SCAFFOLDING AND FADING WITHIN AND ACROSS A SIX-SEMESTER CDIO DESIGN SEQUENCE

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ABSTRACT

This paper will present one part of the experiences and lessons learned during the implementation of an integrated six-semester CDIO design sequence in the new four-year aeronautical engineering and mechanical engineering programs at Daniel Webster College. In the second and third courses of the sequence techniques of scaffolding and fading have been used successfully to increase student interest, and learning in the technical as well as non-technical material. Scaffolding refers to the learning supports and aids put in place to allow students to more easily come to grips with new course material that would otherwise be too complex to readily understand. Fading refers to the gradual removal of the scaffolds over time once they are no longer needed. The paper will examine the application of scaffolding and fading to technical topics within the second and third courses of the design sequence as well as to the teaching of ethics in the final three courses in the sequence. Also addressed is how these techniques can be applied across multiple courses. The results have been a dramatic increase in interest among the engineering students for the technical material, and better comprehension and results with the non-technical material. The authors will be happy to make available syllabi, assignments, parts lists, and other course materials

KEYWORDS

Scaffolding, Fading, Design, Ethics, Undergraduate Engineering Education

INTRODUCTION

In 2005, Daniel Webster College (DWC) expanded its offering of engineering courses from two associate-level degrees to also include BS degrees in Aeronautical Engineering and Mechanical Engineering. As part of developing the new programs, additional courses were defined, mainly for the upper division but there were also changes and additions to lower-division courses. At approximately the same time, the engineering faculty of DWC became aware of the CDIO consortium. The faculty found that the philosophies of CDIO were well-aligned with their own as to how engineering should be taught, and so joined the consortium. Since then the faculty at DWC have been working at developing the new upper-division courses as well as modifying existing lower-division courses in conformance with the CDIO approach.

This paper presents one part of the experiences and lessons learned during the implementation of an integrated six-semester CDIO design sequence in the new four-year aeronautical engineering and mechanical engineering programs at Daniel Webster College. In the second and third courses of the engineering design sequence techniques of scaffolding and fading have been used successfully to increase student interest, and learning of the technical as well as non-technical material.

Scaffolding refers to the learning supports and aids put in place to allow students to more easily come to grips with new course material that would otherwise be too complex to readily understand. In some cases, standardized 'one-size-fits-all' scaffolds may be implemented for all the members of a class. In other cases scaffolds can be customized to student teams or individual students. Fading refers to the gradual removal of the scaffolding over time as it is no longer needed.

One example of how scaffolding and fading have influenced the evolution of the design sequence can be seen in the redesign of Engineering Design II, which is taken in the spring semester of the freshman year. The engineering design sequence at DWC consists of the following six courses:

- Engineering Design I (EG110)
- Engineering Design II (EG112)
- Instrumentation & Measurements (EG207)
- Engineering Design III (EG310)
- Capstone Design I (EG416)
- Capstone Design II (EG417)

Initially Engineering Design II included five weeks of advanced solid modeling techniques, followed by ten weeks of C programming. The programming component of the course was outsourced to the Computer Science department and taught by regular CS faculty in a traditional way. During the ten weeks of programming students would also continue to work on their design projects, which were primarily mechanical in nature. However, the students in general were dissatisfied with the programming part of the course, not seeing how it applied to what they were doing with their design projects.

For the spring 2006 semester the programming part of the course was redesigned to better connect this component of the course with the students' design projects. One part of the redesign was bringing the programming component back 'in house' so that it is taught by the regular engineering faculty. A second part was the inclusion of a kit of electronic parts for each student that includes a prototyping board, printed circuit board and components for a power supply, a PIC microprocessor, switches, an I^2C temperature sensor, a speaker, LEDs, and an LCD display. The students assemble and debug the microprocessor device prior to the start of the programming portion of the course. Once the programming exercises start, they can download their C code into the microprocessor for testing. Inclusion of scaffolding and fading techniques was also part of the redesign. An example of scaffolding within the course was that programming topics that might be difficult to learn in the abstract are broken down into smaller exercises that the students can accomplish with their microprocessor system.

The result has been a dramatic increase in interest among the engineering students for this part of the course. More importantly, the students learn the programming concepts better than was the case previously.

Scaffolding and fading have also been used successfully in the ethics education that has been integrated into the design sequence. It was customary and still is at many schools to send engineering students off to another part of the campus to learn about ethics in a free standing course taught by a philosophy professor, a practice considered satisfactory because the minimum expectation of the accrediting agency was met at little cost to the engineering department in time or effort. The unfortunate result was that by implication and example students were encouraged to place engineering and ethics into non-overlapping compartments, making engineering seem like a value-free technique. To surmount this disconnect, the designers of the DWC curriculum chose to embed ethics into several engineering courses taken over three semesters in sequence.

Students were originally introduced to ethical concepts in Engineering Design II, the second semester of their freshman year. However, it was quickly realized they generally weren't yet ready to assimilate abstract verbal concepts. Although used to mastering new ideas, they had difficulty with the non-mathematical nature of the ethical theories and found it difficult to think analytically about the ethical issues presented in the cases, their responses usually falling back on emotion or the simple moral prescriptions they were taught as children. While neither is without merit, neither is conducive to the kind of analytical reasoning they may need to use if confronted by an ethical dilemma in the workplace. As part of the 2006 redesign of the freshman course, ethics was moved to Engineering Design III and Capstone I and II, taken in the junior and senior years, delaying the introduction of these concepts to a time when the students are intellectually better prepared to understand them and are more proficient at writing after having completed their freshman writing and sophomore general education courses. The later introduction of ethical reasoning and the use of scaffolding and fading techniques have substantially improved student comprehension of the major theories and ability to write thoughtful analyses of the ethical problems presented in the case studies.

LITERATURE REVIEW

Scaffolding and fading as instructional or teaching techniques have been around for a long time; indeed, it is something that comes naturally to most parents, teachers and mentors. Formalization of scaffolding & fading as pedagogical techniques grew out of Vogotsky's [1] ideas on the zone of proximal development (ZPD). Vygotsky defined the ZPD as "the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers" (p. 86). The connection between Vygotsky's ZPD and scaffolding was first defined by Cazden [2].

As related to the concept of the ZPD, scaffolding addresses the nature of the guidance that is provided by the adult or more capable peers. This guidance may take many forms: focusing of the learner's attention to particular details of the problem, the asking of leading questions, temporarily simplifying aspects of the problem, and so on. Fading addresses when, to what degree, and under what circumstances the scaffolds are removed.

The term 'scaffolding' was first used in the educational context by Wood, Bruner, and Ross [3]. The use of the term grew out of discussions at Oxford and Nottingham universities regarding "…mother-infant interaction in the service of language development…" [4]. The translation to English and the publication in the West of a number of Vygotsky's papers [1, 5, 6] approximately thirty years ago was the impetus and starting point for formal research in the areas of scaffolding and fading.

A good example of scaffolding can be found in the work of Wood, Bruner, and Ross [3]. In their study of three-, four-, and five-year olds being tutored in the construction of a pyramid of interlocking blocks, they investigated the need to increase the focus of the student as well as demonstrating or modeling ways of solving a particular task. Increasing a student's focus is another way of expressing the need to reduce the distractions and extraneous information that might lead a student away from that which is the core of a particular problem or exercise. Modeling solutions to a particular task is an obvious technique used frequently in many teaching contexts.

The work of Palincsar & Brown [7] and Brown & Palincsar [8] in reciprocal teaching is one of the earliest and most widely cited examples of the deliberate use of scaffolding in classroom instruction. Their 1984 paper stated, "We designed an intervention that … was based on the notions of expert scaffolding…" (p. 122).

Stone [9] discusses the relationship between the scaffolding metaphor and the ZPD. In that paper, he identifies four key features of scaffolding:

- "A scaffolding interchange involves the recruitment by an adult of a child's involvement in a meaningful and culturally desirable activity beyond the child's current understanding or control" (p. 349);
- Focused assistance based on the tutor's diagnosis of the child's understanding and/or skill level along with carefully calibrated support towards accomplishing the specific goal or subgoal;
- The adult/tutor can provide a range of types of support--the particular support given depending on the nature of the task (or subtask) to be accomplished
- The support is assumed to be temporary and is withdrawn "in order to foster a transfer of responsibility from the adult to the child" (p. 349).

The first bullet is speaking specifically to the concept of the ZPD, that the activity is beyond what the child can do on his or her own. The second and third bullets speak to the need for continuous assessment and the crafting of support customized for the needs of the particular child. The final bullet addresses fading, that the support is removed over time so that the child learns to function autonomously.

Looking at scaffolding and fading in the context of teaching engineering, and in particular, the teaching of engineering as outlined in the CDIO Initiative, it is clear that these can be appropriate and valuable teaching techniques. It is all too easy for an engineering student to get lost in the details of some new material to be learned, to not be able to see the forest for the trees. Scaffolding, by narrowing the student's focus and the modeling of solution techniques, is clearly something that would be useful as a teaching technique in engineering (or related) courses. Fading, the removal of the scaffolds, needs to be done so that the student can eventually learn to cope with all of the details independently of the teacher.

THE PEDAGOGICAL UNDERPINNINGS OF CDIO

Crawley, et al. [10] take a very rigorous and methodical approach to the pedagogical underpinnings for CDIO. Their work could be seen as a proposal for "Reengineering

Engineering Education" as their approach, reasoning, and arguments for the case were constructed much as an engineer would approach a problem.

In a section of Chapter 2 entitled "Pedagogical Foundation" they argue that "engineering students tend to learn from the concrete to the abstract" (p. 31). Even though this statement may be an oversimplification, the problem as Crawley, et al. see it (and we agree) is that, unlike earlier generations of engineering students, students today "no longer arrive at universities armed with hands-on experiences from tinkering with cars or building radios" (p. 30). This relative lack of hands-on experience is compounded by the fact that "the engineering science educational reforms of the latter half of the 20th century largely removed many of the hands-on experiences that engineering students once encountered at university. As a result, contemporary engineering students have little concrete experience upon which to base engineering theories" (p. 30).

The CDIO approach to teaching engineering is very much shaped by this worldview, that:

- Graduating engineering students need to have practical, hands-on experience in order to be desirable to, and successful in, industry;
- Engineering students arriving on campus typically have little previous hands-on experience;
- Engineering students therefore need to acquire hands-on experience while also acquiring their knowledge of engineering science.

The solution to this problem is to teach engineering theory in a manner such that the students acquire practical, hands-on experience as they go along.

Crawley, et al. [10] state that "The CDIO approach is based on experiential learning theory that has roots in constructivism and cognitive development theory" (p. 30). They go on to note three important principles, developed by Jean Piaget and those who followed him, that apply to the CDIO approach to engineering education (p. 31):

- *The essence of learning is that it involves teaching learners to apply cognitive structures they have already developed to new content.*
- *Because learners cannot learn to apply cognitive structures they do not yet possess, the basic cognitive architecture must first evolve on its own.*
- *Learning experiences that are designed to teach concepts that are clearly beyond the current stage of cognitive development are a waste of time for both teacher and learner [13]*.

It is the last of these points with which we may take some issue. Taken at face value, the statement would seem to argue that there is no point in scaffolding, that it does not and cannot work. Yet scaffolding is used successfully in many educational contexts, engineering and otherwise. The issue may be one of interpretation: When using scaffolding to help in teaching a new concept, does the learner in fact have to be at some appropriate level of cognitive development in order for learning, even with scaffolding, to be successful? If that's the case, then we would agree with the statement as it is really saying that the material to be learned must be within the ZPD of the learner.

A position similar to Piaget's was taken by Duckworth [11] in her paper *Either We're Too Early and They Can't Learn It or We're Too Late and They Know It Already: The Dilemma of "Applying Piaget."* This paper delves into the history of Piaget's work (and related work of other

Genevans) and then begins to examine at a finer level of granularity exactly what is going on in some example-learning situations. A key point from Piaget's early experiments with young children in the areas of seriation and conservation was that "Simply telling children the truth about something could not make them understand it" (p. 298). This lead to the belief that "Surely we had only to devise the proper situations, focus the children's attention on the pertinent factors, elicit and reinforce the correct responses, and the job would be done" (p. 298). This sounds much like a description of scaffolding, and could lead a reader inclined towards scaffolding (as we are) into believing that she supports the notion of scaffolding. While several studies [12-14] are cited that could be said to inform a discussion of the value and/or efficacy of scaffolding (supporting as well as being critical of), it is near the end of the paper where Duckworth finally makes her position on scaffolding clear where she says "…another current interpretation of Piaget is that one should diagnose children's intellectual levels and tailor individual instruction accordingly. This has always seemed to me an impractical aim" (p. 310). Her argument is rooted mainly in a strict interpretation of scaffolding taken from an apprenticeship model of one-on-one interactions, which we agree generally will not scale well to a regular classroom situation. She does later propose that "The solution for the teacher, however, is not to tailor narrow exercises for individual children, but rather to offer situations in which children at various levels, whatever their intellectual structures, can come to know parts of the world in new ways" (p. 311).

Duckworth finishes her paper with two key paragraphs that are worth quoting in their entirety as they relate directly to the types of classroom experiences that are being promoted in the CDIO Initiative:

I return to Blanchet's thumbnail characterization of a good experimental situation in order to propose it again as a criterion for a good learning situation: it "must permit the child to establish plans to reach a distant goal, while leaving him wide freedom to follow his own routing." If we can create situations like this, then differences among children are by definition taken into account – without our having to diagnose in advance a child's level in a dozen domains. We can also be sure that children will take their own individual notions further as they strive to make sense of any situation, without our having to be obsessed with relating any particular activity to one of the notions highlighted by Piaget.

Finally, I would like to refer again to two themes brought out in the current Genevan research: the interplay between the child's attempt at a practical result and his or her efforts to understand, and the interplay among the various access routes to knowledge perceptions, actions, and words or formulas. <u>Both of these themes suggest that practical situations, which are the ones that correspond most to children's natural activity, are not only sufficient, but are also the best kinds of learning situations.</u> In the course of solving practical problems, children spend time reorganizing their levels of understanding; in real situations, children develop multiple access routes to their knowledge. Learning in school need not, and should not, be different from children's natural forms of learning about the world. We need only broaden and deepen their scope by opening up parts of the world that children may not, on their own, have thought about thinking about. (p. 311, underlining added)

While Duckworth did not refer to studies in her paper that addressed anything other than young children, it seems reasonable to think that the position she takes at the end could apply equally well to older students, such as those studying engineering at the undergraduate level. The philosophy of offering practical engineering experiences interwoven with engineering theory proposed by the creators of CDIO certainly seems to be well aligned with Duckworth's position on learning experiences. Finally, scaffolding, in the form of helping each learner to "establish plans to reach a distant goal," would seem to be scalable in an undergraduate engineering situation and consistent with the ZPD as defined by Vygotsky and the generally accepted interpretations of scaffolding.

The section by Crawley, et al. [10] on the pedagogical foundations of CDIO continues with a discussion of a particular application of constructivism and social learning: experiential learning. Cited in this section are Kolb's [15] six characteristics of experiential learning (p. 31):

- *Learning is best conceived of as a process, that is, concepts are derived from, and continuously modified by, experience;*
- *Learning is a continuous process grounded in experience, that is, learners enter the learning situation with more or less articulate ideas about the topic at hand, some of which may be misconceptions;*
- *The process of learning requires the resolution of conflicts between opposing modes of adaptation to the world, that is, the learner needs different abilities from concrete experience to abstract conceptualization, and from reflective observation to active experimentation;*
- *Learning is a holistic process of adaptation to the world, that is, learning is broader than what occurs in classrooms;*
- *Learning involves transactions between the person and the real-world environment;*
- *Learning is a process of creating knowledge, that is, in the tradition of constructivist theories.*

The section ends by tying together the threads of constructivism, Piaget's cognitive development theories, and experiential learning into the concept of "*dual-impact* learning experiences" (p. 32). These learning activities "are crafted to support explicit pre-professional behavior" (p. 32). As a result, "they will facilitate the learning of personal and interpersonal skills, and of product, process, and system building skills" (p. 31). Moreover, these learning experiences will also support a student's 'knowledge structure for understanding and learning the abstractions associated with the technical fundamentals" (p. 31).

Although not mentioned directly, it seems that there is also a fair amount of constructionist theory being applied in the CDIO curriculum, too. The experiential and hands-on nature of typical CDIO learning activities seems to be very much in line with those espoused by Papert [16]. Papert worked with Piaget in Geneva in the late 1950s and early 1960s, so it is not surprising that there are similarities in their views on learning. There are important differences though. As Papert puts it:

Constructionism – the N word as opposed to the V word – shares constructivism's connotation of learning as 'building knowledge structures' irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe (p. 1).

For engineering students, the entity being constructed can be (and often is assumed to be) something physical, but it need not be. The obvious connection between CDIO and constructionism is the creation of physical artifacts, which is certainly an important part of what the CDIO authors want to have happen in the curriculum. But the students could just as easily be constructing an understanding of the application of techniques learned in linear algebra (Cramer's Rule, for example) to solving Kirchoff's Voltage Law equations for a complex set of loops and meshes in an electrical circuit. Nothing physical is being constructed in this case, but something is indeed being constructed: an understanding of the deep relationship between what might at first blush appear to be two quite disparate topics in engineering theory.

For example, in the Instrumentation and Measurements course taught at DWC, the students are challenged to construct their own understanding of LabVIEW™ while also designing, constructing and operating a physical artifact, a weather station. This course blurs the line between artifact and knowledge: the students are constructing something physical and, in the process, constructing their knowledge of how to do that properly. They are at the same time constructing their knowledge of LabVIEW, how it works, how it can be used to help solve engineering problems, how it is quite different from the programming language they learned the previous semester (C), and so on. The constructionist approach is, in our opinion, particularly important when learning a programming language like LabVIEW. It is a tremendously powerful tool but, as one might expect, there is also a tremendous amount to learn. Simply lecturing to students about what LabVIEW can do and how to do it would be deadly boring. There is a small component of the course where students are lectured about LabVIEW, but the purpose is to simply make them aware of various capabilities and to briefly sketch out how they are similar to (and different from) what they may have previously seen. After that they are given small, focused hands-on assignments that provide them with the opportunity to construct their own understanding of the particular capability.

SCAFFOLDING AND FADING WITHIN ENGINEERING DESIGN II

Technical Content

As noted earlier, the Engineering Design II course initially included five weeks of advanced solid modeling techniques, followed by ten weeks of C programming. The programming part of the course was ‘outsourced’ internally within DWC to the Computer Science department. The students were taught the C programming language by a member of the computer science faculty in a traditional way using Microsoft Visual C and their usual curriculum (although condensed somewhat due to the shorter time available). During the ten weeks of programming students would also continue to work on their design projects, which were primarily mechanical in nature. Consistent feedback from the students, through formal mechanisms such as the end-of-semester course evaluation forms as well as informal conversations, indicated that, in general, the students were dissatisfied with the programming portion of the course. Their particular complaint was that they did not see how it applied to what they were doing with their design projects. They were not complaining that they didn’t see the worth of learning a programming language, or that they were being poorly taught, but rather that the material was disconnected from everything else going on in the course.

Given this fairly consistent feedback, one of the authors (Putnam) suggested that the programming part of the course be brought back ‘in house’ to be taught by engineering faculty and revamped to address the students’ concerns. The first part of the revamping consisted of finding a project that would allow for strongly connecting the mechanical project portion of the course with the programming portion. That project turned out to be the design, construction and operation of a model elevator controlled by the previously described PIC microprocessor system.
The second part of the revamping, and the part of particular concern to this paper, was reconstructing the manner in which the C programming material is delivered. One of the goals of the course revamping was to help students understand why learning how to program is important to them as they progress towards a career in engineering. The need to be a

competent programmer is frequently not self-evident to freshmen engineering students. Rather than using the types of problems well established as useful in training software engineers, similar problems were found that could be placed in the context of their engineering project: the model elevator system.

One of the problems students encounter when learning a programming language, and in particular when learning their first programming language, is that the number of things they need to know in order to get a program to work at all is formidable. For this reason, scaffolding was incorporated into the progression of exercises that students are taken through as they learn the C language. The scaffolds used for the first few exercises are designed to hide much of the complexity. For example, the first program the students create is one that incorporates four LEDs that sequentially display (in binary) the values 0 – 15; the sequence then repeats. The code is shown below in Figure 1. One could think of this as the embedded or Mechatronic systems programming equivalent of the canonical “Hello World!” program used in many traditional introductory programming courses. Students are taken through the process of entering their first code into the editor in the integrated development environment (Microchip’s MPLAB®), and then creating the project and workspace files. The code is simply given to the students for them to type into the editor; details involved in the setup of the IDE workspace and project files are glossed over with the explanation that the details will be supplied later. The goal is that the students have their first program running, and have had some time to experiment with it, by the end of their first (two-hour) programming class.

```
#include <p18f452.h>
#pragma config OSC=HS
#pragma config WDT=OFF
#pragma config LVP=OFF
unsigned char counter;
void main(void)
{
TRISA=0;
while (1==1)
{
counter=0;
while (counter<=15)
{
PORTA=counter;
counter=counter+1;
}
}
}
```

Figure 1. Code for Programming Exercise 1

Note that this is a truly awful piece of code. There are no comments, nor is there any formatting (indentation of statement blocks, white space between sections of the program …) to make the code easier to read. The students are told all of this at the outset and are also told that over the next few programming exercises this code sample will be step-by-step turned into a properly constructed program along with explanations of *why* each thing is being done.

Even with such a simple first exercise and essentially handing the students the code to type in, much can be learned. Students typically will not pay close attention to capitalization and several students will end up with keywords or symbols that are not recognized by the complier. This provides an entree for the instructor to let the students know that C is a case-sensitive language. On a similar note, at least a few students in the class will manage to drop a semicolon or two, which in turn allows for a discussion about the role of the semicolon as a statement terminator.

As the program stands, it executes much too quickly for the students to be able to see any pattern in the LEDs. When the program is run all of the LEDs appear to be continuously lit. The students are shown how to stop and then restart the program. Each time they stop the program they will likely see a different collection of LEDs lit. They are asked to speculate as to what is going on. Some students have no idea but there are always a few that immediately understand that the program operates too quickly to see the pattern in the lights and that the program is being stopped at random values between 0 and 15. This is the set up for a future exercise, the introduction of a delay loop to slow things down.

The first few exercises are all highly dependent on scaffolding. For the most part, the early scaffolds are hiding complexity as much as is possible. For example, not all parts of the program are discussed in these early exercises and the parts that are discussed are not discussed in detail. The goal is to create a series of early successes and get the students excited that they have created their first computer programs. It is not uncommon for students to be reluctant to leave at the end of the first programming class as they immediately want to start refining the program.

A specific example of scaffolding where complexity is being hidden (or at least minimized) is in the creation of the MPLAB workspace. This process involves going through a multi-step 'wizard' to create and populate the workspace, but that is then followed by several manual steps to get the workspace set up as needed for our particular environment. The students are led through the process step-by-step with essentially no explanation the first time other than it is necessary to setting up their programming environment. The second and perhaps third times through the process are much the same. But starting with either the third or possibly the fourth time through the process, the instructor starts giving less hand-holding on the process steps. This is an example of where fading is beginning to take place. This particular set of supports for the students, the workspace scaffolding, is starting to be removed.

The classic definition of fading involves frequent assessment on the part of the instructor to determine when, and to what extent, to remove the existing scaffolding. In the example just cited, the instructor uses his or her judgment (based primarily on how many "Hang on, what was that step again?" questions are being asked) as to whether to begin removing the scaffolding with the third iteration of creating a workspace or the fourth. Here the assessment is not being done with an individual student or even a student team but the class as a whole. The fading decision will likely not be optimal for all of the students; for some it will be overdue and for others it may be premature. But at this point, even for the students where it may be a little premature, there are other resources (such as their classmates) they can rely on.

The process of scaffolding, by initially hiding complexity and then, once students have come to grips with the simplified new topic, fading the scaffolds and getting more into the details is repeated several times during the Engineering Design II course. Examples of where this is done are the code involved in handling timer interrupts and then subsequently the code for generating a pulse-width-modulated (PWM) signal.

Non-technical Content

In its first configuration, freshmen were introduced to applied ethics in Design II, with a two to three hour overview of the nature of professions and the public trust role they play, the place of ethics in ensuring that practitioners live up to that trust, and the three major ethical theories. Following the introduction, a test was administered as motivation for the students to learn the concepts and to gauge how well they had mastered them. Then over the next several weeks they would write responses to two case studies that presented them with ethical dilemmas that might be faced by an engineer in the workplace (a variety of scenarios are available from online case collections.) The plan was to follow the freshman year with additional analytical writing about ethics in Design III in the junior year.

However, in the first two years of operation the results of the test and the three to four page papers were less than satisfactory. The freshmen readily grasped the public trust nature of the engineering profession but often had difficulty understanding deontological, consequentialist, and virtue ethics. They were also prone to making snap decisions about what should be done in a case without factoring into their decision all the competing pulls that an engineer experiences on the job. Their written analyses were rudimentary and often casual. All are problems typical in trying to get engineering students, or for that matter most students enrolled in technical programs, to learn material outside the province of engineering as they narrowly define it.

The faculty teaching the design courses settled on the solution of delaying ethics until the junior year and following it up with additional case responses in both semesters of the senior year. The benefit is that the students come to their ethics education with two additional years of increased intellectual maturity and writing proficiency. Moreover, spreading out ethics education over three consecutive semesters avoids the problem of forgetfulness that occurred when students spent the entire sophomore year without any reinforcing of what they had learned as freshmen.

The changes have proven themselves successful. This is not to say that all the problems have been solved. Some students come to the classroom on the days ethics is being discussed as if they were being forced to swallow a dose of bad tasting medicine, though the number is smaller, and the amount of time they are willing to invest in thinking and writing can still be less than is desirable. They are also still prone to making a quick decision on a case and then "reverse engineering" the reasons to justify the decision. On the whole, however, there is improved learning and thinking.

The introduction to ethics in Design III is similar to the content that was provided in the freshman year, though it can now be more detailed and covered more quickly. Students still begin with the characteristics of professions and their special role in society, but more attention can be paid to the codes of ethics prescribed by different engineering organizations. Freshmen tend to think of the professional organizations and their codes as being remote from their lives. Juniors, however, see the horizon more clearly and recognize that professional guidelines about ethical behavior may well play a part in their working lives and are worth knowing more about. They are shown the ABET code, as well as those of the National Society of Professional Engineers, the Institute of Electrical and Electronics Engineers, the American Society of Civil Engineers, the American Institute of Aeronautics and Astronautics, the American Society of Mechanical Engineers, as well as a few others.

Most of the students have never seen professional codes of ethics before and their first reaction is surprise that practicing engineers are expected to live up to these standards of behavior.

More detailed discussion encourages them to see that as comprehensive as the canons and standards appear to be, they are often vague, potentially self cancelling, such as the expectations that an engineer simultaneously be a good employee and work for the welfare of the public, and rarely offer guidelines for acting in specific situations. Although this discussion is not scaffolding, the students are being prepared to recognize that ethical reasoning has to go beyond the generalities of the professional codes and that they need a conceptual framework that will provide them with the analytical tools with which to think about dilemmas they might face in the workplace.

Before beginning the introduction to the three major types of ethical reasoning, the juniors are presented with the case of the 1986 Challenger shuttle explosion and the question of the ethical responsibilities of the engineers and managers at Morton Thiokol and NASA. It is at this point that scaffolding is first implemented in their ethics education. After reading about the accident they are asked to explain whether the managers were ethically right or wrong to proceed with the launch in unusually cold weather. Most are quick to conclude that managers in both organizations were wrong, although they are usually unable to articulate in any detail why their answer is justified other than technical considerations were ignored. They are then asked to reconsider their decision using the scaffolding of a series of questions presented by the instructor that leads them to take into consideration the non-engineering factors that may have been behind the decision by NASA and Morton Thiokol. The Rogers Commission report on the accident reveals that a number of engineers had expressed worries to their managers that the O-rings might not hold, but was this enough for them to have lived up to their ethical obligations or should they have done more to try to stop the launch? If more was required, what should they have done? What is the proper balance between an engineer's responsibility to the public and responsibility to be a good employee? Is it not a material consideration in Morton Thiokol's decision-making that it had to prove itself with a successful launch so it would be awarded a contract renewal and keep numerous engineers employed? In deciding a go or no-go decision, shouldn't NASA legitimately consider the value of a successful mission in persuading Congress to continue and possibly increase its funding so the shuttle program could stay alive?

This scaffolding of directed questions helps students to begin recognizing the tangled web of considerations that makes ethical reasoning more complex and uncertain than just deciding whether technical elements like temperature and elasticity had been adequately evaluated. The goal of the technique is to get engineering students, whose tendency is to eliminate ambiguity as much as possible, a disposition intensified by their technical training, to see that a wide range of considerations must be part of effective ethical reasoning.

After this discussion students are taught the three major branches of applied ethics, much as it was done in the freshman year, but now more time is spent on the kinds of ethics within each of the branches. For example, in studying the class of deontological ethics, students are introduced to divine command theory, Kant's categorical imperative, and rights theory. A second class, consequentialist ethics, introduces them to subjectivism and utilitarianism, in which the result of an action on the actor or a group makes it ethical or not, while virtue ethics, the third class, presents them with the concept that it is the effect on a person's character that makes an action right or wrong.

Case studies are then used to make the abstract theories concrete, and it is here that scaffolding is used most extensively to provide a framework for student thinking. They are asked to consider an ethical problem that an engineer might face, such as intellectual property, conflict of interest, or research ethics, and then evaluate how each of the different theories applies in the situation or does not, and why. They are encouraged to see that the theories need to be thought through with more care than they might initially have believed. A good illustration is utilitarianism. Students tend to think at first that the “greatest number” includes only those immediately affected by the decision. Only after discussion do they see that one of the most complex issues in utilitarian reasoning is determining just how wide the moral circle should be drawn. They are also discouraged from calculating answers, reasoning that because two or more theories agree on a decision that it must then be the right choice. They are asked to consider the larger social context of the situation and to think realistically about the competing pressures on the actors in the case before coming to a conclusion on the ethical action.

In one case a graduate student is conducting a drug test on animal subjects under the supervision of a professor who has received a grant from a pharmaceutical company for the research. The project is also the subject of the student’s dissertation. The results from one group of subjects indicates that the drug has been effective; a second subject group has yielded less positive data, but the graduate student believes the drug was improperly administered to this group of animals. To re-do the second test will take months, and the pharmaceutical company is pressuring the professor to publish the results and the student wants to finish her dissertation and start a job that has been promised her after graduation (slightly modified from John Fernandez’s “Ethics and Pressure” at the Center for Ethics in the Professions).

After reading the case students usually begin by making quick judgments about the ethically responsible action, based, it often seems, as much on what they believe the professor wants to hear as their own moral beliefs. It is both habits of mind that the scaffolding is intended to unsettle. Instead of feeling the answer and justifying it after the fact they are coached to think through the scenario repeatedly, using the ethical theories as analytical tools and discovering how different theories frequently lead to the need to consider different actors and motives. This process of crisscrossing the same terrain repeatedly is an essential part of the scaffolding because it slows the students down, discouraging them from forming hasty conclusions. Each ethical concept provides a different lens with which to look at the case, and students are shown how each brings to the foreground new features that must be considered. They also learn that specific theories may be less helpful than others in a given situation.

In the case above, for example, subjectivism might lead to the conclusion that the graduate student should finish the project using only the data from the first group of experimental subjects because she will then be able to finish her dissertation and begin her professional career. Virtue ethics suggests the opposite, that she should delay the project to get the data from the second subject group; she will then be a better scientist for conducting herself according to the best practices of the profession. When they evaluate the case using utilitarianism, students might conclude that the researcher would be right to wrap up the study using the one data set because she would be creating good for the professor supervising the research and the pharmaceutical company, but if the moral circle were widened to include the general public then the opposite conclusion seems justified because of the small but real possibility that a product based on incomplete preliminary evidence could be tested on human beings with potentially adverse effects.

As might be expected, for freshman engineering students, who are accustomed to applying a technique and arriving at unambiguous answers, the multiple tracking over the same case is frustrating and the contradictory answers baffling. Their impatience often leads them to stop analyzing and fall back on the platitude, “it’s all relative” (which can lead to the interesting discussion of how relativism is a form of subjectivism, and that by making no decision they are unwittingly making one, and it may not be a good choice). By the time they are juniors, and seniors, however, they have begun to discover that engineering techniques do not always lead to unequivocal answers and that uncertainty is inescapably part of sophisticated thinking whether it be mathematical or verbal.

Scaffolding of a different type is provided once the students begin writing their analyses of the two new case studies they complete in the course. Although they are comfortable with technical report writing by the time they are juniors, they are hesitant about organizing their thinking on more unfamiliar subjects, so a suggested sequence of information is offered as a pattern to follow to allow them to concentrate on the analysis without the added complication of how to organize it. They are told to begin with a précis of the case and in the following paragraph explain in an overview what action(s) they believe the actor in the case should take and why. The longer third and fourth sections of the paper contain multiple-paragraph blocks in which they analyze which theories apply in the case and which do not. In the former case they are to explain their reasoning and what particulars were most salient for a given theory; in the latter, which theories were not helpful, again explaining both their reasoning and the facts of the case that made the theory irrelevant in coming to a conclusion. A summary then concludes the analysis. This organizational pattern is similar to the standard argument model they have already been introduced in their freshman writing and subsequent general education courses, but presenting it to them anew gives them the comfort of a ready-made scaffold on which they can hang their ideas.

By the end of their junior year the scaffolding for their ethics education has been twofold: a series of directed questions to lead them to think systematically and meticulously about the ethical theories and a paper format that encourages them to carefully analyze the material in two case studies before coming to a conclusion about the proper action to take in each.

In the senior year, these scaffolds are gradually faded and the students are required to think through new problems without the assistance of the scaffold. In Capstone I they are asked to write two more case responses. The first of the cases in Capstone I is engineering related, bringing to a total of three the number of engineering cases they write about. The second case in that course and both cases in Capstone II, however, are unrelated to engineering and instead are on larger social issues of a kind that the students may need to consider in the future. For these last three papers students write on topics including non-therapeutic genetic engineering (i.e., designer babies), genetically modified foods, age-based health care rationing, corporate social responsibility, surveillance, security, and freedom, and others. The intent behind this procedure is obvious: while they need to learn to reason through to ethically responsible decisions in the engineering workplace they also need to be able to apply those same reasoning skills and knowledge of ethics to issues they will face as adults in a democracy. By teaching them to stop making reflexive decisions, to think analytically about the issues before they come to a conclusion, they will be better prepared to be ethical engineers and citizens.

For the last three papers the scaffolding is removed entirely and students are given no classroom guidance on either analyzing the cases in light of the ethical theories or the format for the papers they write. Since the subject material is so different from what they have become accustomed to, the change presents some distinct challenges. The faculty member teaching ethics is available for advice outside of class, but the students are encouraged to think through the problems of analysis and paper organization for themselves, based on what they have already learned.

The results from using the ethics scaffolding and gradually fading it have been encouraging. Problems of time and motivation, if these are not the same thing, are still present, but in general there has been an overall increase in the precision of their thinking and writing about ethics. For freshmen, the zone of proximal development (ZPD) is often narrowly circumscribed. They can understand the basic ethical concepts with some determined coaching, but the number of variables and the difficulty of grasping multiple perspectives before arriving at a solution to the case often prove more than their capacity to comprehend. By the time they are juniors and seniors, their ZPD has enlarged considerably, making them better able to keep the large number of variables and the conflicting answers in play while coming to a conclusion. They still often need to be coaxed to spend the time to think through the problem systematically and to write well about it, but the scaffolds have shown them how to do both successfully.

SCAFFOLDING AND FADING WITHIN INSTRUMENTATION & MEASUREMENTS

Instrumentation and Measurements is taken by engineering students of both majors in the fall of their sophomore year. The course did not start out to be a design course, but as it has evolved it has come to be recognized as such.

As the course name implies, students study various commonly used instrumentation and sensors, how to construct and conduct experiments, how to make measurements using those sensors, and how to analyze and present data from those experiments. Students learn the LabVIEW® programming environment and are introduced to some commonly used National Instruments® data acquisition hardware. The course takes a building-block approach with an interlaced series of lectures and hands-on lab experiences culminating in a team-based final project.

The students are told at the outset that the final project is for each team is to Conceive, Design, Implement, and then Operate a five-instrument weather station capable of gathering data on temperature, relative humidity, air pressure, wind speed and wind direction. Beyond coming up with a design for and then constructing the weather station, the students are told the weather station needs to successfully operate for a minimum of 72 continuous hours gathering and logging the data. Given the weather in New England in the late fall and early winter, this is no small task; past weather stations have had to deal with upwards of six inches of snow or an inch of ice. Students are required to give progress reports as the project progresses, maintain a project website for the team, and finally to deliver a written final report as well as a presentation to an audience of their peers, faculty, members of the Industrial Advisory Board, and often parents.

Early in the course each team is given a small kit of parts which they will need to incorporate into their weather station. The kit of parts mainly consists of four of the five sensors they will need. Other components in the kit can be used to create the fifth sensor.

LabVIEW is a rich and therefore somewhat intimidating programming environment. The students in I&M have done programming previously in Engineering Design II, but LabVIEW is very different. First of all it is a graphical programming environment. While this is often a plus (students really seem to be drawn to the different programming paradigm), it is very different from what they previously experienced in Engineering Design II with MPLAB and the C programming language.

As was done in Engineering Design II, scaffolding is initially used to hide complexity. Students are taken through a series of exercises that reintroduce programming concepts they have seen previously such as data declarations, the assignment and other mathematical operators, the IF-THEN-ELSE statement, FOR-NEXT and WHILE loops, etc. These concepts are re-introduced in the new context of the LabVIEW graphical programming interface as part of exercises that also have them interfacing simple sensors to the data acquisition hardware.

As the students progress, the initial complexity that was hidden is gradually revealed. For example, in an exercise that reflects an earlier exercise in Engineering Design II, students create a simple loop that runs too fast and needs to be slowed down to 'human speed.' They are shown how what they did in Engineering Design II using C (creation of a delay loop) can be accomplished in LabVIEW, so in this case we are actually reusing a scaffold from a previous course. Then this scaffold is faded as additional richness in the LabVIEW environment is revealed (the delay loop is replaced by a simple LabVIEW timed loop). This too is later faded out as an even more complicated, and therefore more functional, loop timing mechanism is revealed.

SCAFFOLDING AND FADING ACROSS COURSES

The examples of scaffolding and fading that have been mentioned so far have mainly been within a course. Complexity has been hidden and problems are initially simplified so that students can more easily come to grips with the new material. As they get more comfortable with the new material, more complexity is revealed but other aspects may still hidden or simplified. But scaffolding and fading can also be used across courses and in a very different manner than has been discussed so far.

Engineering students at DWC begin their engineering studies with Engineering Design I and II in their freshmen year, followed by Instrumentation and Measurements in the fall of their sophomore year. As freshmen they face many new and different demands on their time and attention. They often lack the discipline and mental maturity to be able to organize their work effectively, construct and hold to a schedule, decompose complex tasks into smaller, more manageable units of work, and so on. These problems are certainly not unique to engineering students, but given the demands of their chosen major it is incumbent on the faculty to work with the students to help them master these skills as soon as possible. In our efforts to do this, we have found that we naturally have used scaffolding and fading as a way of helping students to develop the organizational and time management skills they will need to be successful.

It would be easy to take material introduced in an earlier course (such as free-body diagrams in Physics), which is then used in a later course, say Statics, and call the material in the earlier course scaffolding for the later course. But that would not be an accurate use of the term. The FBD knowledge and techniques acquired in the earlier course should more accurately be called an affordance [17, 18], since they become tools that are used as a matter of course in problem solving, much as a calculator becomes a standard engineering tool once someone knows how to use it effectively. Here we are more concerned with scaffolding and fading at a higher level, such as, for example, how to use scaffolding and fading in the teaching of such things as argumentation, modeling, critical thinking, and personal and interpersonal skills and attitudes, and to teach these skills across courses rather than using scaffolding and fading for the teaching of mathematical or procedural tools and techniques only within courses.

Let's go back and look at the needs that are driving the CDIO reform effort. The intent is to educate students who can:

understand how to conceive, design, implement, and operate (Section 4) complex value-added engineering products, processes, and systems (Section 1) *in a modern team-based engineering environment (Section 3), and*

are mature and thoughtful individuals (Section 2). [10] (p. 24).

The section numbers refer to the major sections of the CDIO Syllabus. Section 2 of the syllabus, Personal and Professional Skills and Attributes, and Section 3, Interpersonal Skills: Teamwork and Communication, both present many opportunities for scaffolding and fading, not only within but also across courses. Some of the topics addressed within the engineering curriculum at DWC, the areas of Personal and Professional Skills and Attributes (Section 2) and Teamwork and Communications (Section 3), are good examples of where cross-course scaffolding could take place.

Starting with their first engineering course (Engineering Design I) in the fall of their freshman year, students are expected to work in small teams and make frequent oral presentations of their work. As the course progresses, students are required to design and implement several small parts as projects. The final project is for the students to design, implement, and operate a DC electric motor driven sprocket & chain reduction system that must meet certain design criteria.

A significant amount of scaffolding support is made available for students:

- Pre-defined project criteria: Each of the introductory projects is very small and well defined. This allows the students to focus on applying what they have just learned and to not be distracted by other, larger issues. Even the final project is still well defined (although the students have by this point been given a little more leeway in certain aspects of the design, a chance for some creativity).
- Pre-defined project milestones: Specific deliverables and dates are preset, so the students do not need to concern themselves with creating a schedule. All they need to focus on is adhering to the schedule, which for many is challenge enough.
- The course is team-taught by a member of the Humanities faculty: This makes it easier for the students to get and apply feedback on their report or presentation outlines, writing, grammar, presentation skills, and so on.
- The project teams are kept small (three students per team) to make it easier for them to organize and manage their work.
- Students are provided with what they need to know. There is little need for them to go hunting for additional information, or to teach themselves any new material.

Moving on to the Engineering Design II course in the spring of their freshman year, many of the same constraints are in place as in Engineering Design I, but there are some noteworthy changes:

The final project, while still very well defined, is more complex. Students this time have to grapple not only with a mechanical design component of the final project but also a programming component in which they have to create and program a microprocessor-based control system to operate the device. The scaffolding in this course is slightly less extensive:

- The project milestones are still pre-defined for them. A new tool, Microsoft Project, has been introduced, however, to help them grapple with the added complexity of the project (at the cost, however, of having to come to grips with the tool itself).

- The course is still team-taught by a member of the Humanities faculty. Oral and written progress reports are required at various points as the course progresses. The bar has been raised though; significantly more polish is expected by the time of the presentation of the final project.
- Students are still largely provided with everything they need to know. Given the amount of material, however, there may be need to do some independent reading (not everything will be covered in detail in the lectures). This is pointed out to them frequently.

In the fall of their sophomore year, the engineering students will take the Instrumentation & Measurements course. Here there are noticeable amounts of fading of some of the previous scaffolds:

- There will be scaffolding for the new material the students are learning within the course, and some fading of that support as the semester progresses. But while there are several small lab exercises (projects) that the students will do as the semester progresses, they are much less structured than before. Each project will have some overall goal to be achieved, but *how* the students should organize their work to get it done will not be as well defined, though it should still be pretty obvious.
- The course will have a final project, but unlike in Engineering Design I and II, the project will be less well defined. There will still be very clear overall goals that need to be met for functionality as well as deliverable dates, but the path to those goals will not be as prescribed as before.
- The final project will require students to synthesize material from previous courses, particularly Engineering Design I and II, as well as newly learned material. Scaffolding will be provided in the form of focusing prompts: "Remember when we talked about <topic> in Design II? How would you apply that here?"
- Milestones for the final project are not defined. It will be up to the students to produce a credible project timeline (with feedback from the course instructor) and then manage their work to it.
- This course is not co-taught with someone from Humanities. The students still need to do written and oral progress reports as they proceed with their final projects. They can, of course, seek out help from the Humanities faculty member, but that help is not integrated into the course as before. The quality hurdle for the final presentation is set at the 'poster presentation' level, what would be expected, for example, at a student poster competition. Scaffolding for that, in the form of presentations by upper-level students who have presented at student poster competitions in the past, is provided.
- As mentioned earlier, there is far too much material to be covered solely in the lectures. Students will need to take initiative to find and read sections of the books that cover the particular things they want to do in their projects. Faculty will help by pointing students in the right direction, helping them to understand what they are reading on their own, giving students examples of how to apply what they have read to their particular project situations, and so on.

Let's now turn to the Engineering Design III course taken in the junior year. Here we can see more fading of the earlier scaffolds the students were afforded in the areas of teamwork and communication skills:

- The projects may be student driven, meaning that the students propose what the projects should be, or the projects may be proposed by faculty or industry. The level of scaffolding the faculty provide at this time is more in the form of "sanity checks" for such things as scope and goals (can the project be reasonably accomplished in the allotted time?), safety (are there any dangerous materials or mechanisms involved?), cost (is the project likely to cost more than has been budgeted?), and so on.

- Students are expected to be more independent when defining the deliverables of the project. Faculty will advise and guide as necessary.
- Student teams may be larger at this point (perhaps four to five students). This provides additional challenges in team management and work scheduling. Faculty will assist with the team dynamics when necessary, but the process of scheduling, setting and meeting milestones, and developing reports and presentations are largely student driven.
- Students are expected by this point to be able to synthesize material across multiple courses and apply it successfully. Faculty will work with students as necessary to focus their thinking on opportunities to do this. The more specific prompts afforded, for example in the I & M course, will be partially faded by now. Students will have to work harder at getting those same types of very focused prompts from faculty members.
- Project presentations should by now be sophisticated and polished enough to be acceptable as conference presentations. Faculty will act as advisors to students regarding such things as focus, clarity, timing, use of graphics, and so on.
- Students at this point should be capable of at least realizing that they may not have everything they need to know in order to solve a problem or complete a project. They should by now have the initiative to at least seek help from the faculty in getting pointed in the right direction and answering conceptual questions the students may have. Students should often be able to figure things out for themselves and often work independently of faculty help.

Finally, in their senior year, students will take the Capstone Design I and II courses. By now the earlier scaffolds have been almost completely faded. Students are expected to largely stand on their own:

- Projects are either student driven or perhaps suggested by industry partners. The projects are, by design, open ended and have no “right answer.” The students are expected to act largely as though they were operating in their first true engineering job. The role of faculty is to be mentors and guides.
- The project deliverables may be specified by the industry partner or, in the case of a student-defined project, by the student. In either case the faculty will act mainly as advisors.
- Project teams may be quite a bit larger than before, further increasing the challenges of team management and work scheduling. Faculty are mainly in the role of assessing by now; the students ought to be able to define and manage the project mostly on their own.
- The point of a Capstone Project is to provide a real-world engineering experience that requires the students to pull together everything they have learned to date. They are expected to either know what they need to apply to solve a particular aspect of a problem, or know where to go find out what they need to know, or know that they need to go learn for themselves what they need in order to succeed. Faculty will work with students to encourage, motivate, and guide them as they wrestle with their project challenges.
- Project reports and presentations should be quite polished by now. Faculty help by providing feedback to students and pointing out examples of good work for them to emulate.
- Students should by now realize that they will often have to find and teach themselves new material, in other words, to engage in life-long learning. Students should be able to

operate largely independently of the faculty in their projects. Faculty should need only to occasionally guide and mentor students, provide insight into difficult problems, and point them in the right direction.

CONCLUSION / PLANS FOR THE FUTURE

Scaffolding and fading as instructional or teaching techniques have been shown to be applicable and successfully used not only within courses but also across a sequence of related courses within an engineering curriculum. Further, the techniques have been shown to have applicability not only to the teaching of technical topics such as programming but also to non-technical topics such as ethics.

The conclusions drawn are based primarily on data from student end-of-course evaluations as well as an informal analysis of in-class discussions, students' homework assignments, exams, and papers as well as classroom observations. More formal testing of the techniques themselves may be able to reveal the extent to which they influence course and program outcomes and how they may be optimized for the teaching of different topics.

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