Teaching Engineering: A Comparative Commentary on Analyzing Engineering Teaching as Complex Cognitive Work

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Abstract

Teaching engineering can be considered as complex cognitive work occurring in a sociotechnical system. Engineering faculty, engineering students, and other stakeholders such as administration, accreditation agencies, industry, etc., are components of a *social* system in the engineering education enterprise. The social elements in the system are organized to achieve technical goals (learning engineering, for instance). Jointly optimizing the social and technical subsystems continues to be a formidable challenge. Based on an NSF grant, we have been examining faculty development issues in teaching engineering. Given the multiple stakeholders and the many perspectives they bring into the problem of engineering education, designing the *complex cognitive work* that engineering teaching is, has been our specific interest. In this paper, based on cognitive work analysis methods, we propose and critically compare three work analyses approaches for designing engineering teaching (considered the work activity) as part of the engineering educational sociotechnical system. The three approaches we compare are the normative (prescriptive) approach, the descriptive approach and the formative approach. The normative approach, very commonly found in engineering education enterprises, attempts to prescribe, in model form, how the engineering educational system should behave. The descriptive approach, attempts to describe how the engineering educational system actually behaves in practice. A formative approach to designing the engineering educational system lets the engineering educator *complete* the design of the work.

Engineering Education as Complex Cognitive Work in a Sociotechnical System

Engineering education and teaching can be considered complex cognitive work activity for engineering educators. Some elements of engineering teaching that make it a complex cognitive work activity include:

1. The presence of large problem spaces: Engineering educators, when they plan and implement their teaching activities, often have to wrestle with the type and quantity of engineering content, engineering pedagogy and their teaching methods, any requirements of stakeholders such as ABET, student learning goals and measures, administrative requirements

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(such as obtaining good teaching evaluations), among other aspects. Engineering educators have to deal with large problem spaces.

2. Presence of humans and the resultant social dimension to engineering education systems: Engineering education enterprises are sociotechnical systems, with a social subsystem and a technical subsystem. The social subsystem consists of people in the system such as the faculty, the students, university administration, industry, accrediting agencies, and other stakeholders in the system. Each stakeholder has a role to play, and there is a social network manifested in the social subsystem. Social goals may include achieving good quality in working life for system members. The technical subsystem enables technical goal achievement. Student training is the key technical goal in the system. The challenge for work system design is to jointly optimize the social and technical subsystems for achievement of social and technical goals.

3. Heterogeneity in system solution perspectives among system stakeholders: Every stakeholder in the engineering education enterprise has goals they want achieved in the system. These goals may not always be congruent. For example, faculty may try new pedagogical methods in the classroom in an attempt to improve student learning, but if the new methods don't result in good teaching evaluations because students do not welcome changes, university administration may not approve of faculty methods. There is great degree of heterogeneity in perspectives that affect how faculty plan and implement their teaching practices.

4. Presence of a high degree of coupling among subsystems, and the potential for interactive effects: One could conceive the engineering education enterprise to consist of several subsystems. For example, a learning subsystem, a faculty development subsystem, an administrative subsystem, and perhaps an external stakeholder system (consisting of employers of graduates, industrial partners, ABET,) etc. There is a high degree of coupling among these various subsystems. Changes in one subsystem can adversely or positively impact changes in other subsystems.

Work Analysis of Engineering Educators: Three Approaches

In analyzing complex cognitive work activity of engineering educators, we draw from a broad classification of cognitive work analyses methods[1,2] from the cognitive systems engineering domain. These methods may be normative, descriptive and formative in analyzing cognitive work. We briefly review the normative and descriptive, and present in some detail key steps in a formative method. We then present a brief example of our work in abstracting how engineering educators navigate their instructional planning and implementation.

Normative Models of Engineering Educators' Work

Normative models of work, as the name suggests, *prescribes* how a work system should behave. It is analogous to the concept of directions in spatial navigation. The prescriptive nature of work in a system designed using the normative approach makes any cognitive work like teaching engineering, very task-oriented. Additionally, normative models are predominantly formulated based on existing theory. When the work of engineering educators is designed using normative approaches, there may be an underlying assumption that all engineering educators, students, and the educational environments are similar, and therefore can be expected to use the same set of prescribed teaching tools and methods, and achieve performances to the same degree.

While normative approaches to designing the work of engineering educators have the benefit of mental economy for an engineering educator (because the work of engineering educators is reduced to a set of directions that they follow), normative models also have several disadvantages. They are inflexible from the perspective of an engineering educator being able to adapt their teaching to contingencies. Normative task-based approaches have narrow scope of applicability (every situation will demand a set of prescriptions and directions). Additionally, they provide the engineering educator very limited ability to recover from errors.

Descriptive Models of Engineering Educators' Work

A descriptive model of work seeks to describe current practice. A description of current practice includes challenges engineering educators actually face on the job, and a documentation of any ingenious practices they may have developed to cope with those challenges. Descriptive models help capture context-conditioned variability in the activities engineering educators actually perform in practice (versus what they may be directed to do from a normative method).

Descriptive models of work performed by engineering educators have the potential to reveal not only current work practices, but also actions from engineering educators that may be workaround activities (to accomplish their instructional tasks). Additionally, it can reveal action possibilities for future work. Unfortunately, descriptive models suffer from the task-artifact cycle. Even though study of current practice may lead to design ideas for supporting such practice, because engineering educators adapt and create new practices continually, their evolving practices have to be studied again to design new supporting artifacts for practice.

Formative Models of Engineering Educators' Work

The formative approach to cognitive work design is based on assigning priority to ecological constraints in the work domain rather than to an individual's cognitive constraints. The key ideas behind designing work of engineering educators in a formative way are to support flexible, adaptive work, where the engineering educators complete design of the work system. Development of a formative work model contains several distinct steps (figure 1) as design interventions. A brief description of each step is provided in the following paragraphs.

The *Engineering Problem Domain* is analogous to a map of the work domain and environment. It is described independently of the tasks that are included in the work domain, the strategies for performing work tasks, the organization of people and technology for executing strategies, or the competencies people must exhibit for effective task performance. When completely described, the engineering problem domain represents the possibilities for action considering the inherent constraints that exist in the work domain. Describing the engineering educators' work domain as a map of possibilities for action provides several advantages to the educator. Because the work domain represents all possibilities for action, it provides flexibility in adapting to contingencies (for example in the classroom). It also provides the engineering educator the ability to recover from errors they make in their classroom planning and implementation of teaching strategies. In the next section of the paper, we have presented a case example to illustrate development of a work domain for engineering educators.

Control tasks denote goals that need to be achieved in the work domain. Control tasks signify desired outcomes or goals rather than a "way" to achieve them. Hence, control tasks are specified independent of who performs them or how they are to be achieved. Control tasks not only inherit intrinsic work constraints from the problem domain, but also add another set of constraints to the analyses themselves (for example, task precedence constraints). Control tasks are dependent on the work domain, but independent of the strategies for accomplishing these tasks, the organization of people and technology, and the cognitive competencies of individuals who must perform these tasks.

Strategies help achieve performance and completion of control tasks. Strategies are "how" outcomes of control tasks are achieved. Strategies inherit all constraints in the problem domain, and in the control tasks. Strategies do not depend on the way people and technology would be organized, or on competencies of individuals.

Given that people and technology have to share in solving the problem, *social and organizational* factors need to be analyzed and modeled for effective problem solving. Social and organizational elements inherit all constraints of the problem domain, the control tasks, and the solution strategies that could be used for problem solving. Roles, communication, and organization into teams are modeled at this stage.

Student (in a general sense, the trainee or the engineering educator in this specific case) competencies refer to the individual cognitive constraints engineering educators bring to the problem. Analysis at this stage would identify skills, rules and knowledge individuals should have if they are to effectively tackle all constraints identified in the previous levels.

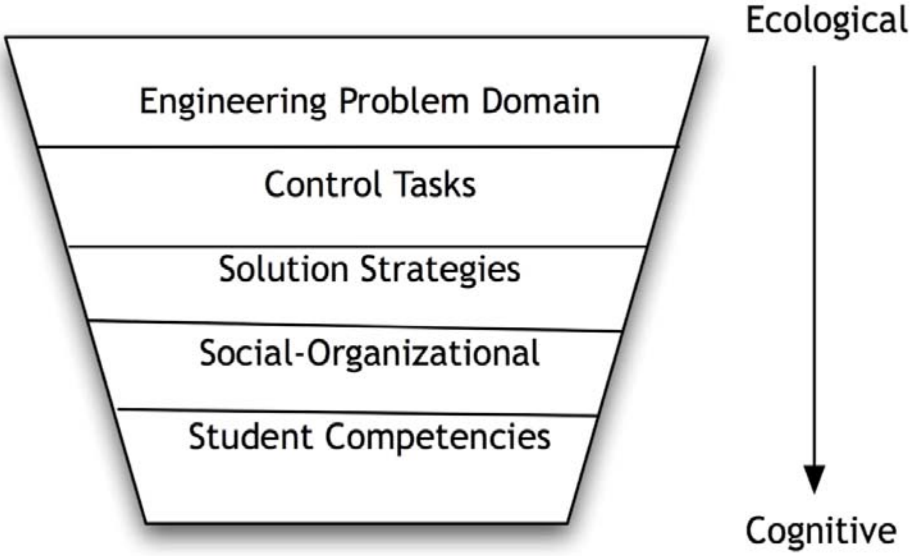

Figure 1. Formative approach to designing work of an engineering educator (adapted from Vicente[2]).

Engineering Teaching as a Navigation Problem: A Case Example

As mentioned previously, engineering educators, in planning and implementing their instructional activities, deal with large instructional planning spaces. For example, choosing from

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a myriad of instructional techniques for delivering outcomes or choosing from a host of assessment techniques for measuring learning outcomes. In this section, we present an example of formative work design for engineering educators. Specifically, the example we present pertains to a creating a representation of the *engineering education work domain* (the first design step in formative work design).

In an NSF CCLI Phase 2 project, a group of engineering faculty from University of Texas at El Paso, New Mexico State University, University of Texas Pan American, Baylor University, and Prairie View A & M University, is collaborating with faculty from education to study authentic discourse for engineer of the 2020. A major part of the study is engineering faculty metacognition. Engineering faculty reflect (in written text form) on their class plan, and after implementing class activities such as a discussion, reflect on their implementation, successes and struggles.

Analysis of written reflections from engineering faculty participating in our project indicate that in thinking about their planning and implementation of instruction, faculty are always attempting to consider and balance two key aspects of engineering education – educational pedagogy and engineering content. This section presents an example of a work domain analysis model being developed to address the problem of representing, modeling and analyzing engineering educators navigating the engineering instruction space.

Work Domain Analysis Model

Figure 2 presents the general work domain analysis spatial representation based on cognitive work analysis methods developed by Rasmussen[1] and Vicente[2]. The work domain analysis space consists of two main components, a means-end abstraction hierarchy component, and a whole-part decomposition hierarchy component.

The means-end abstraction hierarchy consists of five levels of abstraction about the problem domain, ranging from the most abstract levels of functional purpose, to the most concrete levels of physical form. Functional purpose denotes what the work domain was designed to do. Abstract function refers to the underlying laws and principles of the work domain. The processes involved in the work are captured in the generalized function component. Physical function refers to the tools and instruments involved and their capability. The physical appearance of tools is captured with the physical form component of the work domain.

The whole-part decomposition hierarchy consists of different levels of granularity of the problem domain ranging from the component parts to the whole system. Hence, in figure 2, moving from left to right along the decomposition hierarchy, for example, would increase the level of detail of the representation of the problem.

Figure 3 presents the cognitive work domain analysis representation of the engineering instructional navigation space we have developed based on a survey of engineering faculty participating in the NSF CCLI project. The model is a representation of the engineering instruction space, and attempts to capture the dynamic tension in planning between educational pedagogy and engineering content.

A survey of engineering faculty in our project indicates that they abstract educational pedagogy broadly along three dimensions – teaching philosophies and beliefs at the most abstract level, followed by goals and objectives they have for their teaching (which represents more concrete function), and tools used (which is a very concrete representation of instructional tools they use such as PowerPoint or WebCT). Engineering faculty think of the whole-part decomposition elements of engineering content as broadly consisting of engineering concepts (the highest level) which are broken down into specific topics (an aggregation of topics would lead to a concept), with topics consisting of learning elements or specific chunks of learning (the most granular level of content).

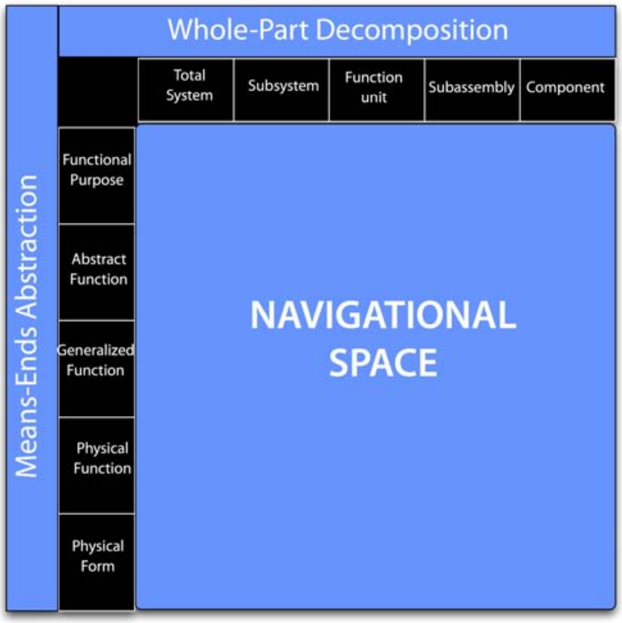

Figure 2. Abstraction-Decomposition Hierarchical Space.

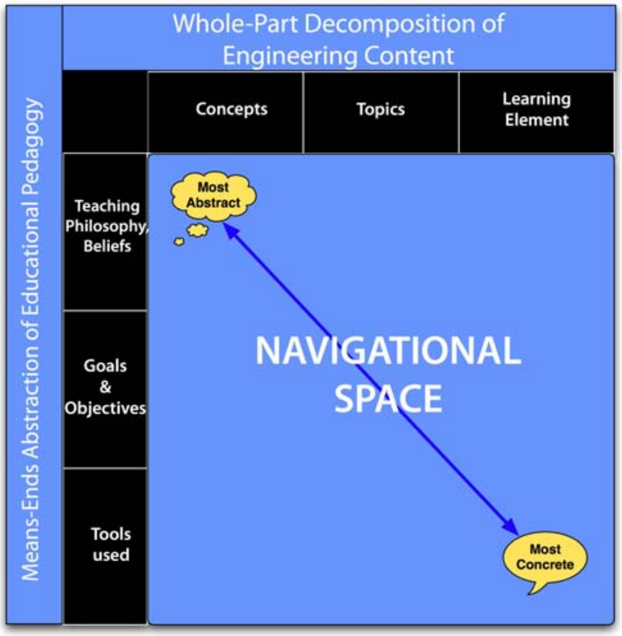

Figure 3. Abstraction-decomposition Navigational Space for Engineering Educators' Work

Figure 4 illustrates one example of how we are using the work domain representation in the NSF project. Each cell in figure 4 describes the same engineering instructional space, but at different levels of abstraction and detail. Hence, each cell may have its own unique set of terms, concepts and principles. The lower levels of abstraction and the lower levels of decomposition are related to higher levels. The nodes numbered 1 through 5 represent textual descriptions from an engineering faculty member reflecting about their planning for a class session. The trajectories of their reflective thinking move from very concrete (node 1) to very abstract (node 2), for example, and are indicated by the directional arrows in figure 4.

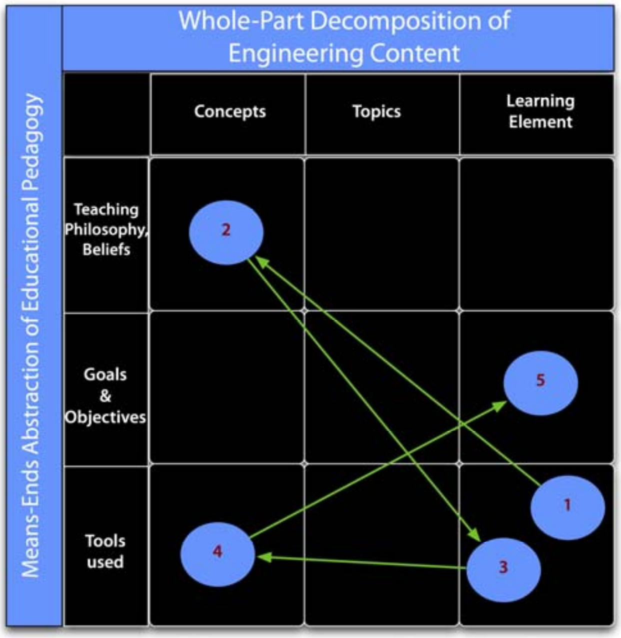

Figure 4. Written faculty reflections mapped onto an abstraction-decomposition space

Expected Outcomes from Work

A key aspect of our research as depicted in figures 2 and 3 is to improve planning. All engineering educators, even experts, engage in some type of planning. Planning and strategizing before class implementation are significant labor-intensive activities. Therefore, studying planning and strategizing processes among faculty, and optimizing planning is important. Planning and generation of strategies precede classroom implementation. Planning is, in a sense, *a rehearsal* of what should play out in the class. Planning and strategizing captures how faculty think about relating learning outcomes with content and delivery of content. Hence, studying planning and strategizing processes and making them effective are vital components of improving engineering teaching and student learning outcomes. Classroom interventions and activities to improve student-learning outcomes typically involve a broad array of controllable and uncontrollable factors. But, the cognitive activities involved in planning and strategizing only involve the instructor. Therefore, there is greater potential for making instruction effective during the planning stage compared to the execution or implementation stage. Conscious planning and strategizing, implementation of plans, and feedback and continuous evaluation of plans and strategies are likely to have a positive synergistic effect in improving reflective teaching practices among engineering faculty. Hence, formal study of planning and strategizing among engineering faculty becomes important. Effective and successful plans and strategies, when captured, understood and described, can be shared among engineering educators. Sharing can result in validation and strengthening of strategies and contribute to optimal use of planning and execution time for faculty. Being able to convey faculty-planning struggles to students can result in students understanding faculty struggles in being able to abstract, decompose and think about content. In the long run, this should result in students thinking about and learning content using the same strategies that faculty use to plan and teach content.

As part of this work, we are developing a virtual strategy generator. We consider a strategy to be a sequence of operations (procedures) to go from an initial state of knowledge to a final state of knowledge. In our conception, strategies are *how* faculty achieve specific learning outcomes/goals by execution of the plan. Hence, strategies would inherently be embedded in the plans. We can use the planning data collected from the faculty to identify the *abstraction* and the *decomposition* elements to create a valid and general work domain model representation. The work domain model we will develop will be analogous to a *map* of the work domain. The model is intended to assist the engineering educator in generating sets of *ways* to reach goals. It is intended to help the engineering educator navigate from one cell to the final goal depending on where the engineering educator is in the work domain model initially.

Because the work domain model also represents the *object of action*, every faculty-planning trajectory in the work domain model, would represent a *strategy* (a string of nodes representing faculty thought about *how* they will achieve desirable end results). Each node in the planning trajectory would be contained in a cell. Each cell contains a description of what, why, and how a faculty thinks about actions intended to achieve desired outcomes. A certain level of abstraction and decomposition defines each cell. The string of nodes in the trajectory represents the sequence of planned actions or operations to achieve desired goals, and would represent *one strategy*.

Hence, our strategy generator will generate strategies by keeping track of faculty-planning (initial and improved) trajectories we are able to generate in the project. We can also compare planning trajectories in the model with execution trajectories (obtained from post-execution reflection data). From the student data collected (through *e-diaries* from students, for example), we will be able to develop trajectories of student comprehension and understanding. Superimposing student comprehension trajectories on faculty planning and execution trajectories can provide revealing insights into any differences between faculty expectations and evaluation, and student comprehension and understanding.

Conclusions

Several research issues are currently being investigated with a formative work design approach to the design of engineering educators' work and representation of instructional planning space. Some research questions are: (1) are the abstraction-decomposition elements valid and general? (2) is there (should there be) an ideal planning trajectory? (3) are planning trajectories different from execution trajectories? (4) for the same engineering content, are individual faculty trajectories different? (5) for different engineering content, are trajectories different? (6) can we map student learning (understanding) trajectories onto to the same map and understand differences to improve faculty instructional planning?

Acknowledgment

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