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Restructuring an Engineering Core Course to Prepare Students for Design Experiences*

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This paper describes the restructuring of a core electrical engineering course in electromagnetics to better prepare students to do engineering design. Traditionally the course was taught in a linear mode, one step following the other. There was also little attention to practical applications, or to the relation of the material to other courses in the core. The paper begins with a review of some of the current literature on teaching and learning, particularly as it relates to the restructuring. This includes a discussion of student intellectual development, the reality of uncertainty in the world and student reaction to it, some assumptions that instructors need to take into the classroom, and finally some thoughts about the possible relation of child development to student development. The restructured course is then described. The linear approach to teaching is abandoned. Students are asked to face the reality of uncertainty, as well as its implications for engineering design. A daily handout sheet is designed to facilitate student integration of ideas across classes and courses. A design project is introduced. The response of students to the course is briefly discussed. The paper closes with a set of questions designed to guide continuing restructuring of the course.

Keywords: electrical engineering; core courses.

INTRODUCTION

For most of the twentieth century the primary approach in most schools to educating engineering students for design experiences was to introduce core concepts in the first three years, and then to give students a capstone design experience, assuming that they would effectively make use of what they have learned in core courses. In recent years it has become increasingly clear that for a number of reasons, discussed below, this teaching model is substantially less than optimal. This paper describes the restructuring of a core course in electromagnetics in an electrical engineering department, developed to prepare students more effectively for design experiences. The paper begins with a brief review of the traditional way of teaching the course. The motivation and rationale for change are then discussed and the restructured course is described. The response of students to the change is assessed and the next steps in the evolution of the course are presented. The paper concludes with some thoughts on what the author has learned from this restructuring and the study associated with it.

The course discussed in this paper, ELEN 105: Electromagnetics II, is the second of two five-unit junior-level ten-week courses in electromagnetics required of all students in electrical engineering at Santa Clara University. While the first course in the series has also seen some of the changes described here, the focus in this paper is on the second course.

A TRADITIONAL APPROACH TO THE COURSE

The course in question has been taught by the author of this paper for more than twenty years. Until two years ago the teaching model was very traditional. Essentially all of the material was presented through lectures and reading assignments. In addition the course has a three-hour problem session devoted to solving problems using the theory introduced in class. The author has always taught the material in this course, and other technical material as well, in a very linear manner: no idea introduced before its time, no concept presented without a sound technical basis. Examinations determined whether students were able to use the concepts introduced in class to solve relatively routine problems.

This approach has historically characterized all of the core courses in the department. In addition, almost no effort was made to formally connect ideas from one core course to another, essentially leaving the task of integrating concepts to the student. The faculty of the department was relatively accepting of this situation although there was periodic grumbling that students did not seem to know what they had supposedly been taught in earlier courses.

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About four years ago, in anticipation of an ABET visit in the Fall of 2004, the School of Engineering began a comprehensive assessment of its programs. A number of members of the faculty, including the author of this paper, attended several assessment workshops and teaching and learning-related conferences. The resulting exposure to contemporary theory and practice in teaching and learning was the genesis of the restructuring described in this paper.

As the restructuring of the electromagnetics course was proceeding, the Department of Electrical Engineering undertook a number of individual efforts, as well as a joint effort, aimed at providing greater cohesion in the core, and more emphasis on design-related activities. In 2004 the School of Engineering as a whole received a National Science Foundation grant for Department-Level Reform of Undergraduate Engineering Education. The study has three main thrusts: revision of an existing freshman cornerstone course to include an introduction to design, introduction of service-learning (community engagement learning) to engineering, and faculty development relating to teaching and learning theory and practice. These activities are not discussed in any detail in this paper, as the focus is on the electromagnetics course, but they do help set the context for the changes in the course.

THE IMPETUS FOR CHANGE

The twentieth century was a time of great progress in the study of how people learn, led by the work of such luminaries as John Dewey (1859–1952), Jean Piaget (1896–1980), and B. F. Skinner (1904–1990). But it has only been in the last decade or two that teaching and learning theory found its way into most of academia in a significant way. This paper will not attempt a comprehensive review of such work, but will instead point out some sources that are particularly relevant to the course changes in question.

The problem that our students face in learning to design, and that we face in helping them to achieve that goal, is well-described in a recent paper by Felder and Brent [1]. They map the necessary development of a student from a state of 'ignorant certainty to intelligent confusion.' Using models developed by William Perry, by Mary Belenky *et al.*, and by Patricia King and Karen Kitchnenr, Felder and Brent model four levels of intellectual development.

1. *Absolute knowing*. All knowledge is certain. The teacher is the omniscient authority whose job is to pass on the correct information to the student. The student's responsibility is to memorize information and repeat it back when asked. Many students who enter college closely conform to this model.
2. *Transitional knowing*. Some knowledge is certain; some is not. The instructor communicates the certainties. Students make up their own minds about the uncertainties.
3. *Independent knowing*. Most knowledge is uncertain. Students take responsibility for their learning, collecting evidence to support judgment, though perhaps superficially. When knowledge is uncertain, all judgments about it are equally good if a correct procedure is used.
4. *Contextual knowing*. All knowledge is contextual, that is, it is not isolated but is rather found in a context that gives it meaning and at the same time enhances the understanding of the context. Contextual learners recognize that they must construct their own knowledge. They do this by objective analysis and by intuition. They bring their own thoughts to bear on a problem, and they recognize, with care, the expertise of others. They have learned to evaluate their sources critically.

It seems clear that good engineering design requires contextual knowing. Felder and Brent [1] put it this way:

> These students' skepticism and willingness to challenge what is currently known and to question the assumptions underlying all assertions, their tolerance of ambiguity (which deters them from rushing to accept the first plausible explanation that arises), their inclination to use both logic and intuition in their investigations, and their unwillingness to transfer judgments made in one context to another without critical evaluation, could almost stand as a definition of what first-rate scientists and engineers do.

It is not a simple task for us to bring our students to embrace contextual learning. Absolute knowing of information that comes from an accepted authority is really much less difficult and challenging than constructing one's own knowledge. That's true for all of us. Almost three decades ago the economist E. F. Schumacher pointed to the difference between convergent and divergent problems [2]. The former have straightforward solutions that most reasonable people accept. Our students like to find these kinds of problems on tests and homework. Such problems are more comforting, less dangerous, especially if you get the 'right answer.' Divergent problems, however, have no clear answer. Is abortion acceptable? Should we fight to spread democracy? Shall we add a second person in thermodynamics to the faculty? What type of bridge should we build? Is the car safe enough? How high is that smokestack? How thick are those walls? Schumacher [2] knew the difficulties for us, and for our students, when we face such problems.

> Divergent problems offend the logical mind, which wishes to remove tension by coming down on one side or the other, but they provoke, stimulate, and sharpen the higher human faculties, without which man is nothing but a clever animal.

Let's bring in one more economist, the Stanford

Nobel Laureate, Kenneth Arrow [3]: 'The sense of uncertainty is active: It actively recognizes the possibility of alternative views and seeks them out. I consider it essential to honesty to look for the best arguments against a position that one is holding. Commitments should always have a tentative quality.'

Our students as a rule have fine logical minds, and that's good, it just isn't enough. If they are to design, they must accept and learn to live with the tensions of divergence, and to seek out alternative paths.

The related question of convergent and divergent thinking as it appears in engineering is addressed in some detail by Dym *et al.* [4], who ask whether the formal identification of convergent and divergent thinking can help guide the development of better pedagogical approaches to scientific theory and analysis, and to engineering design. It is this question that the author will address in the section on the specifics of restructuring a core engineering course. But first it is instructive to consider some additional ideas from the literature in teaching and learning, and from the cognitive sciences.

A major factor in the success of any teaching process is the assumptions that the instructor brings to the classroom. The highly reputed *How People Learn* (*HPL*) [5] begins with three key findings that are widely accepted in teaching and learning theory today:

- Key Finding 1. Students come to the classroom with preconceptions about how the world works. If their initial understanding is not engaged, they may fail to grasp the new concepts and information taught, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom.
- Key Finding 2. To develop competence in an area of inquiry, students must: (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the concept of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and application.
- Key Finding 3. A 'metacognitive' approach to instruction can help students learn to take control of their own learning by defining goals and monitoring their progress in achieving them.

If our students come to our class with the preconceptions of Key Finding 1, how do we discover them, and what do we do about it. Some pre-testing may uncover some of the problems, but much of what our students bring to class is too subtle and not apparently related to our 'subject.' Identifying preconceptions and misconceptions is not a simple task. Perhaps the best we can say is that we will identify what we can, and then keep clearly in mind that we have almost certainly done an incomplete job. Another question is what we do about misconceptions if and when we are able to identify them. From the perspective of neuroscience Zull [6] claims that misconceptions are very difficult to remove because they are hard-wired into the brain. When we learn we form a neuronal network in the brain, a physical entity, not some shapeless cloud.

> . . . no teacher, with the wave of a hand, a red pen, or even with a cogent and crystal-clear explanation can remove an existing neuronal network from a student's brain.
>
> The useful approach for a teacher is to find ways to build on existing neuronal networks. Starting with whatever our students already know and building from there is a biologically based idea for pedagogy . . . Existing neuronal networks open the door to effective teaching.

Many years before the modern neuroscience of the brain, and before *HPL*, David Ausubel [7] articulated the same basic idea:

> If I had to reduce all of educational psychology to one principle, I would say this: the most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.

Ausubel went on to suggest some ways of helping students relate what they learn anew to what they already know. One approach is an 'advance organizer', which is a device introduced at the beginning of a class to create a bridge between past learning and new ideas. Such devices might also suggest a structure that the student will fill in as the lesson progresses. This might, for example, take the form of a handout with some previous material on it, and the skeleton of the development of new material. (See below, and the appendix of this paper for an example of such a handout.)

Key Finding 2 from *HPL* insists on the importance of a solid foundation of factual knowledge, but demands also that such knowledge be embedded in a meaningful conceptual framework, reflecting the general topic of study. The expectation is that properly embedded and organized knowledge can be effectively retrieved and used.

Key Finding 3 asserts that thinking about the thinking process helps learning. Some ways to do this are suggested below.

Another fascinating perspective on how our students learn comes from the cognitive science of child development. In *The Scientist in the Crib*, Gopnik *et al.* [8] argue that from birth on, and perhaps even a bit before, the tiny child is the world's greatest scientist, seeking information, eyes flitting from one source to another, reaching out, touching, feeling, tasting, critiquing the information received, comparing today's tidbit with yesterday's gem, deciding what to keep and what to discard, learning huge amounts of information in a very short period of time. And all of that learning, of facts and of technique, is designed to prepare us for a lifetime of learning. To Gopnik and her colleagues we are all just big babies. So, the question is whether the new science of child development can help us understand how our students developed as they did, and how it can inform the way in which they learn and we teach. Consider this passage [8]:

> From the time human babies can move around, they are torn between the safety of a grown-up embrace and the irresistible drive to explore. A toddler in the park seems attached to his mother by an invisible bungee cord: he ventures out to explore and then, in a sudden panic, races back to the safe haven, only to venture forth again some few minutes later. Indeed, we probably never quite escape the bungee cord even as grown-ups; it seems part of the human condition to be perpetually torn between home and away, the desire for comfort and the dread of boredom, the peace of domesticity and the thrill of adventure.

Is this what T. S. Eliot was getting at in *The Four Quartets*:

> Go, go, go, said the bird: human kind
> Cannot bear very much reality.

Is it hard for our students to spend too much time in the real world? Is it important—is it necessary—for them to follow the bungee cord periodically back to the safe harbor, back to the convergent world, to the world of ideal models, the world of sure answers? It certainly seems something they want to do. Perhaps it is something to keep in mind in restructuring a course that has always in the past had a very short bungee cord.

It is about time to get on with restructuring our course, but before we do so, let's take one last look at the child, and the lessons that we might learn. Here is a story of the adventure of a two-year old scientist [8], not long out of the crib. As you read the story substitute for the two-year old one of your own students, perhaps a student in a course, or maybe one you have known for four years. And of course take the experiences of the two-year old as metaphors for your student's experiences. Read the story as your adventure too, along with your student.

> Think of some completely ordinary, boring, everyday walk, the couple of blocks to the local 7-Eleven store. Taking that same walk with a two-year old is like going to get a quart of milk with William Blake. The mundane street becomes a sort of circus. There are gates, gates that open one way but not another and that swing back and forth if you push them just the right way. There are small walls you can walk on, very carefully. There are sewer lids that have fascinatingly regular patterns, and scraps of brightly colored pizza-delivery flyers. There are intriguing strangers to examine carefully from behind a protective parental leg. There is a veritable zoo of creatures, from tiny pill bugs and earthworms to the enormous excitement, or terror, of a real barking dog. The trip to the 7-Eleven becomes a hundred times more interesting, even though, of course, it does take ten times as long. Watching children awakens our own continuing capacities for wonder and knowledge.

A RESTRUCTURED COURSE

It is assumed here that the restructured course in electromagnetics must help the student acquire the following if it is to make an effective contribution to the development of the design engineer:

- An understanding of the fundamentals of electromagnetics
- An understanding of approximate models
- An appreciation of uncertainty and probabilistic models
- A willingness to challenge what is said to be true
- An ability to critically evaluate alternatives
- An innate curiosity about the world around us.

It is common for instructors to claim that it is not possible to add any 'frills' to a course such as this because there is already too much material to cover. The author was determined to accomplish the desired changes in the course without sacrificing any significant content, and at the same time increasing fundamental understanding of concepts. The steps taken to accomplish this objective are described in this section. Student reaction is discussed below.

The first step in restructuring the course was to move away from a 'linear' approach to presenting the material, in which each idea comes along in its own time, with appropriate solid development of the background theory. In its place the author introduces and begins to use fundamental results at the beginning of the course, justifying and explaining these ideas in depth only later on. The assumption here is that this approach models more accurately the way that people learn in general, and that it is reasonable therefore to apply it in the classroom. Furthermore, some derivations of concepts are sacrificed. Derivations are only carried out when they clearly illustrate a fundamental concept. The assumption here is that working with the concepts is more important than deriving them formally in an introductory course. The objective of these two steps is to lighten the 'rigor' of the course while increasing the understanding of fundamental concepts.

To test for student understanding coming into the course, that is, to attempt to determine preconceptions and misconceptions, the course begins with a test on material that is assumed to have been learned in previous courses.

To test for conceptual understanding as the course proceeds, each examination in the course begins with a closed-book 'concept inventory' in which the goal is to assess understanding of the ideas rather than the ability to solve relatively straightforward numerical problems.

To address the question of the role of the instructor in the class, and to encourage metacognitive thinking, students read the paper by Felder and Brent on stages of development of learning [1]. They write a short paper discussing the article, and it is then discussed in class. The idea that the instructor is not the font of knowledge from which they mindlessly drink is reinforced throughout the course through appropriate cartoons, stories, and quotes. Metacognitive thinking is also introduced through a discussion of Bloom's Taxonomy as it is applied to the learning process.

The idea of the fundamental limitations of human knowledge is reinforced during the introduction of the laws of electromagnetics (Gauss, Coulomb, Faraday, etc.). It is shown that these are very limited laws, approximate models that describe nature with a very narrow scope. It is also shown that such laws are never proven, though they must be assumed 'true' in order to get on with the enterprise.

To establish clearly the difference between convergent and divergent problems, students are given simple analysis problems that show convergence, and this fact is pointed out. Then they are given open-ended problems in the same area, simulating some simple aspects of design. Again, they are taught to recognize which problem is which. The intention of these exercises is to reinforce the development concept of Felder and Brent, the taxonomy concept of Bloom and, of course, the distinction between convergent and divergent problems due to Schumacher.

Each class begins with the distribution of a 'daily handout': a two-sided sheet that serves a number of purposes. First, it provides information, sketches, pictures, etc. that are used during the class presentation. Second, it allows the development of bridge information, tying new information to old. Third, the bottom box on the second page allows students to ask questions on any subject. At the beginning of the next class the instructor takes the first five to fifteen minutes to answer the questions that come in. This allows students to ask for clarifications in material, complain about procedures, or perhaps ask some off-the-wall question that just intrigues them. This process captures student attention, and also gives the instructor the salubrious opportunity to occasionally say 'I don't know the answer to that one', reinforcing in the process the idea that the instructor is not omniscient. The questions that students ask occasionally show an amazing level of curiosity.

To date the use of Ausubel's 'advance organizer' (see the previous section) in relation to the daily handout has been implicit at best, relying on reminder questions from previous classes. This is an area that will be significantly developed in the next offering of the course.

To encourage collaborative learning and teamwork the class is divided into a number of teams of four students. These teams occasionally work together on a question raised in class. They also make one thirty-minute presentation during the term, on a technical subject related to the course. Finally, they work together on a three-week design project. In 2005 the project was to design a time domain reflectometer (TDR) to be used in a course in electromagnetics to teach students about transmission lines and about signal integrity.

It is the author's belief that these steps have helped students to achieve each of the six goals listed at the beginning of this section with the exception of an appreciation of uncertainly. This limitation will be addressed in the next offering of the course.

ASSESSMENT OF STUDENT RESPONSE

Students were generally quite positive about the course. They were unanimous in their support for the question period at the beginning of each class. Some liked the teamwork, some did not, though most recognized it as a necessary part of their engineering education. They did not at first like the concept inventory part of the test, preferring to work numerical problems. As the course went on, however, they became more successful with these parts of the tests, and presumably more comfortable, though this was not assessed.

Students largely resisted the arguments made by Felder and Brent [1], claiming that it was easier and more efficient to consider the instructor as the source of knowledge. They exhibited in the class discussion of the paper a classic discomfort for uncertainty and ambiguity. As the course progressed the concept of contextual learning was reiterated, and the instructor is confident that the course helped many students to realize its importance, and to progress beyond the lower stages of intellectual development.

The instructor kept a record of the questions asked on the daily handouts. Of the 30 students in the class 19 asked one or more questions. One student asked 11 questions. The questions asked can be divided into three groups: questions about the technical content of the course, questions about the running of the class, and questions that had nothing directly to do with grading, but seemed to come from innate curiosity. Listed below are some representative questions from each group. The number following the group name is the percentage of the total questions that fit into that group.

Technical: (56%)	Can you repeat the equations relating EIRP and power density?
	How do you find the percent of power reflected from a load?
Operations: (12%)	How did you grade the presentations?
	Why are the homeworks becoming so long?
Curiosity: (32%)	What is the biggest antenna in this area?
	Why aren't there perfect conductors?
	What made you go into EE?

The instructor found the curiosity questions to be particularly encouraging since curiosity is an essential need for the design engineer. Two questions arise. Were the rather large number of questions exhibiting curiosity a result of the restructuring of the course, or did they simply come up because of the opportunity to ask questions on the daily handout? The second question is whether it is possible to encourage greater curiosity, and if so, how can this best be done.

At the end of the course the class fills out a 'Design Preparation Survey', intended to assess student's perceptions of their readiness to do design. Results suggested that students have a mixed feeling about their basic hands-on skills (soldering, working with devices, programming, using software tools, etc.), with a wide range of levels of confidence. They were significantly more optimistic about their ability to analyze digital and analog electric circuits.

THE NEXT STEPS

The course restructuring described in this paper is very much a work in progress. It is the author's intention to continue to pursue issues in teaching and learning theory, and to revise the course accordingly. A series of questions or issues that will be addressed are raised in this section.

Questions

1. What additional changes in the course would help students move away from absolute knowing and toward contextual knowing?
2. To what extent and in what ways does the science of child development inform our study of the development of the engineering student, particularly as it relates to design?
3. How can the concept of contextual knowing be made clearer so that students can aspire to it, and understand how to accomplish it?
4. Can a recent work by Jeff Hawkins [9], relating the workings of the brain to the development of computers, inform the subject of student learning?
5. Can more effective ways be found to encourage and assess student curiosity?
6. What can be done to the daily handout so that it serves as a more effective integrator of the course?
7. Would concept inventories be more effective for students and more meaningful for the instructor if the students were required to explain their answer to the multiple choice questions?
8. Can the ideas developed here be effectively adopted by other faculty?

These questions and others that arise from them will be addressed in the months ahead, and will influence the continuing restructuring of the two electromagnetics courses.

SOME CLOSING THOUGHTS

The central question that we face in this paper is how best to prepare our students, through our teaching, for engineering design. An important corollary question is whether our teaching life is more one of prose or one of poetry. The author casts a cautious vote for poetry. But it is a poetry full of content, of metaphor that reaches out to reality, of meter, timing, gentle pauses at appropriate moments. All of these things must find a way into our engineering programs.

It has been said that one should never end a paper or a talk with a quote. The author's words should end the story. So, let's break that rule. Over four hundred years ago Shakespeare penned six lines that seem an almost perfect description of science, and perhaps of engineering design as well. There it is in Act V, Scene 1, of *A Midsummer Night's Dream:*

> The poet's eye, in a fine frenzy rolling,
> Doth glance from heaven to earth, from earth to heaven;
> And as imagination bodies forth
> The forms of things unknown, the poet's pen
> Turns them to shapes, and gives to airy nothing
> A local habitation and a name.

REFERENCES

1. R. Felder and R. Brent, The intellectual development of science and engineering students. Part 1: Models and challenges, *Journal of Engineering Education*, **93**(4), 2004, pp. 269–277.
2. E. F. Schumacher, The nature of problems: An argument against final solutions, September/October, 1977, *Quest*, pp. 77–84.
3. K. Arrow, I know a hawk from a handsaw, in *Eminent Economists: Their Life Philosophies,* Cambridge University Press, New York, (1992).
4. C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer, Engineering design thinking, teaching, and learning, *Journal of Engineering Education*, **94**(1), 2005, pp. 103–120.
5. J. D. Bransford, A. L. Brown, and R. R. Cocking, *How People Learn: Brain, Mind, Experience, and School*, National Academy Press, Washington, DC, (2000).
6. J. E. Zull, *The Art of Changing the Brain: Enriching the Practice of Teaching by Exploring the Biology of Learning*, Stylus Publishing, Sterling, VA, (2002).
7. D. P. Ausubel, *Educational Psychology: A Cognitive View*, Holt, Rinehart and Winston, New York, (1968).
8. A. Gopnik, A. Meltzoff, and P. Kuhl, *The Scientist in the Crib: What Early Learning Tells Us About the Mind*, Harper Collins Publishers, New York, (1999).
9. J. Hawkins, *On Intelligence,* Times Books, New York, (2004).

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