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Teaching Design Using Multiple Hierarchical Engineering Education Models*

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This work seeks to add to the theoretical underpinnings of design education through the use of hierarchical educational models by Haile and Egan, building on a foundation laid by Vygotsky. We fit commonly used techniques of design education into Haile's hierarchical model to ensure that a proper foundation is laid before the next level of the structure is built. Relating Haile's hierarchy of technical understanding to Egan's general hierarchy of understanding helps anchor the study of technical understanding in the more general context provided by the cognitive sciences. Using this perspective, we gain access to examples of design education from other fields such as music, writing, and art. These examples improve the understanding of design by strengthening the pattern of what design is and by clarifying how engineering design is different from these other examples. Vygotsky divides the reorganization of knowledge into four steps: (1) conceptualization, (2) transference, (3) generalization, and (4) extension. The use of this model of reorganization helps guarantee that learning will proceed from concrete situation to abstraction and then, by extension, can be applied to different concrete situations. Vygotsky's framework is particularly useful in integrating the perspective of three schools of thought regarding design education identified in previous work by Dym.

Keywords: design education; Vygotsky; cognition

INTRODUCTION

THE APPLICATION of hierarchical models is used to address a number of concerns that have been raised by engineering design educators. The teaching of engineering design is currently dominated by the discovery approach, particularly in capstone design courses, yet the role of faculty members in that process is not well defined. Whereas design educators frequently assume the role of 'coach' in these educational experiences, when and how the coach should intervene is not well understood [1]. From these models, we develop intervention strategies for engineering design faculty in working with students at different levels of development. Concern over the lack of knowledge about how to coach design is magnified among those that first introduce design to children—elementary school teachers who may lack both the competence and confidence to teach design. There is concern that engineering design competitions, as commonly implemented, may develop misconceptions regarding the design process [2]. It is difficult to be sure whether engineering design competitions develop misconceptions; while there is some literature indicating that students do have misconceptions about design, the misconceptions are not well diagnosed or classified [3, 4]. Nevertheless, this paper offers a framework for the design of activities intended to get students excited about engineering that both addresses concerns over the development of misconceptions and may explain why and in what ways some design competitions are successful and others are not.

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REACHING OUT TO DIFFERENT SCHOOLS OF THOUGHT OF DESIGN EDUCATION

Three schools of thought regarding design education were identified by Dym: one asserting that design ability is innate, a second that gives no credence to design education because it cannot be explained analytically, and a third that studies design education from the perspective of the cognitive sciences [5]. The work of the authors places us firmly within the third school, which developed following Simon's assertion of the different perspectives of the design sciences and the natural sciences [6]. This paper seeks to make a contribution to the third school by studying design within hierarchical educational models by Haile [7–11], Egan [12], and Vygotsky [13]. At the same time, we address the concerns of the other two schools, demonstrating to the first that describing the design process does not strip it of its power and to the second that design and analysis are symbiotic in nature. Just as there are many approaches that one may use to design a part or a system, there are many approaches to teaching design, and using a variety of approaches enhances student development [14, 15].

Haile defines levels of understanding of technical material based on findings from neurological and cognitive sciences, characterizes the motivation for transition to each higher level, and describes the reformulation that must occur for each transition to take place. By ordering the use of commonly used approaches in design education according to appropriate places in Haile's hierarchy, we help ensure that a proper foundation is laid before the next level of the structure is built. Haile's hierarchy of technical understanding is based on that of Egan and Vygotsky. We reconnect with Egan's general hierarchy of understanding to anchor the study of technical understanding in the more general context provided by the cognitive sciences. Using this perspective, we gain access to examples of design from other fields such as music and writing. These examples improve the understanding of design by strengthening the pattern of what design is and by clarifying how engineering design is different from these other examples.

We further revisit Haile's incorporation of Vygotsky, who divides the reorganization of knowledge into four steps: (1) conceptualization, (2) transference, (3) generalization, and (4) extension. The use of this model of reorganization helps guarantee that learning will proceed from concrete situation to abstraction and then, by extension, to different concrete situations. Further, Vygotsky's framework will help integrate the perspective of the different schools of thought in design education. By attaching meaning to concrete experiences, we hope to appeal to nascent design ability at such a fundamental level that those in the first school of thought would believe to be common among even those believed to have low innate design ability. Further, we believe the analysis implicit in approaches such as case studies and reverse engineering will appeal to those in the second school of thought. Those of the third school of thought will be drawn to the overall cognitive model represented in our work.

In the manner described above, Egan's model is more than a general version of Haile's—it gives our study of design the depth of perspective that enables us to meet students where they are developmentally, appeal to them at their level, and help them develop new levels of understanding. In the process of addressing Egan's various levels of understanding, a variety of learning styles will be addressed, claiming the pedagogical advantage known to result from diversity of teaching style [14, 15]. Vygotsky's model then provides a general structure that applies to the higher levels of understanding and Haile's model helps address the specific challenges of technical education (design education in this case).

REVISITING VYGOTSKY'S MODEL

Haile describes Vygotski's model, derived from studies of language acquisition in children, using Fig. 1 [10]. Recognizing that conceptualization,

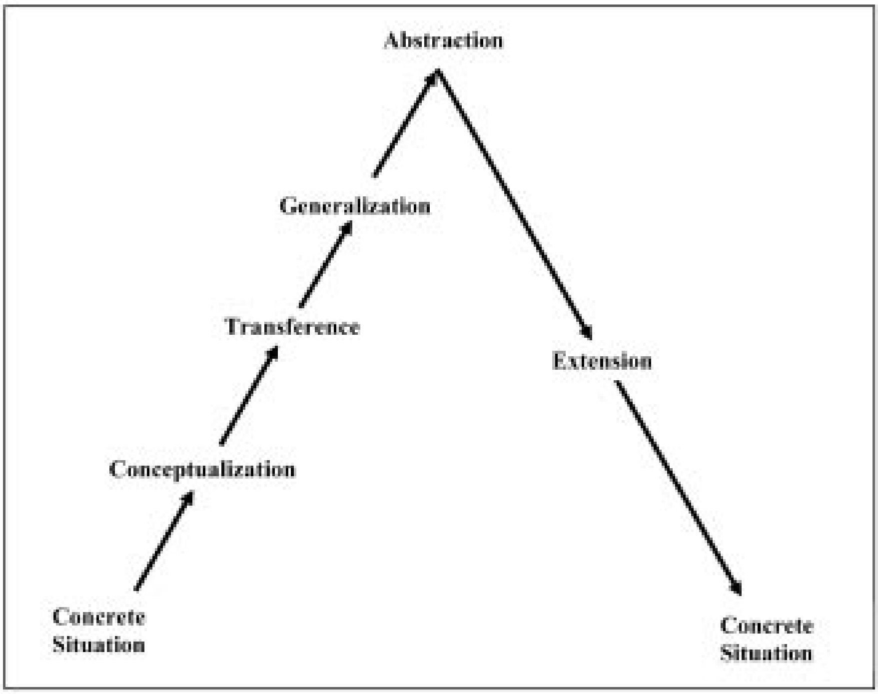

Fig. 1. Vygotsky's model according to Haile.

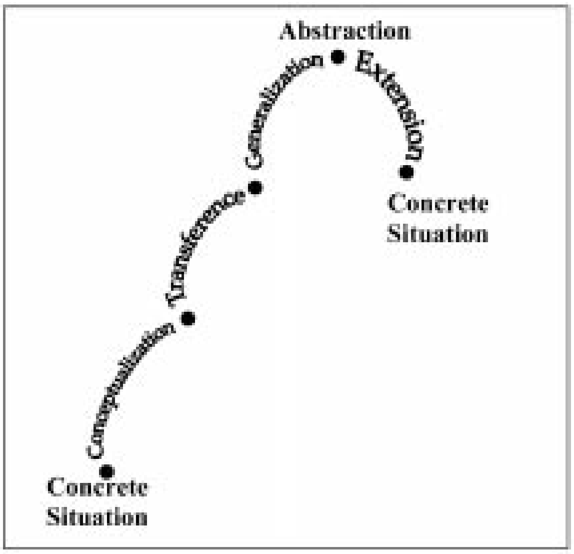

Fig. 2. Vygotsky's model adapted.

transference, generalization, and extension are processes of change that occur as a novice becomes an expert, we prefer to view Vygotsky's model as shown in Fig. 2, in which these processes are a path to move from one operating point to another, but are not a resting place.

Just as Haile's model indicates that we should proceed from concrete situation toward abstraction in order to extend our knowledge to other concrete situations, we look toward other fields that teach design for concrete examples of approaches to design education.

LESSONS FROM OTHER FIELDS THAT TEACH DESIGN

Haile uses learning music as a metaphor for the importance of variation in engineering education [9]. The relationship between music and design is a strong one. Schon's philosophy of design and design education [16] draws many musical connections:

- A musical composition that has already been designed is interpreted by the performer, adding to the original design. In the same way, engineering designs are not complete when they leave the drawing board—they are reinterpreted by other designers, the manufacturer, and the customer.
- Learning music requires experiential learning, as is the case in learning engineering design. Neither can be taught by didactics or discourse alone.
- Music composition exists both through performance and in written form just as engineering designs exist on paper and in artifact.
- Design of music is holistic—the whole system lends to the pattern that the musical composition reveals. In engineering design, the interaction of the parts of the design system comprises the whole.
- Music is taught primarily by practitioners through a master–apprentice relationship. Schon therefore posits that design teachers are coaches who are experienced designers.

Schon's work sheds light on the coaching relationship: that coaches should (a) talk through design examples with novices, explaining the decisions that lead to a design, (b) translate the novices' descriptions and decisions into the language of design, and (c) help the novices manage the cognitive dissonance that results from the paradox of trying to learn design by doing it in spite of the fact that they do not yet know how to design. Schon places a significant emphasis on the importance of learning the 'language of design'—what Haile describes as 'making conversation' and 'identifying elements'—tapping into Egan's mythic oral tradition [16].

Building on the work of others [17], Lerdahl has used music improvisation as a tool for teaching design, noting other important elements of the metaphorical relationship. He notes that design goals impose certain constraints on the design process in both cases. While music composition is sometimes done as a team, music improvisation is commonly a team activity, which makes it more like an engineering design process [18]. Demonstrating the interrelationship of design in music and writing, van Schalkwyk compares thesis writing to music composition [19].

Sharples has done extensive work studying writing as creative design [20, 21]. In his earlier work, Sharples identifies a number of apparent contradictions in understanding the writing process. These contradictions resonate with the discourse on the design process [20].

- Writing is a demanding cognitive activity, yet some people appear to write without great effort. This supports the belief of the first school of thought on design—that design ability is innate.
- Writing is analytic, requiring evaluation and problem-solving (the second school of thought on design), yet it is also a synthetic, productive process (the third school of thought on design).
- Writing is primarily a cognitive activity, but it cannot be performed without physical tools and resources (the third school of thought on design, especially if the tools and techniques of design are included).
- As Sharples explores the nature of writing as creative design, some observations suggest new ways to look at engineering design. Other observations reinforce familiar perspectives.
- In writing, the writer's knowledge and experience are considered along with the other constraints. There may be situations in engineering design where it is important to consider those constraints, particularly if a critically important point of view is missing in a design team.

- 'The paradox [of writing] is that constraint enables creativity.' Sharples discusses how working within constraints allows the writer to systematically challenge the limits of existing constraints. This is a common approach to engineering design.
- Sharples delineates a series of questions to stimulate creative writing. The series of questions is quite reminiscent of Osborn's list of questions to stimulate creative thinking during problem solving [22].
- Sharples' contention that 'to explore and transform conceptual spaces we must call up constraints and schemas as explicit entities, and work on them in a deliberate fashion' bears similarity to the need to operationalize definitions in order to begin a design process.
- As Sharples discusses the tools of creative writing, he notes that a tool's properties are noticeable only if the tool ceases to function properly. Under normal conditions, the tool is an extension of the self. This suggests the importance of understanding how tools are used and how they break down. This lesson applies both to designed tools and to tools used by designers.
- Sharples establishes a system for classifying writing media. This classification system (with slight modification) could be used to study different design media. Sharples' list includes the ability to annotate (in design, collaborative sketching is one example), the ability to reorder, the ability to be indexed, the ability to be re-represented, and others.

APPLICATION OF THE MODELS

With respect to the proposed model of engineering design education presented, we argue that the initial starting point in teaching students the design process is to begin with a concrete example. Just as one would provide tangible examples of the principle to be investigated in scientific education, design educators may provide students with examples of designed artifacts. This might vary by domain. For example, in mechanical engineering, one can begin with a product such as a bicycle or a toaster and in civil engineering one may begin with a product such as a bridge or local highway. It is important to carefully select artifacts that are both readily accessible to the students (artifacts with which the students have experience) and understandable to the students (artifacts which do not include working principles beyond their current knowledge). These two dimensions of the artifact (experience and knowledge) will vary by discipline, by level, and by region. Figure 3 illustrates several different products and where they might lie in the dimension for sophomore and graduate mechanical engineering students. We readily admit that this is not an exact classification, but issues that might be measured to assist in locating designed artifacts in this space could be the number of components, the disciplines involved, the number of functions, or the commonness of the product in student homes. The selected product will form the basis for 'conceptualization' in the hierarchical model of learning. It is further suggested that

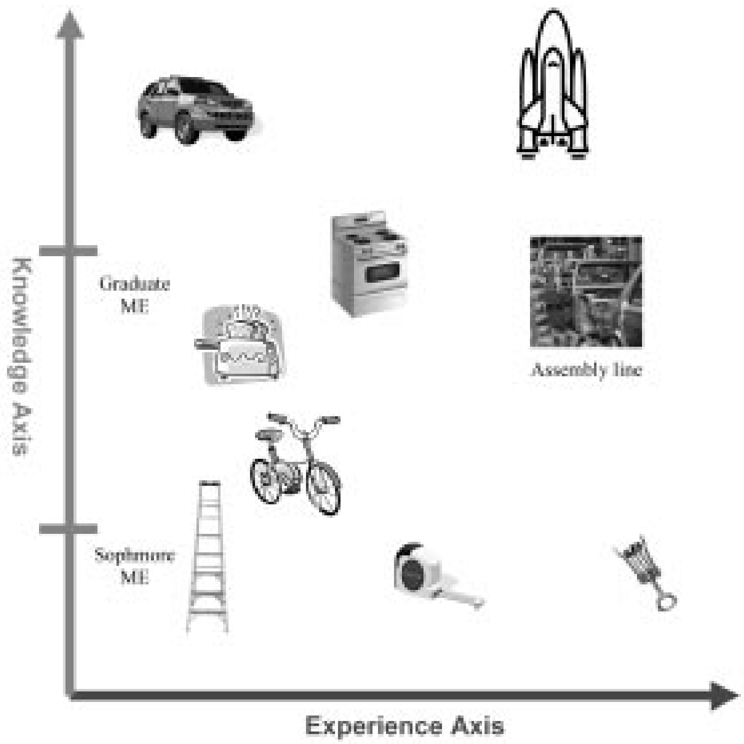

Fig. 3. Possible designed artifacts to be used for concrete case studies.

well-documented case studies of designed artifacts be used, such as disk drives [23], a bicycle seat [24], or computer stand [25].

Once the concrete artifact is selected, seek to follow the 'conceptualization' process as described by Vygotsky. The goal here is to introduce students to the motivation of design and how design tools might be used to understand the rationale that the designers used in arriving at the resulting designed artifact. Reverse engineering and dissection [26] can be employed to illustrate how design tools can be used. Tools such as function modeling [27, 28], failure modes effects analysis (FMEA) [29, 30], quality functional deployment [31, 32], and morphological charts [33, 34] might be used to understand the designed artifact. Function modeling is used to create an abstract model of the functions that are associated with each of the components. From this function model, students can apply FMEA to elicit potential areas of failure. In doing so, students can work on rationalizing why different materials were selected, why different geometries were chosen, or why different working principles were selected. To explore alternatives, students can be introduced to morphological charts to generate alternatives for each function identified, using the current solution as the first nucleus in the matrix. Likewise, other design tools may be illustrated through the use of reverse engineering.

The second stage in the hierarchy is 'transference'. Here, the student is expected to apply the design tools through reverse engineering of a similar designed artifact. A competing product is suggested as the platform to facilitate 'transference' of the students' understanding of design. The students should be successful in applying the design tools appropriately without relying heavily upon direct guidance and supervision. The students need to be allowed to explore the limits and the advantages of the design tools under different scenarios. Students can then explore the differences between the sets of the resulting reverse engineering processes. In this manner, the students are simultaneously learning about the designed artifacts (product A performs better for criterion Z) and the value of the design tools. For example, while failure modes effects analysis can be used to guide design teams in identifying potential failures that should be addressed before product release, it may also be used to identify potential areas of competitive advantage or potential areas of improvement between products. Students are developing an experience base in a systematic manner through the use of ordered tools.

The next step in learning is 'generalization'. Here students are expected to make the transition from understanding (benchmarking) existing designed artifacts to applying these tools in a completely new approach of designing a solution to a problem—moving from design problem to design artifact. It is at this point that many design education experiences begin by asking students to design a new product. Traditional engineering design education typically expects students to learn the design process through doing: by designing a solution to a design problem. This approach asks the students to learn an abstract concept, the design process, while applying it to an abstract artifact, the as yet unrealized design artifact. We agree with others [35] that this stage of generalization is best done only after grounding the design tools and methods in concrete experiences based upon realized artifacts through reverse engineering. This stage is limited to applying the design tools and the design process to new design problems that are in the same domain as the originally reverse engineered designed artifact. It is at this stage that the traditional design process might be discussed. The students are now at least conversant in many of the tools of design. We, as educators, can now put these tools in context through generalizing to the design process.

Finally, in 'extension', students are expected to discover the design process in other applications. This might include designing artifacts that were not previously considered (e.g. software packages, written reports, processes). The process that one employs in writing software is similar and uses similar strategies to those of engineering design. One must first understand the design problem and then create a high-level systems view of the potential architecture. This is followed by creating simple components and testing the components individually. Once these are found to be suitable, the programmer then begins to systematically integrate the developed components, testing throughout the process. This is ideally what a systems top-down approach to designing a product would be like.

Additional types of extensions might be for the students to generate new design tools for new situations. Consider the example of a set of students in a capstone design project that used the structure and language of QFD to do a function to requirement mapping to identify the functions that are central to the success of the product. This innovative tool may be recognized from an axiomatic design view, but the students developed this tool to meet their needs ignorant of the axiomatic design. They understood that QFD relates requirements to metrics. Knowing that they have a limited time to work on the design project, the team sought methods to help them choose directions of development that would have the greatest overall impact on the project. Having created a function structure, they needed to identify the primary function. At this point, they sought to relate the requirements to the identified functions.

CONCLUSIONS

The application of hierarchical engineering education models to design education provides a rationale for some current approaches to engineering design education that have been used for years and also suggests some new ways of structuring engineering design education that should improve the engineering curriculum. The authors plan to continue their work to develop a framework for design in the engineering curriculum and improve engineering design education.

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