyond controlling the aircraft, such as developing conceptual understanding of complex aircraft systems, effective team interactions, and judgment in making decisions. Here, computer-based instruction has not replaced human instruction, but instead is used as a supplement to existing training. The important implication for educators is to recognize the lessons learned to date about the design of educational technology to support and improve instruction while also realizing the potential brittleness of technology interventions and the changes in instructional pedagogy they require.

**Summary of Cognitive Engineering of Socio-Technical Systems, Including Education**

Finally, cognitive engineering speaks to the structure of education at a systems level. Systems engineering may be viewed as the process of modeling a large, complex system to bring insight to its design and analysis. Historically, systems engineering has been most-often applied to the design of technological systems, where the boundary of the system was drawn around the physical (and, more recently, software) elements of the system, thus delegating to the environment the human operators and broader social structures in which the technology would operate. With such a boundary, systems engineering commonly focused on decomposing the technological components into progressively smaller elements whose detailed design is manageable, drafting functional requirements for these components, analyzing the interactions between the components and their impact on system dynamics, and identifying any potential bottlenecks or sources of weakness within the system.

However, in many domains a broader socio-technical system boundary should be drawn, so that human goals, capabilities and performance can be included. This extension brings the benefits of systems engineering to large-scale domains typified by human activity and information flow, including education. In doing so, it is important that the relevant contributions of human cognition be captured within the systems model. As such, *cognitive systems engineering* methods have been proposed in which the various dimensions by which the system is decomposed include recognition of cognitive contributions to the system.
Engineering education can be examined within this framework as instructors and students interact with each other and various learning technologies (such as Internet based course-management tools) for the purpose of teaching and learning. These people may have different roles, engage in different interactions, and have different ultimate goals. For example, an instructor may create and present lecture materials in order for the students to learn the content deeply; a student may participate in lecture with the ultimate goal of receiving a higher grade in the course.

One important insight from cognitive engineering is that the context of the work significantly shapes the behavior of the people in the system. This has been demonstrated in other domains, such as in a study of commercial airline pilots where Casner showed the significant effects of various environmental influences on pilot behavior.\textsuperscript{19} In education, the context includes various goal structures established both explicitly and implicitly as part of a course. The instructor explicitly establishes part of the goal structure of the course through the grading system. The weight of the grade given to an assignment affects how much time and effort students will spend on it. Grades can serve as goals and constraints in the system. For example, students who prefer to work alone are not likely to work in a group unless constraints to do so are imposed by grade penalties for not participating. Physical constraints such as the configuration of a classroom can also affect behavior; for example if all the student desks are bolted to the floor in rows facing the front of the classroom, it is difficult to carry out discussions and debates among students during class time. Likewise, the technology used can significantly affect behavior in the context of a course. When complete lecture notes are distributed over a course website, some students may not come to class meetings; students who do come may be less engaged in traditional lecture. Alternately, the lecture time may be devoted to active learning activities instead of a traditional lecture.

Thus, recognizing the importance of the context and a thorough analysis of it can contribute significantly to understanding the dynamics of the system. This implies that an educational intervention applied in one context will not necessarily have the same effect in other contexts. For example, Hawisher and Pemberton relate an instance where an asynchronous learning network was applied in a small course for students to discuss readings outside of class.\textsuperscript{20} The instructors expected students would be excited to discuss the readings and this application would result in many insightful posts by students. Instead, students made very few posts, and these were largely summaries of the readings. After some investigation, it was found that the students were making posts believing they would be evaluated in some way on their work, rather than believing they had the freedom to discuss and share insights. A more successful example is from Picciano where an asynchronous model was applied in a course at a large, urban university.\textsuperscript{21} Students in this course were all adults, part-time students, participating in class from home or work, and did not possess extensive technical skills. These factors were considered in the design of the technology and procedures to support the course, and students were generally satisfied with the course’s effectiveness. Cognitive engineering has developed methods such as contextual inquiry to examine and model the context of work in detail.\textsuperscript{22}

As noted previously, there may be explicit and implicit structure in the education system and cognitive engineering is concerned with both. A work domain defines the full structure of the system of work, including the goals of the system, the functions the system performs, and the
atomic components of the system. While the focus in most courses is on having students perform certain physical actions, such as attending lectures or working homework problems, the assumption is that those actions also cause students to engage in cognitive activities, such as reflection and practice, that will produce learning. These cognitive activities are not typically stated but are the true purpose of the physical actions. Likewise, there may be many emergent behaviors when students and instructors each bring to the larger system their goals and expectations. To understand education fully, all elements must be identified and seen as interacting to produce the outcomes of the system. Work domain analysis, a method of cognitive engineering, provides a framework in which to model the system and identify the elements and their interactions.\textsuperscript{23,24}

Two applications of viewing education as a socio-technical system and analyzing it with cognitive engineering are in designing and evaluating education. Both require a system model meeting several requirements:

- The system model must contain sufficient capture the effects of an instructor's interventions.

- The system model needs to help manage the complexity that arises when all the relevant details are included in the model. This aspect is traditionally handled through decomposition of the system in one or more dimensions so that both high-level entities (e.g. system goals) may be focused on, and then traced progressively down to detailed design elements.

- The choice of decomposition must capture all relevant behaviors within the system when viewed from different viewpoints and at different levels. This requirement may be framed as capturing the different types of emergent behaviors within the system, i.e. behaviors which only make sense at one level and are caused by the collective behaviors generated at a lower, more detailed level.

- The choice of decomposition must capture the relevant aspects of cognitive behaviors and human activities in engineering education. This requirement extends the task from 'systems engineering' to 'cognitive systems engineering', and the relevant behaviors may be drawn from knowledge of cognitive science and human-machine interaction.

The field of cognitive systems engineering has established systems models for socio-technical systems, most notably based on the insights provided by Rasmussen\textsuperscript{23} and by Vicente.\textsuperscript{24} Of interest here are various forms of the abstraction hierarchy, which is the product of work domain analysis. Essentially, an abstraction hierarchy decomposes a system into levels of abstraction to produce a complete model of the system at each level, and showing how elements at each level relate to those at other levels.

Nickles and Pritchett have proposed an abstraction hierarchy for engineering education relying on three decompositions: (1) parts-whole, (2) means-end, and (3) roles of humans.\textsuperscript{25} This abstraction hierarchy is not specific to a single domain or educational approach. Instead it provides the underlying structure of this type of education system for the instructor to fill in with items appropriate for a specific course. These decompositions are detailed in the following subsections. As an example, Table 1 is an abstraction hierarchy showing the parts-whole and
means-ends decompositions from the students' perspective, capturing the parts of an undergraduate engineering course at Georgia Tech (ISyE 4009) related to the third homework assignment.

Table 1: Abstraction Hierarchy for Homework 3 in ISyE 4009 from the Student’s Perspective

<table>
<thead>
<tr>
<th>Parts-Whole Decomposition</th>
<th>Course Level</th>
<th>Assessment Level</th>
<th>Content Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Educational Objectives</strong></td>
<td>Learn how to identify and design for the needs of workers and organizations; Be able to identify and communicate the properties of a machine's interface, Understand the limitations of human operators under a variety of situations, Achieve good grades</td>
<td>Demonstrate understanding of opportunistic decision making by applying concepts to real-life examples and analyzing for blocks to good performance</td>
<td></td>
</tr>
<tr>
<td><strong>Cog./Edu. Functions</strong></td>
<td>Identify skills to learn, skill practice, Reinforcement, pattern recognition, feedback, Motivate learning, Apply concepts to analyze designs</td>
<td>Reflective thinking, Rehearsal (via note taking), Modify mental model</td>
<td></td>
</tr>
<tr>
<td><strong>Learning Activities</strong></td>
<td>Read assignment, Search for designs, Document and submit results, Examine corrected work</td>
<td>View/Read lecture visual aids/notes, Ask questions of instructor, Attend lecture, Take notes in lecture, Review aids/notes, Attend office hours</td>
<td></td>
</tr>
<tr>
<td><strong>Atomic Elements</strong></td>
<td>ITWeb, Instructor, Students, Classroom, [syllabus.doc], Office hours, E-mail</td>
<td>[homework3.doc, examplegoodandbad.ppt], Student submission, Feedback to student on submission, Grade, Design sources</td>
<td>[DecisionMakingOverview.ppt, OpportunisticDecisionMaking.ppt, SupportingOpportunisticDecisionMaking.ppt, ResearchStudyofOpportunisticDecisionMaking.ppt], Student generated notes</td>
</tr>
</tbody>
</table>

**Parts-Whole Decomposition** The parts-whole dimension of system decomposition is used to break down larger elements into smaller ones, such as breaking a physical system down into meaningful subsystems. Its purpose is to give the overall context of the system as well as the smallest relevant details. In the case of education, the system is structured around information and cognition rather than physical objects. Thus, the parts-whole dimension must be based on the elements and sub-elements of information in education. For education, this dimension is not simply a list of subsystems of equivalent granularity, but categories of sizes of information sets. A curriculum can be seen as a large set of information, broken into smaller sets contained in courses and subsequently broken into lectures and/or topics.

The most detailed form of information in education considered in this model is the individual topic of course content. A topic is a single cohesive concept that students must learn as part of a course. Topics are associated with specific instructional material and may have various relations with each other, such as prerequisites. There is no restriction on the size of topics in terms of
breadth, depth, or learning activities, but it is suggested that a topic may range from 3-4 topics per class lecture to 1-2 class lectures per topic. Each topic has a set of activities and delivery methods associated with it that are designated, either explicitly or implicitly, by the instructor to acquire the knowledge and/or skill of the topic. These activities are also at the topic level and may include reading and memorizing the topic material, or applying the information in the topic to a new problem.

The next level of the parts-whole dimension consists of assessments. Most undergraduate engineering courses are structured so that an assessment, such as a homework or quiz, is designed to cover one or more topics. Thus, a group of topics, which are often related to each other, are covered by a single assessment. There will be some overlap in topics between assessments, particularly due to comprehensive final exams, but a single topic will typically be grouped into only one or a few assessments. When the topics covered by an assessment are not all closely related, such as on a comprehensive exam, the assessments tend to have multiple questions where each one relates to a set of one or more cohesive topics, and can be treated as separate assessments. Assessments have a very strong influence on the structure of a course both for the instructor and the students.

The next level in education in moving towards the whole is the course. A course is defined here as a set of assessments made on a set of topics with a consistent instructor (or instructors) where students work to earn a final, comprehensive grade. In undergraduate engineering education, a course is as long as one academic term, but conceptually a course may be as long or short as needed. The structure provided by assessments and grades influences the schedule for the course in terms of what topics will be covered at what time and in what sequence, but more at the level of groups of topics associated with an assessment. Grades on assessments serve throughout the course as motivation for student achievement.

A set of courses makes up a curriculum. A curriculum is a generally recognized set of knowledge and skills, often represented as a large set of topics organized around themes into a logical sequence of courses. A primary student motivation is to be certified as having sufficiently mastered the knowledge and skill set of a curriculum, showing the importance of the structure provided by grades and assessments in courses.

In university education, students are expected to grow and develop in their cognitive abilities. However, students cannot jump to higher levels of thinking without initial cognitive development. As pointed out in Bloom's Taxonomy and research into transfer of learning, different stages of cognitive development require different learning behaviors.\textsuperscript{26,27} Thus, the learning activities and student behavior expected over a curriculum, and sometimes over a single course, should build up in sequence with this development process. The parts-whole dimension reflects this ordinality in that a group of topics associated with an assessment must be learned before deeper learning can occur in a subsequent set of topics.

\textbf{Means-End Decomposition} The means-ends decomposition separates the system into levels of abstraction. Most systems analyzed by means-ends decomposition have been governed by physical constraints; however, education is also governed by constraints imposed by information...
and cognition. Therefore, the five levels of abstraction discussed below incorporate information and cognition for education in the means-ends dimension.

The lowest level of abstraction is the atomic elements, which is analogous to the physical form level commonly used in the abstraction hierarchy. This level broadly covers the physical objects and information elements that are a part of the course. The distinction between a physical object and information in education can be somewhat blurred. For example, a textbook can be seen as both information and a physical object. Either way, it should be classified at the lowest level of abstraction as it only contributes to educational functions when a human interacts with it in learning activities, but is not itself a function. Other items that are not strictly physical such as PowerPoint files, e-mail messages and feedback from instructors to students on an assignment (in whatever form delivered) should also be classified at this lowest level of abstraction.

The next level of abstraction is learning activities, which are defined as the activities and behavior with a significant physical component performed on and with the atomic elements. Learning activities include creating atomic elements such as an instructor creating a handout or lecture, and interacting with atomic elements such as students reading a textbook or attending lecture.

Cognitive and educational functions are the next level of abstraction. Where learning activities are physical, observable actions, cognitive functions are the internal, unobservable activities of the mind. Cognitive and educational functions are the purpose of the learning activities and the means to accomplish the higher goals of the system. Learning activities do not directly meet the educational goals of a course, rather they are intended to make students engage in cognitive activities that induce learning, meeting the goals of the course. Bloom's taxonomy categorizes objectives based on the desired "depth" of cognitive functions. Several learning activities may be used to induce one cognitive activity; for example, note taking during lecture and subsequent rehearsal of these notes can together produce memorization. Cognitive functions cannot be directly measured, but can be indirectly measured through the related learning activities. It is assumed that positive measurements on learning activities indicate that the expected cognitive functions have taken place.

Educational objectives is the next level of abstraction and consists of the goals for the cognitive and educational functions. The educational objectives typically include, but are not limited to, the course objectives stated in the syllabus. There may be other unwritten goals, such as students desiring to achieve as high a grade as possible.

The most abstract level in the means-ends dimension in this model is general objectives. This includes goals set at the department or institution level for students' education such as producing engineers with exposure to a broad range of domains, strong communication and problem solving skills, or maintaining an institutional honor code. These are the goals the educational objectives serve to achieve. For the student, goals at this level may include certification for completing the curriculum in the form of a diploma, or achieving a high grade point average.

This set of decompositions for education is designed not to specify any particular approach to education. There are a large number of educational approaches that prescribe a set of learning
activities and the cognitive functions produced by those activities. For example, one cognitive psychology approach to learning suggests students must learn production rules through extensive study and practice. Another approach called constructivism suggests students must construct their own cognitive meaning by constructing physical artifacts. The structure of these levels of abstraction is not intended to favor one approach over the other, but to accommodate any approach that is selected as the most appropriate for the desired learning.

Elements at each level of abstraction are related to elements in higher and lower levels of abstraction by means-ends relationships. Related elements at higher levels of abstraction identify why an element is in the system, while related elements at lower levels identify how that element is accomplished. An example of these interactions for the course column of Table 1 is shown in Figure 1.

**Figure 1:** Interactions between levels of abstraction on the content dimension for homework 3

**Personnel Decomposition** The roles of the instructor and students in the education system are quite different. Typically the instructor designs the course, creates or provides the atomic elements, and specifies the learning activities. The students interact with, and often react to the atomic elements from the instructor, participate in the learning activities, and create their own atomic elements such as study notes. There is deliberate influence at each level of abstraction, particularly from the instructor to the students, but the roles are significantly different and need to be represented as separate elements of the model with relationships between them. It may be necessary in some cases to add other dimensions, such as for teaching assistants who have a distinct role in assessments or for administrators who have a role at the curriculum level.

**Application** Insight into the structure and interactions between elements of the system from cognitive engineering can be used in the design and evaluation of courses. The course can be designed to emphasize the elements and interactions that support the goals and desired outcomes of the course. An instructor can begin with the course goals, use those to identify the cognitive
and educational functions students should perform, and then specify appropriate learning activities and atomic elements so students can engage in those functions. In addition, new cognitive functions and learning activities can be introduced in the model before implementing them in the class, which lets the instructor predict the impact of this change on the system from the instructor's and students' perspectives. The model can also reveal the elements of the course that support each course objective, allowing the instructor to judge if there is sufficient emphasis on each objective, if each objective is addressed at an appropriate stage of the course, and where activities can be added, modified, or replaced to better support the objectives.

In systems like education, where elements are highly interrelated, it is difficult to effectively evaluate by examining individual components in a "divide and conquer" fashion since much depends on the interactions between elements. No single measure or measurement method provides insights that are not subject to concerns about construct validity when used for detailed system evaluation. This suggests, then, the use of measurement triangulation, i.e. the combined use of multiple measures and measurement methods to establish a more comprehensive and valid interpretation than that possible with the sum of each alone. The strengths of triangulation are in providing broad coverage and confirming evidence among measures.

In measurement triangulation, an array of measurements are collected and examined collectively. However, more sophisticated and informed triangulations (for both better coverage and better construct validity) require better modeling of education as a system. Measurements can be applied in the context of the abstraction hierarchy model, showing which parts are examined by each measurement and how much of the system is covered directly by the measurements or indirectly through relationships to other parts of the system. Relationships between parts of the system show how closely measurements on those parts are related, and so show to what extent measurements confirm each other.

These efforts to develop systems models of engineering education and to apply them to design and evaluation are on-going. One potential use of this method is in supporting rigorous course design and planning evaluation. When a new course is designed, it can be conceptually designed by creating the abstraction hierarchy model of the course. This would support instructors in explicitly choosing the elements at each level of abstraction, including the level of Cognitive and Educational Functions which is usually implicit, that support the objectives for the course. Also, instructors can identify all the elements of a course that support a particular course objective, allowing them to determine how well they have met each objective. Another potential use of this method is in assessing program outcomes to meet the ABET Engineering Criteria. Curriculum-wide outcomes such as communication skills can be incorporated in the model and the means-ends relations reveal what elements of the course support these goals. The relevant elements can then be measured during the course to determine if and how much they are contributing to the desired outcome.

Conclusion

This paper has reviewed how several concepts and methods from cognitive engineering are directly applicable and have been applied to education. These include insights into how students learn, the design and application of educational technology, and how to frame education as a
socio-technical system for design and evaluation. It is the authors’ hope that these examples will encourage researchers and practitioners to examine cognitive systems engineering for concepts and methods that can directly benefit engineering education.

References


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