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Reformulating General Engineering and Biological Systems Engineering Programs at Virginia Tech

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ABSTRACT

In 2004, a group of engineering and education faculty at Virginia Tech received a major curriculum reform and engineering education research grant under the department-level reform (DLR) program of the NSF. This DLR project laid the foundation of sponsored research in engineering education in the Department of Engineering Education. The DLR investigators adopted a spiral curriculum approach to reformulate curricula in general engineering (also called freshman engineering) and bioprocess engineering programs. The spiral curriculum concept recognizes the inherently recursive nature of learning. During this recursive process, students elaborate and strengthen earlier learning, correct misconceptions, develop a more holistic picture of their discipline, and become increasingly self-sufficient as learners. This paper documents the step-wise process that we developed and implemented to rewrite the bioprocess engineering curriculum using spiral theory. Specific examples of learning modules from bioprocess and general engineering are discussed. Assessment approaches and results are presented to highlight the usefulness of such efforts. Adaptation of our spiral curriculum efforts by faculty in other engineering programs to develop a nanotechnology option and ethics spirals is described. We describe lessons learned in three key words: (i) *Patience* – Reformulation results may take time to show up, (ii) *Diligence* – Assessment results are powerful, take these seriously, and (iii) *Awareness* – Students' perceptions may be difficult to interpret. Finally, we discuss the challenges encountered in our unique cur—riculum reform and engineering education research project and also include a few funding related recommendations for the NSF.

Key Words: Spiral curriculum, freshman engineering, bioprocess engineering

INTRODUCTION

In May 2004, the Department of Engineering Education (EngE) was created within the College of Engineering (CoE) at Virginia Tech (VT) to improve engineering pedagogy within the CoE and to initiate engineering education research activities. Freshmen in the CoE (~1600 every year) are required to complete a 1-year long General Engineering (GE) (also called freshman engineering) program before they can advance to one of 14 degree programs, offered by 12 degree-granting departments. The EngE faculty is responsible for conducting the GE program. Another primary mission of EngE faculty is to conduct rigorous research in the area of engineering education. Such research efforts in engineering education require collaboration between engineering and education faculty within and outside the university. A National Science Foundation (NSF) supported planning grant "Bridges for Engineering Education – Virginia Tech (BEEVT)" laid the foundation for such an engineering-education collaborative at Virginia Tech in 2003 [1]. One objective of BEEVT was to create a contemporary framework for undergraduate engineering pedagogy, beginning with freshman engineering experiences. Accordingly, BEEVT investigators, comprised of engineering and education faculty, proposed to reformulate the curriculum in one of the engineering programs, namely, Biological Systems Engineering (BSE), using a spiral curriculum approach proposed by Bruner [2]. The proposal resulted in a 5-year (2004–2009) curriculum reform and engineering education research grant under a Department-Level Reform (DLR) program of the NSF (hereafter referred to as DLR project; [1]).

This paper documents the accomplishments of our DLR project. The paper is organized as follows. First, we briefly discuss traditional approaches adopted in curriculum reform efforts, then the theory in support of the spiral curriculum approach to curriculum development. The next section presents the step-wise process that was developed to implement a spiral curriculum in our BSE program. Specific examples of learning modules developed in support of the spiral curriculum from both BSE and GE programs are discussed in the next section. A summary of assessment data along with various strategies adopted for assessing the learning outcomes of the reformulation efforts are discussed along with curriculum development activities. In the next section, we reflect on our experiences of working on this 5-year long, spiral theory-based curriculum reform project and present a summary of our dissemination efforts with educators within and outside the United States. Finally, we conclude the paper with a brief discussion of major impacts of the DLR project and a summary of lessons learned.

TRADITIONAL CURRICULUM REFORM APPROACH

Reform is a concept that probably has been too readily applied to education, perhaps in part because of the persistent idea that we can always steer the process to better results. Inevitably, many, if not most, reform movements tend to circle back to a few fundamental ideas that have been difficult to dislodge from the public consciousness. Essentially we "know how it should go" and when pressured to find ways to "do it better" it is easy to conclude that the reason for lack of success is that we have simply not enacted the basic moves well enough. Assessment is a prime example, where we conclude that if we tighten the screws on measuring learning to a greater extent, improvements will follow. Similarly we might conclude that more time for school or more time for study or more homework would do the trick. And the story goes on with the main theme being better or more of "the basics." It is a more difficult proposition to conclude that we really need to do things in a fundamentally different way. This is not part of the familiar cultural experience, and so the move to different thinking is more difficult for people, especially those who see themselves as responsible for making high level decisions..such as boards of education and the like.

The reform spotlight is now shining brightly on the engineering profession, and educators once again must negotiate the pressure for change against the inertia of traditional behavior. Part of the calculation in deciding to do something different is an assessment of the stakes: "What happens if nothing happens?" An example of this dialogue about change and the need for it appeared in the October 2006 special edition of the Journal of Engineering Education of the ASEE. In the introduction to this issue, the needs side of the equation spoke to the competitiveness of the emerging global economy and the idea that engineering itself has changed in ways that make it imperative to reconsider alternatives to current educational paradigms. For example, few now believe that engineering is primarily about applying well-formed technical knowledge to predictable problems. New engineers entering the workforce will more likely be working in contexts that involve complex collaborations around problems that are inherently "messy" in nature and perhaps only solvable through knowledge and technologies that were simply not part of their recent educational experiences. This shift in reality for new engineers raises the question of what educational strategies and structures provide the most suitable preparation. Traditionally, educators have answered the call for educational reform by remaining with what is known as the general *linear* curriculum. Familiar to all who have attended school over the past fifty years or so, the linear model is the frame around which most courses of study are formed, and to which faculties and students alike must adhere. The chief idea is that the curriculum is designed mainly to deliver knowledge and produce skills deemed necessary for some future endeavor such as business, law, engineering, or education. Once the content is decided upon, the curriculum itself can be organized in a linear and hierarchical fashion.

The key pedagogical move is to arrange things so that the instructional trajectory is from simple to complex, so that students will presumably always be confronting material for which they have some prior grounding. So arranged, the curriculum moves ahead steadily under the assumption that students acquire knowledge and skill and then retain it in some usable fashion for future needs. Of course, learning problems do arise but these can be handled with appropriate sensitivity to whether students have actually "gotten it" as they move from course to course and level to level. Once students successfully exit the program with the required number of content *credits* the assumption is they will then be equipped with the technical expertise to negotiate what life presents to them, at least in professional terms. However, not all have accepted this general linear model.

THEORY SUPPORTING A SPIRAL APPROACH TO CURRICULUM DEVELOPMENT

As early as the 1960s, alternatives to the general linear model were beginning to emerge—the principal idea being that learners simply do not advance in their development in a straight-line trajectory. Jerome Bruner, in his book *The Process of Education* (1960) [2], proposed that a learning curriculum ought to be capable of engaging students of any age in any subject matter and do it in an intellectually honest manner. This proposal at the time seemed radical, and indeed may still appear somewhat farfetched, mainly because it does not make the usual assumption that education is preparation for some future endeavor that is not yet within the reach of learners at a beginning stage. Bruner's argument took a different stance—proposing that education should involve *early legitimate participation* in the important work of any discipline of choice. Bruner's idea was that learners—even beginners—could engage successfully with the central problems and questions inherent in any discipline *if* those key questions could be represented in a manner that invites real experimentation and inquiry at the appropriate level. One key to this idea is that the learning curriculum could be arranged so that the central questions, or themes in a discipline, would be returned to again and again as learners advance in their knowledge and intellectual capacity. *The learning trajectory is thus represented as a spiral rather than the linear pathway that is characteristic of traditional schooling.* As learners participate in increasingly complex investigations, organized carefully around the major themes of choice, they acquire in a more natural way the knowledge they need because it is connected to problems of real import and interest, and they acquire also the full intellectual apparatus associated with *being* the scientist, historian, or engineer rather than *learning about* their chosen discipline. In particular, it is this notion of *learning to be something*, rather than *learning about something*, that we saw as a key basis for reformulating our curriculum. If the curriculum includes early opportunities for prospective engineers to engage in solving problems that are representative of engineering work, albeit at introductory levels, then students would more likely move toward aligning their identities with the profession.

Since Bruner's first proposal that the key to successful learning lies in more artful curriculum building, we have seen a number of decades of research into human learning that now allows a more complete fleshing out of this idea that learners must be more actively engaged in constructing their own knowledge. The book *How People Learn* [3] has been a recognized source, especially in the STEM areas in higher education. When Bruner first suggested the notion of a spiral curriculum, the psychology of learning was just transitioning from a behavioral tradition to a whole new set of theoretical constructs centered on the metaphor of learners as information processors. Human memory took center stage in this movement. Howard Gardner's (1985) [4] documentation of the cognitive revolution is detailed and insightful as are other notable contributors in telling this story (see, for example, Norman, 1968 [5], Bransford, 1979 [6] and Anderson, 2000 [7])

The bottom line is that instead of focusing on how people learned to behave in complex ways through drill and practice, aided by selective reinforcement, we shifted to a focus on how people acquire complex knowledge and how that knowledge could be represented in memory so that it would always be available and accessible when needed (see Schraw, 2006 [8] for a recent review). This became quite a complex story, because it turns out that learners do not simply store direct representations (mirror images) of what they hear or see; rather they construct their own unique representations (memories) that are guided substantially by what they already know (prior knowledge). Invariably, these representations, or understandings, are flawed by their incompleteness and they often contain misconceptions that are extremely difficult to dislodge and fix [9–11]. Astute educators recognize this type of learning as a building process, and they know that any curriculum that has learning as its objective must contain provisions to double back to build on, elaborate, and correct what students have acquired at any given point in time [12–14]. This means that learning is inherently a recursive process, involving both construction of meaning and reconstruction at a later time in a course of study.

The spiral curriculum that we have been working toward is inherently tuned into this natural recursive process identified through years of research. Yet, there is even more to be considered. Developments in learning research in just the past two decades have moved beyond the primary emphasis on cognition and memory to focus on learning as a culturally, socially situated phenomenon. This research emphasizes that learning always occurs in some type of context or culture (e.g., [15–18]). Classrooms and campuses represent a distinct type of culture for student learners just as companies that make products or sell services provide a distinct culture for workers [19] who are also engaged in an ongoing learning process. The more we learn about the role of context in learning, the more we understand the limitations of formal educational processes that are essentially context free, as is the case with most classroom and textbook learning. This issue with context, or "situatedness" (Greeno, 2006 [20] is a relatively recent development in learning research [16, 17] but has taken on increasing importance as investigators consider what is *left out* when abstract presentations dominate educational practice. In the case of engineering curricula and pedagogy for example the missing elements may include most of what practicing engineers have access to including the actual work settings, tools of the trade, other professionals with diverse talents and skills, and the actual discourse of engineering work. These additional elements are integral to the practice of engineering of course and in socio-cultural theory the entire *situation* is thought to co-produce the learning that occurs [15, 16]. The absence of these key supportive elements is what is meant in our reference to education that is "context free." It is important to point out, however, that criticisms of education conducted in a more traditional abstract manner have resulted in some debate over the degree to which a movement toward "situated cognition" and away from abstract expository instruction should prevail as a general rule (see Anderson, Reder, and Simon (1996) [21] and Greeno, 1997 [22) for a sample of this debate.

Jerome Bruner has weighed in on this in two of his more recent books, *Acts of Meaning* in 1990 [23] and *The Culture of Education* in 1996 [24], and there are numerous other sources (e.g., [25–30]) that have documented the importance of context and social dynamics to learning. In formal schooling environments we have tended not to think very much about the impact of the cultural setting in terms of how it supports and shapes the learning process. Inside schools we have simply taken for granted the idea that what students need to know about any discipline can be stripped from its natural context and taught as a codified body of facts, rules and principles. We assume that once students enter a professional or real-life domain they will simply apply what they have learned in schools to the new context. This *assumption of transferability* has now become one of the major issues because of the concern that knowledge gained in classrooms does not easily transfer to situations outside of schools [20, 22]. To understand why, it is useful to examine some of the differences between a purely cognitive orientation to learning and what we now know about learning that occurs in authentic social contexts. Five key propositions may provide keys to curriculum work in the future.

1. There tends to be a lot more support for learning in rich social contexts [29–31]. This support includes other people, tools of the trade, stories that develop around the practice itself, and well structured ways that people actually participate in the practice in question. Learning in schools tends to be more of a solo process [24], and we tend not to let in those supportive elements that are taken for granted outside of school. The emerging trend is to recognize that the physical settings, people, tools, and shared discourse that we see in real contexts are all important in scaffolding the learning in question.

2. Learning in natural cultural contexts may be defined differently than it is in schools. Rather than focus on what can be stored in memory, we tend in real settings to think about how someone participates in the practice in question. In other words, learning involves acquiring a particular role that is important to the practice and that may be seen in relation to roles that other people play [17] [19]. A design team, for example, would not have all participants playing the same role. Further, the roles that people play would change as they become increasingly mature or central participants in the practice [19].
3. Learning involves identity development [19]. This is something we tend not to think about or evaluate in schools, but as people become adept at the roles they play in social settings they begin to develop an identity as a particular type of practitioner. In essence, they know *who they are* as a practitioner, and this is actually one of the major outcomes of a learning trajectory that is more richly contextual.
4. Learning in cultural contexts tends to be immediate rather than future oriented. This is because learning is a natural part of doing, rather than preparation for something that may occur in the future [17]. Learning that has no utility value is difficult for many reasons, including motivational issues, and this fact is not lost on teachers who are constantly struggling to find ways to make classroom learning more relevant.
5. Finally, the way that learning is documented in our formal programs is through the certification process of testing, grading and transcripts. Outside of school, the emphasis is on the mature roles that people can play with their expanded repertoire of skills, and the ability of entire communities of learners to advance together.

Collectively, these characteristics suggest that it may be necessary to re-engineer parts of our existing educational system and, in doing so, begin to take on a new mind-set with regard to our responsibilities as educators. This is the broad aim of the curriculum project reported here.

SPIRAL CURRICULUM DEVELOPMENT PROCESS IN BSE

Bioprocess engineering is a formal option of the B.S. degree in Biological Systems Engineering (BSE) in the CoE. While approximately half of the BSE faculty members specialize in the bioprocess area, the full BSE faculty is responsible for the curriculum, so it was essential to involve the full faculty in the curriculum development process .The spiral curriculum development process was led by the “core development team” comprised of the authors of this paper, with the two BSE faculty members who were PIs for the DLR project (i.e., second and fourth authors) taking the lead.

We viewed the curriculum development process as a design problem: "design a spiral curriculum for bioprocess engineering." We developed the design process as we went. As with any design, it was an iterative process. In the following paragraphs, we describe the curriculum design process that evolved over time as a seven-step process. We do this for clarity but want to emphasize that it was not as linear a process as it might appear.

Step 1. Define Overall Outcomes: We asked the faculty to answer the question "What do bioprocess engineers need to be able to do when they graduate with the B.S. in Biological Systems Engineering: Bioprocess Engineering option?". The faculty brainstormed and listed many items that students should be able to do by the time they graduate. Since our goal was to identify the high level outcomes, we continually asked "why do they have to be able to do that?" about each proposed outcome until the answer was "because they are bioprocess engineers." As a result, we defined four high-level, overall outcomes: (1) Design a reactor; (2) Design a process and optimize the process conditions; (3) Select units in the process and design a plant layout; and (4) Control the process. Later, we added a fifth outcome focused on professional skills, for example, teamwork, ethical responsibility, and lifelong learning. Each outcome represents a theme through the spiral curriculum. For example, the first outcome, Design a Reactor, is revisited at increasing levels of complexity, as illustrated in figure 1. The reactor design outcome could be introduced at the freshman level as a hands-on laboratory exercise in a test tube demonstrating enzyme hydrolysis. The same reaction can be studied in a beaker with the addition of a microbial organism producing the enzyme under consideration. At this level, students could be asked to characterize the products. At the subsequent level, students could use a laboratory scale fermenter and modify the operating conditions and evaluate the efficiency of producing desired products. At the advanced levels, students could design reactors for specific applications. In addition, as described in the following steps, specific knowledge areas that are required to achieve the outcomes are also addressed as spirals, i.e., each knowledge area is revisited at increasingly advanced levels through the curriculum. Thus, the spiral concept is used at different scales throughout the curriculum.

Step 2. Develop concept maps: For each of the four outcomes resulting from step 1, we identified the subject matter expertise that would be needed to attain that outcome. We used concept maps to identify knowledge areas related to each outcome. The resulting knowledge representation diagrams (figure 2) provide a visual representation of the knowledge areas that would need to be included in the curriculum. The arrowheads in figure 2 point to the order in which the knowledge should be acquired. For example, methods to evaluate material properties should be known before designing materials handling systems and deciding on the type of raw materials needed in the reactor. When arrows point in both directions, the knowledge acquisition becomes interdependent. At this step, we focused on the general knowledge areas and identified

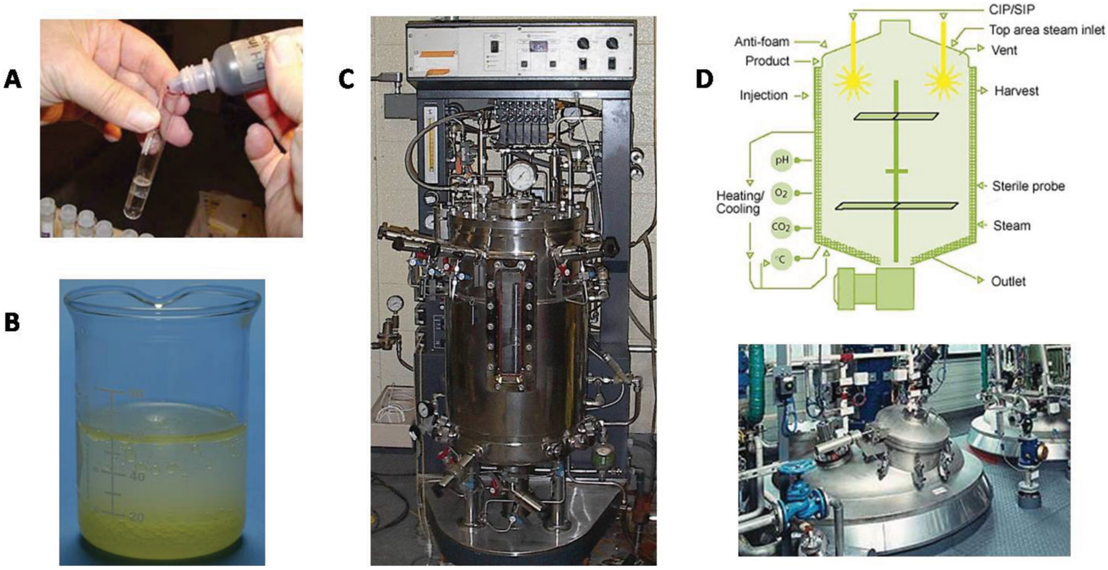

Figure 1. Spiral Concepts for Reactor Design. (A) First the reaction is demonstrated (enzyme hydrolysis) in a test tube. (B) Next step, reactions happen in a beaker (C) Further along, reactions happen in a lab scale fermentation system, and (D) design of a large scale fermentation system.

those knowledge areas that are common to multiple outcomes and those that are unique to a single outcome.

Step 3. Identify knowledge for each outcome at different levels: For each subject matter or knowledge area identified in step 2, we identified the specific topics about which students need to be knowledgeable to attain each outcome. We identified these knowledge areas for four levels (I, II, III, IV) of the curriculum. While the four levels can be regarded as freshmen, sophomore, junior, and senior levels, considering them as knowledge levels provides more flexibility in curriculum development. For example, a student needs to acquire knowledge level II for a particular area before moving onto level III in that area; these two levels could occur within a single course or within subsequent courses, not necessarily in subsequent years. To illustrate this step in the curriculum development process, consider the knowledge area "mass, energy, and momentum transfer," an important area for outcome 1, design a reactor, (also for outcome 2, design a process and optimize the process conditions), since all processes involve mass, energy, and momentum transfer. We identified the mass, energy and momentum transfer concepts about which students need to be knowledgeable (Table 1). We recognized that students should be introduced to some of the concepts at one level

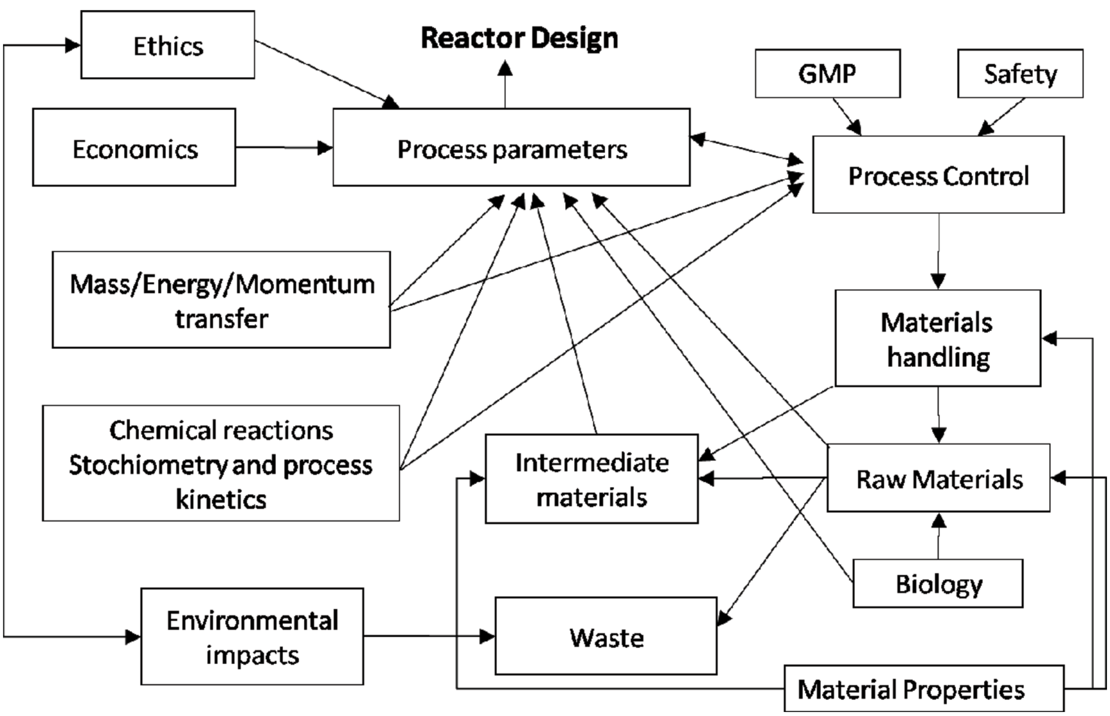

Figure 2. Knowledge areas and their relationship to outcome 1, Design a reactor.

and then again at the next level, thus providing a spiral within the knowledge area, i.e., specific concepts are revisited at a more in-depth level as students move through the curriculum.

Step 4. Develop spiral learning objectives: For each knowledge area, we wrote specific spiral learning objectives to define the specific knowledge and skills that students need to have in order to attain the overall outcomes. Increasing cognitive levels are included moving from level I to II to III to IV. For example, spiral learning objectives for outcome 1, design a reactor, are given in Table 2.

Step 5. Develop learning modules: The term "learning module" was used to describe a combination of learning activities that would facilitate student achievement of a set of learning objectives. Each module also included activities to assess student learning. Because we had an existing bioprocess engineering curriculum, faculty members had already developed and were implementing a number of learning activities on many of the subjects that are included in the spiral curriculum. To capitalize on existing material and to maximize efficiency, we started this step by comparing the spiral learning objectives developed in step 4 ("develop spiral learning objectives") to the course learning objectives of existing courses in the curriculum. The results indicated which spiral

Knowledge Level	Topic Covered
I	Physical and chemical principles (matter, energy, momentum)
	Forms of energy
II	1st and 2nd laws of thermodynamics
	Control volume concept
	Fluid Mechanics
	Phase change phenomena
	Simple mass and energy balance
III	Heat transfer
	Steady state and unsteady state heat transfer; Modes of heat transfer)
	Mass transfer
	Steady and unsteady state mass transfer
	Momentum transfer
	Mass and energy balance in transfer operations
IV	Simultaneous heat, mass and momentum transfer
	Mass and energy balance in Reactor design
	Simulation of a Bio-reactor operation using Process simulation software (mass and energy balance)

Table 1. Topics needed at different levels for the mass/energy/momentum transfer area.

objectives we were likely to already have some learning activities for and which ones were new. We developed module-building teams for different groups of learning objectives. A team typically included a BSE faculty member already teaching in the respective area, an EngE faculty member, an education faculty member, and additional BSE faculty members and graduate students. Each team drafted modules to facilitate student learning of a group of learning objectives. Project PIs and the specific instructors then finalized the various modules.

Step 6. Incorporate the modules into existing courses: The spiral curriculum is comprised of learning modules, however, at our university, subject matter is organized into courses. Thus, we had to either incorporate modules into existing courses (step 6) or combine some number of modules

Level	Learning objectives
I	1. Demonstrate a basic understanding of the design process
	2. Demonstrate basic facility with hands on design and design evaluation, accomplished by working in teams;
	3. Apply the scientific method to problem solving including use of software where applicable;
	4. Demonstrate an understanding of the engineering design process
II	1. Identify the components and modes of operation of a bioreactor
	2. Describe the functions of a bioreactor
	3. Describe types of reactions (exothermic/endothermic) and reaction rate
	4. Describe role of enzymes in a reaction
	5. Describe ways to inhibit/control enzyme in a reaction
	6. Explain relationships between enzymes and their products
III	1. Identify material needs to sustain a reaction
	2. Explain the characteristics of enzymes and microorganisms
	3. Describe the process of isolation of enzymes from specific microorganisms
	4. Describe modes of bio-reactor operation
	5. Describe the impact of reaction parameters on microbial systems
	6. Monitor reaction parameters effectively
	7. Explain relationships between microorganisms and their products
	8. Calculate mass and energy balances for a bioreactor
IV	1. Design a control system for reactors
	2. Design a bioreactor with material constrains: pressure, temperature, corrosion, and contamination, and safety
	3. Explain environmental impact of reaction products, co-products, byproducts
	4. Evaluate economic and technical feasibility of a bioreactor
	5. Optimize the productivity the bioreactor by utilization of concepts such as immobilization, cell recycle, stripping, etc.
	6. Design a scheme for product separation
	7. Design a product purification scheme

Table 2. Spiral learning objectives for outcome 1, Design a reactor.

into new courses (step 7) to work within the existing structure. Some modules have been completely developed and implemented into existing courses. For example, the first learning module that we developed focuses on level II spiral learning objectives for outcome 2, design a process. We began with two laboratory exercises that were already being conducted in the sophomore level *Introduction to BSE* course, which is required for all BSE students who can earn a general BSE degree or specialize in either the bioprocess engineering option or the land and water resources engineering option. Each of the two laboratory exercises was being conducted as a stand-alone activity. The students were given little explicit guidance as to how the exercises were related to each other and how they were related to the broader BSE discipline. By building a learning module around those two exercises, we created a context to enhance student learning and to progress along the spiral. Our first step in designing the module was to encompass a much broader perspective by changing "design a process" to "design a system." A process has several units (unit operations); similarly, a system is comprised of multiple components. Thus, the spiral learning objectives addressed in the module are: (i) define what a process/system is, (ii) differentiate between a component/unit operation and a system/process, (iii) identify the components (unit operations) of a system (process), (iv) draw simple system diagrams (process flow sheets), and (v) perform simple mass balances for a system (process). The learning activities included in-class presentations, group activity, laboratory activity, individual homework and laboratory reports, and individual assessment through a post-laboratory test. The in-class presentation included information about the BSE discipline to give context for the terms "system," "process," "unit operations," "building blocks," and "components." The in-class presentation also included descriptions of natural and constructed systems/processes as well as discussion about building systems and breaking them down. The group activity involved breaking systems/processes into components and compiling examples from individual students to lead a full class discussion with instructor feedback on examples and further clarification of operations and processes. The laboratory activity included two different experiments: oil extraction process and hydrologic system. The oil extraction experiment includes extraction and purification of the oil from cotton seed. The hydrologic system experiment includes a rainfall simulator and runoff boxes to determine how runoff varies depending on the type of vegetation and degree of slope. Individual assessment of student knowledge of operations/processes prior to conducting laboratory exercises included quizzes to match terms and definitions. The learning activities occurred over a four-week period. Intentional incorporation of additional learning activities (group activities, in-class discussions, post-tests, etc.) enhanced the student learning process and made them connect various elements of the profession in the context of systems, components, and flow diagrams linking the inputs and outputs in the system.

We incorporated the module into an existing sophomore course, *Introduction to BSE*. This was straightforward because the major activities, the two laboratory exercises, were already part of the existing course, so the structure of the course did not require change.

Step 7. Develop new courses to include the modules: When we compared the spiral learning objectives to the learning objectives for existing courses, we identified some spiral objectives that are not included in existing courses. Some of those spiral objectives were included in learning modules for existing courses; however, in some cases, there was enough new material to be incorporated into a new course. For example, a number of the learning objectives for outcome 4, control a process, are not included in the non-spiral curriculum. Thus, we needed to develop modules for those spiral objectives. For level II, those modules were incorporated into the existing sophomore course. For levels III and IV, some of the modules were grouped into a new course, taught for the first time in spring 2008 that focuses on instrumentation for biological systems. The other level III and IV modules will be incorporated into existing courses, particularly the Plant Design course. The new, BSE only, instrumentation course replaced the required instrumentation course in the BSE curriculum that was taught for some time by Engineering Science and Mechanics (ESM) and taken by both BSE and ESM students. The new course more closely meets the needs of BSE students by addressing the spiral objectives and focusing on biological systems.

Steps 5, 6, and 7 are often iterative, as we found in our experience. We did not develop all of the learning modules and then incorporate them into existing or new courses. Rather we developed a module and implemented it. This helped guide our development of the next module. These steps helped the core development team develop guidelines for the broader module teams to use in developing subsequent learning modules. Development and implementation of modules is an ongoing process. It takes a significant amount of time to fully reform a curriculum; we are still working towards complete implementation of the spiral curriculum.

Assessment activities have been initiated to determine if the students have attained the four high level outcomes of the spiral curriculum and if they have attained the outcomes “better” than they did with the non-spiral curriculum. Face-to-face interviews with graduates of the bioprocess engineering option in BSE and comparison of student work in various courses before and after implementation of the spiral curriculum are two of the assessment tools being used. Assessment data are being collected, but are not sufficient to allow conclusive evaluation of results yet.

The B.S. program in BSE is accredited by the Engineering Accreditation Commission of ABET. We were conscious of accreditation criteria while we were revising the curriculum. The revised curriculum and increased assessment within courses provides ample opportunities for students to demonstrate, and for faculty to evaluate, attainment of the outcomes specified in the engineering criteria. We anticipate no difficulty in continuing to meet the accreditation criteria.

SPIRAL THEMES: ETHICS AND HANDS-ON LABORATORIES

In addition to the four outcomes-based themes of the spiral curriculum, a professional knowledge and skills theme, including ethics, teamwork, and hands-on laboratories, was woven throughout the BSE curriculum. These skills are applicable to all engineering disciplines so the spiral experiences to develop these skills begin in the freshman year in the GE program. This way each engineering department has an option to continue the spiral as it chooses. To illustrate how that is done in BSE, we focus here on development and implementation of an ethics spiral.

Ethics Spiral

Prior to the spiral curriculum development, there were limited formal activities in the BSE curriculum that addressed ethics instruction. Most of the ethics learning activities happened in an informal setting. The formal coverage of ethics happened in the freshman year (i.e., GE program) and then during the capstone design experience in the senior year. In order to weave ethics throughout the curriculum in a spiral fashion, we identified several such opportunities and developed a set of learning modules on ethics for the BSE curriculum (Table 3). With increasing learning levels, students are given the opportunity to explain ethical dilemmas with more ambiguous and conflicting information.

In association with the oil extraction experiment that is part of the systems module at the sophomore level, students are given an overview about genetically modified (GM) plants to offer herbicide resistance so that a particular herbicide could be applied in the field to remove weeds without killing the plant. This leads to discussion of issues about genetically modified organisms (GMOs); one ethical issue discussed concerns labeling of GM products. Students are asked to discuss these cases using moral theories such as utilitarianism and rights ethics. As part of their written assignment, when asked to identify possible ethics topics related to the BSE discipline, students mentioned environmental issues, food safety, genetically modified products, cloning, animal rights and biopharmaceuticals. More details are discussed in [32].

Level	Moral Theories	Case Studies	Learning Activities
I	utilitarianism ethical egoism rights ethics	Public health International laws Making tradeoffs Natural disasters	"Incident at Morales" video chapter in a textbook ePortfolio assignment Team project
II	utilitarianism rights ethics prima facie duties	Herbicide resistance GM food allergens Labeling laws	flow chart line drawing class discussion
III	utilitarianism ethical egoism rights ethics prima facie duties virtue ethics	Beltsville pigs BST in dairy cattle	online discussion flow chart classroom presentation portfolio assignment
IV	Utilitarianism ethical egoism virtue ethics	Gene patenting Terminating gene Food irradiation Waste treatment Food ingredients	flow chart or line drawing identify moral theories used online discussion in-class discussion

Table 3. Ethics Spiral in BSE.

During junior year, as part of the required BSE professional development seminar course, students conduct literature reviews of a variety of topics related to the discipline. In the past, only a fraction of the students addressed the ethical implications and challenges of the topics they chose. Effective fall 2010, we will formalize inclusion of ethical issues by requiring students to address ethical issues related to the topics they choose. Students conduct peer reviews of the literature; this process will be expanded to require specific evaluation of multiple ethical issues. In this way, students will be exposed to additional ethical situations and be given the opportunity to reflect on them.

During the senior year, in addition to the ethics activities related to the capstone design experience, students are given an opportunity to analyze an ethical dilemma about questionable food ingredients in prepared food products. The roles of the consumer, the government agency, and the food manufacturer in addition to complex and conflicting issues related to who should be held responsible for societal health issues are considered. Pre-and post-tests are administered on issues such as who should be responsible for health problems from prepared food products: the consumer, the government or the manufacturer. These tests indicated that a majority of students did not change their opinion about who should be responsible for safety of food products in terms of questionable food ingredients. However, more students felt after the activity that consumers should be held responsible for the food they eat. More details can be found in [33].

Our anecdotal experience in implementing ethics modules over the last three years suggests that students typically consider money, individual careers, and public safety as the key factors in deciding what to do in an ethical situation. In-class discussions on ethical issues are quite productive as this provides students an opportunity to see that not all of their classmates share the same opinions as theirs.

Hands-On Activities In Freshman Engineering

Another example of spiral linkage between GE and BSE programs is enhancement of hands-on laboratories in both programs. As described previously, hands-on activities remain an important part of the spiral curriculum in bioprocess engineering. As part of the DLR project, we developed and implemented a number of hands-on learning activities in the GE program in the spirit of *early legitimate participation*. These activities were primarily implemented in the freshman engineering course “Engineering Exploration EngE1024”, which is the only common engineering course that all undergraduates, including BSE students, in the CoE take. The course primarily focuses on developing problem solving, critical thinking, and engineering design skills. The delivery format includes a 50-minute lecture with a 90-minute hands-on workshop each week. Assessment of learning outcomes of these activities became an integral part of the activity development as a result of the DLR project. A few examples of workshops are discussed next.

Mechatronics: To give meaningful hands-on learning experiences related to Electrical, Computer Science/ Engineering and Mechanical Engineering to freshmen, a "mechatronics" workshop was piloted in spring 2006 with approximately 180 students in EngE1024. Since then, approximately 5,000 engineering freshmen have participated in this workshop. Students build a 2-wheel robot (figure 3) using several mechanical (gears, wheels, shafts, etc.) and electrical (resistors, capacitors, motor driver integrated circuits, breadboard, battery, diodes, micro switches, etc.) parts. A pre-workshop assignment was designed to assess the "prior knowledge" of students and a couple of self-explanatory PowerPoint presentations were made available to students through the class website. A detailed video presentation that explains the entire robot assembly process was developed and made available to students. Assessment data were obtained using an instant classroom response system (i.e., clickers), and in-class assessment worksheets [34]. In fall 2006, a voluntary survey was given to the students to assess students' prior experiences of working with mechanical and electronic parts. Of the 723 students who responded, 595 were male (82.5%), 120 were female (16.6%), and 8 elected to not report their gender. Of those responding, 426 (59.3%) indicated no prior experience working with breadboards or electronic components. On average, students reported that it took 24 minutes to build the motor driver circuit. As expected, students without prior

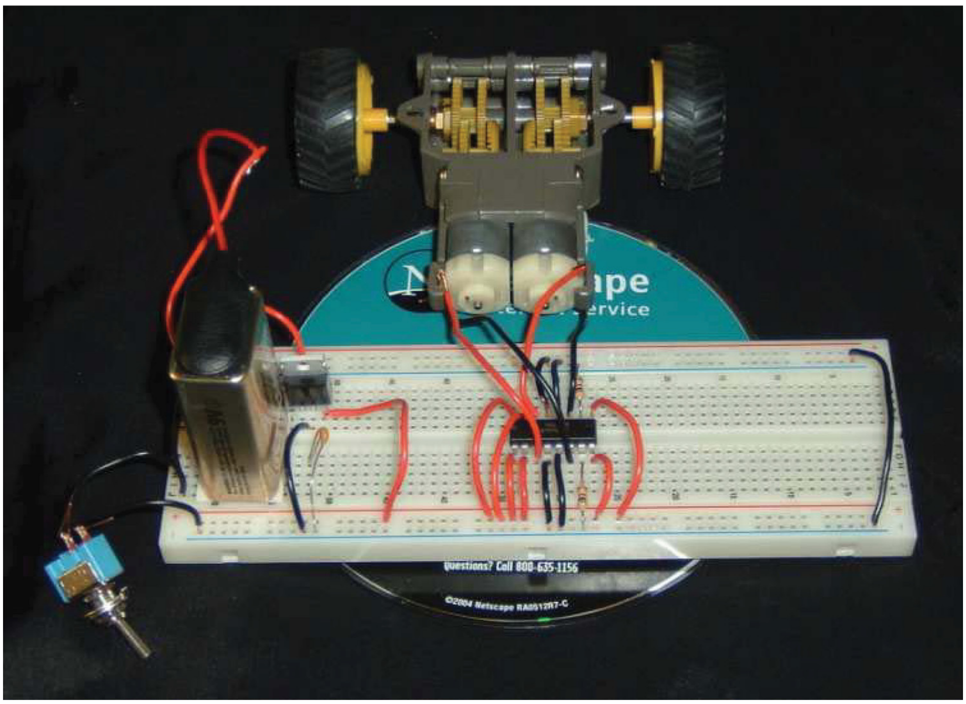

Figure 3. Two-wheel Robot.

experience took a bit longer to assemble the circuit than those with prior circuit building experience (25.9 minutes on average for those with no prior experience as compared to 21.4 minutes for those with prior experience). A larger portion of males (41.9%) indicated prior experience working with circuits and breadboards when compared to their female counterparts (32.5%). Overall perception of the mechatronics activity was independent of gender, with the majority of students indicating a good or excellent perception of the activities. Detailed analysis of students' responses is given in [35]. Students also recommended including some challenging activities as part of this workshop that would promote critical thinking skills. Therefore, an advanced version of this workshop was developed and implemented in EngE1024 in spring 2009. Details are given in [36].

World Map Activity: This activity was developed to introduce critical global issues like energy, population, and environment to students. In this workshop students are provided with a world map, Lego blocks, and data (i.e., population, growth rate, oil production and consumption) for several countries and are asked to construct three-dimensional models of population, oil supply and oil demand (figures 4A & 4B). For example, in fall 2008, relevant data were provided for Brazil, India, China, USA, Nigeria, and Russia. One of the topics in EngE1024 includes fitting linear, power, and exponential functions, using the method of selected points and least squares regression. Students use the real-world data, for example, on population growth, literacy rate from various countries, and price of a barrel of oil over the years, to fit these functions. The key advantage of this module is that it provides a hands-on exercise to help students better visualize the real-world data. Results from a spring 2008 post-activity survey showed that this activity improved students' global awareness and motivated them to pursue green engineering practices (figure 5). More details are provided in [37].

Sustainable Energy Design Project (SEDP): Piloted in fall 2006 with 1200 freshmen, a Sustainable Energy Design Project (SEDP) has been successfully implemented in EngE1024 for the last eight semesters. Student teams are asked to design and construct a "promotional invention" that promotes awareness of a renewable energy source. Each team of 3–5 students selects one of five renewable energy sources, i.e., hydropower, geothermal, solar, wind, and biomass, based on the team's interest and research. Teams are instructed to assume that the audience is the general public, who may have limited knowledge of renewable energy sources. Student teams are instructed to consider the following parameters in creating design solutions: *(i) It should be functional, safe, and interesting; (ii) It must highlight one or more key components of a renewable energy source; (iii) It should strive to educate and entertain as well as generate further inquiry and interest in renewable energy sources; and (iv) It should aim to have broad appeal across gender, age, race, and nationality.* Students are coached to follow various steps of the engineering design process in this 8-week long design project. Instructions are provided for online collaboration using Tablet PCs and Microsoft OneNote software to share design ideas [38] and create design logs and design briefs in support

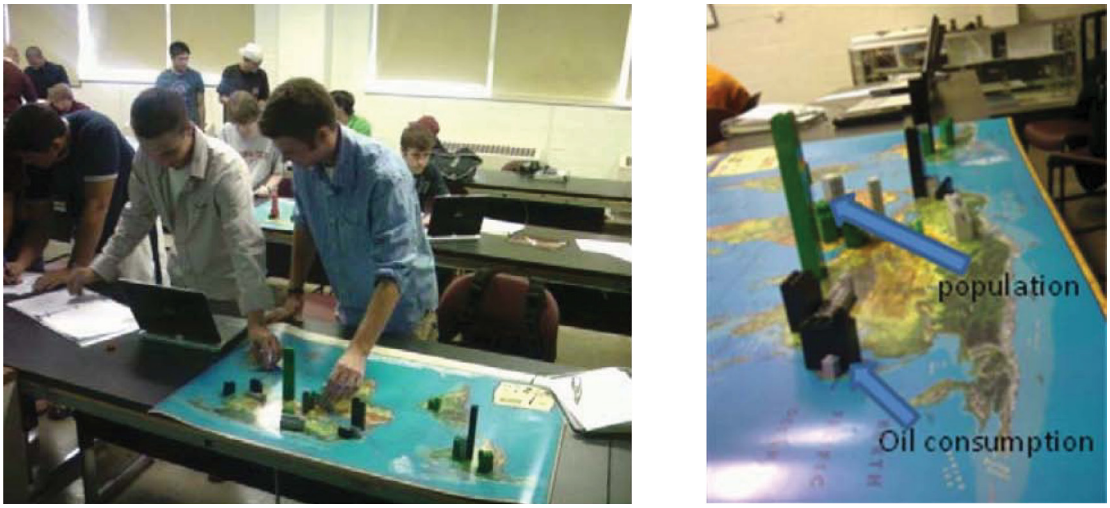

Figure 4. (A) Students Taking Part in World Map Activity. (B) Lego Blocks showing Population and Oil Consumption Dat.

Survey Question: Did the representation of oil consumption, production and world population using legos help you visualize these numbers better?

Survey Question: Oil production, consumption and economic impact were the crux of last week's activity: Do you believe that this activity has initiated/encouraged you to think of "green" engineering methods for the future?

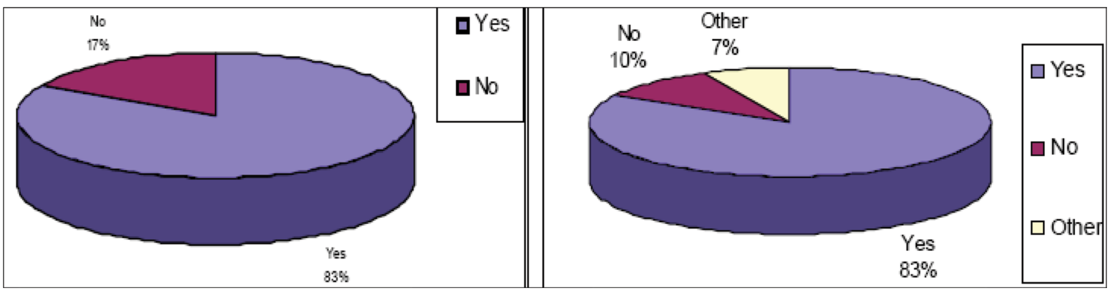

Figure 5. World Map Post-activity survey (Spring 2008, n = 30).

of the final designs. The project includes both individual (e.g., research questions on potential of renewable energy sources, design sketches, etc.) and team (e.g., brainstorming activity, design report, class presentation, etc.) assignments. Students are allowed a budget of $20 per team for completing their designs. In fall 2007, the DLR investigators organized a sustainable energy design showcase to select the top three designs out of approximately 300 designs. Figure 6 shows two winning designs covering hydropower and solar energy sources.

Most of the student designs only addressed parameters (i) through (iii) as listed above. A detailed grading rubric is used to grade the design project reports and it does not include any direct references to parameter (iv) (i.e., *It should aim to have broad appeal across gender, age, race, and nationality.*). This is one of the challenges we face in implementing this project. Table 4 shows results from three course exit survey questions related to the SEDP. A majority of students felt they benefited from their experiences with SEDP and appreciated the relevance of sustainability as part of their early design experiences.

More details on the SEDP implementation including additional assessment data can be found in an award winning paper titled *"Sustainable Energy Design Projects for Engineering Freshmen"* at the 2007 Annual Conference of the ASEE [39].

Basic programming skills: Approximately half of the engineering freshmen join our engineering program with prior programming experiences and half without such experience, which presents a major challenge to design programming instruction for EngE1024 instructors. Prior to fall 2004, EngE1024 included MATLAB instruction for developing logical thinking and basic programming skills. In fall 2004, MATLAB was replaced with a programming language called Alice (www.Alice.org). Alice provides a completely new approach to learning programming concepts as it uses 3D Interactive Graphics Programming Environment to teach fundamentals of programming; it has been used in introductory programming courses in computer science. A number of engineering programming activities (e.g., simulation of a sine wave, simulation of a circular motion of an object, simulation of a motion of a pendulum) were developed and implemented using Alice [40]. While several

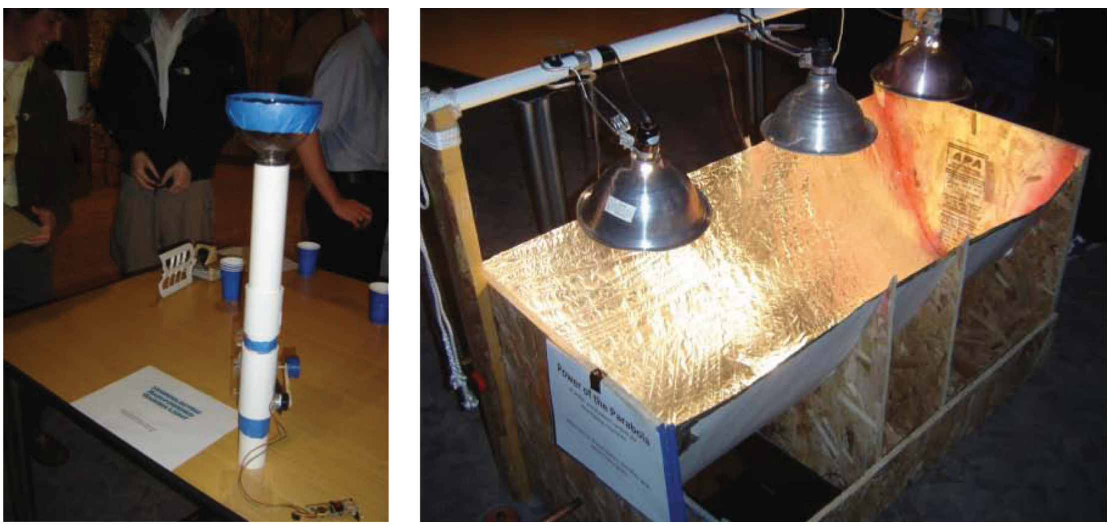

Figure 6. Rain Powered Garden Light (HYDRO) and The Power of Parabolas (SOLAR).

Question	Semester (number of respondents)	Percent of Responses					
		SA	A	N	D	SD	NA
I see the relevance of sustainability in engineering design.	Fall 2007 (n = 536)	43	47	6	1	2	1
The SEDP is a good way to introduce sustainability concepts into freshman engineering.	Spring 2008 (n = 49)	41	53	4	2	0	0
	Fall 2008 (n = 314)	18	45	19	12	5	1
My understanding of the engineering design process increased as a result of the hands-on design projects in EngE 1024	Fall 2007 (n = 536)	27	49	14	8	2	0
	Spring 2008 (n = 49)	29	51	8	10	2	0
	Fall 2008 (n = 314)	23	53	14	8	1	1

Response key: SA = strongly agree; A = agree; N = neutral; D = disagree; SD = strongly disagree; NA = no answer

Table 4. SEDP related exit survey statements and results.

first time programmers liked the programming approach in the Alice environment and pre-and post-test results showed positive learning gains [41], repeated assessments including focus groups with students showed that students, particularly those with prior programming experience, did not enjoy the Alice programming environment. Based on systematic evaluation of all assessment data, we decided to replace Alice with LabVIEW programming in spring 2007. A summary of lessons learned in the Alice experiment is as follows: (i) When introducing a new programming tool for a freshman class, make sure that the software is free from programming bugs, (ii) Start with a few core programming concepts, particularly in the first semester, and gradually add new concepts and/or applications, (iii) Show real life engineering applications of the programming environment, and (iv) If programming is not a major component of the course, then assigning a programming project involving a student competition is not a good idea, particularly if the class includes a significant number of students with prior programming experiences.

LabVIEW Programming: LabVIEW (**Lab**oratory **V**irtual **I**nstrumentation **E**ngineering **W**orkbench) is a graphical programming language from National Instruments. LabVIEW uses a dataflow programming model in which the output of each computation node is calculated when all the inputs are determined for that node. A LabVIEW program, called a virtual instrument (VI), includes a front panel and a block diagram. A review of literature on use of LabVIEW in classroom instruction is presented in [42]. Following the lessons learned in the Alice experiment we tried gradual integration of LabVIEW core concepts into EngE1024 (figure 7). Students have responded well to LabVIEW instruction and we are currently exploring extension of LabVIEW instruction to cover environmental sustainability [43]. Major programming concepts covered in EngE1024 using LabVIEW are shown in Table 5.

In order to assess student familiarity with basic programming constructs using LabVIEW, a pre- and post- survey was administered during fall 2008. These questions examined students' knowledge of general programming concepts as well as dataflow programming. The average number of correct responses out of 10 questions (n = 676) increased from 5.54 to 6.41; this increase was statistically significant at the .0005 (or 0.05%) level (paired t-test). The authors do realize that the large sample size can be one of the factors in obtaining statistically significant gain. Further, the variance of the scores was reduced from 3.72 (pre-test) to 3.33 (post-test). During the three semesters that LabVIEW was introduced (i.e., fall 2007, spring 2008 and fall 2008), student responses to an open ended question "What have you learned in this class [EngE1024] that you think will be useful in your engineering studies?" revealed that 14-21% of students perceived LabVIEW to be useful in their engineering studies. Further analysis of data indicated statistically significant increase in percentage of students from fall '07 (17%) to fall '08 (21%) who believed that LabVIEW would be useful in their engineering studies [42]. Use of LabVIEW continues in EngE1024 at the time of this writing.

A number of assessment (formative and summative) activities are implemented in EngE1024 as a result of the DLR project to evaluate the learning experiences of engineering freshmen. A variety of survey instruments (e.g., engineering education new student survey; computer attitude survey; learning style survey, adopted from Felder and Solomon [44]; pre-and post-tests on programming

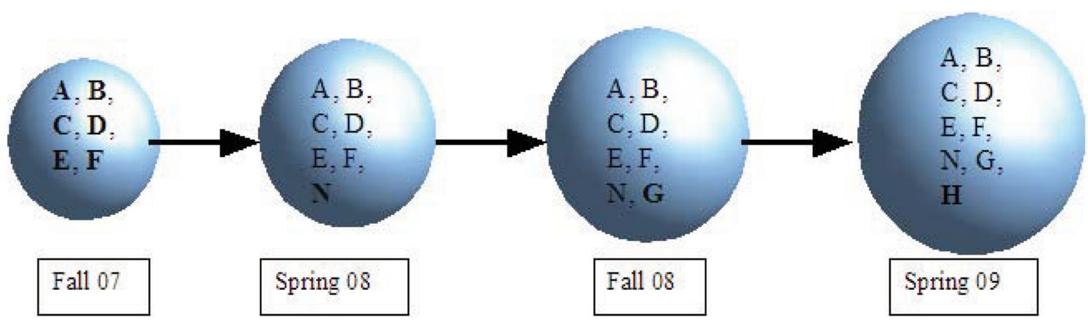

Figure 7. Gradual integration of LabVIEW core concepts/applications into EngE1024 (letters represent LV core concepts/applications, newly introduced items for each semester are shown with bold letters; (see Table 5 for explanation).

LabVIEW (LV) Topic	Activity / Homework
A. Introduction to LV programming environment, VIs	Watching short LV videos that introduce programming environment and dataflow programming paradigm
B. Controls and Indicators, Data Types	-Writing a simple VI for computing class grade using grades in variety of course activities -Observing data flow by execution highlighting
C. Overview of Control Structures in LV; Examples of Repetition and Decision Structures	VI for a water tower problem. In this problem, students develop a VI to calculate height of discharged water in cylindrical and rectangular tanks periodically until the user-entered time is reached.
D. Repetition Structure in LV: For Loop	Students develop a VI for controlling movement of a two wheel robot
E. Boolean Variables in LV	Same as in D in previous row
N: Repetition Structure in LV: While Loop	Nanotechnology activity using LV. In this problem, students develop a VI to plot a potential function for characterizing forces at a nano scale. Also, they used another VI for measuring size of a carbon nanotube.
F: Decision Structure in LV: Case Structure	Students develop a VI to compute letter grades from numerical grades
G: Introduction to data acquisition	Collection and analysis of data from three sensors (temperature, force, and motion) and fitting empirical functions (linear, power and exponential)
H: Publishing a VI over the Internet, acquiring real-time water quality data	Demonstration of water quality data collection and processing activity from server computer connected to multi-probe sonde [43].

Table 5. LabVIEW Concepts/Applications in EngE1024.

concepts; focus groups; and course exit survey) are used to gather student data in support of various curriculum development activities. Results from the learning styles survey (figure 8) show that the majority of the students are active, sensing, visual, and sequential learners. The pattern of learning styles for engineering students at VT is comparable to the pattern reported by Felder and Brent [45] for engineering students from Iowa State University. Also, our experiment with Alice programming and current use of LabVIEW are motivated by the fact that the majority of our students are visual learners.

Examples of additional hands-on activities that were implemented in the freshman course include a water tower activity designed to discuss basic principles of fluid flow [46], a Darcy's Law activity designed to address basic principles of flow through porous media [47], and a systems activity designed to introduce systems concept to freshmen [48]. The variety of activities in the freshman course provides many choices for the different engineering programs to use as a base in their programs. For example, sustainability is a central theme of the BSE program, so the world map activity and the sustainable energy design project are part of the spiral in BSE. LabVIEW is also used in the BSE spiral for the outcome on controlling a process, with significant use in the new instrumentation course.

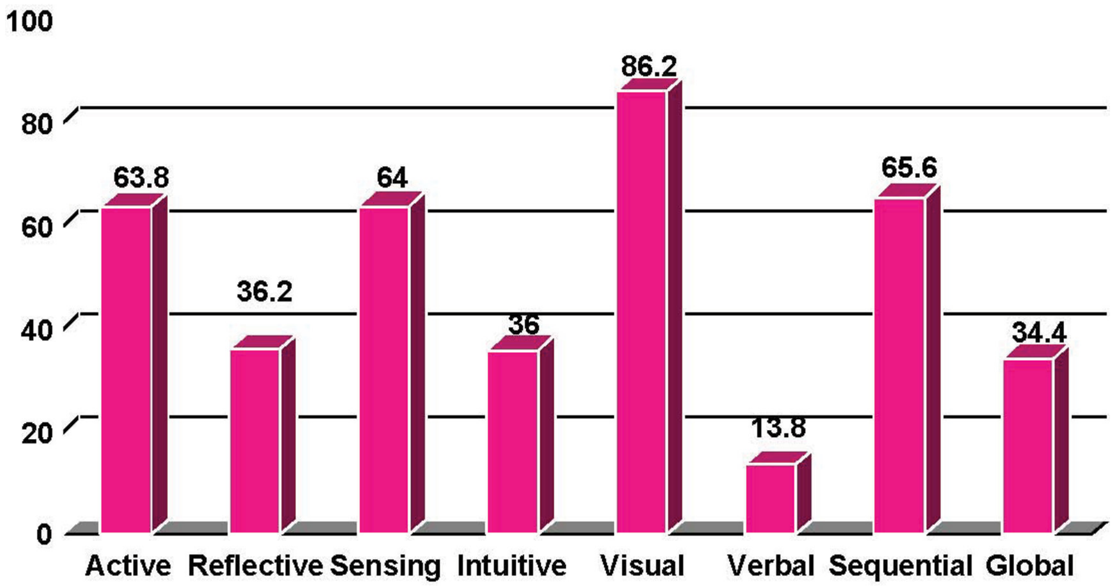

Figure 8. Learning Style Preferences – Percent of Engineering Freshmen at Virginia Tech.

DISCUSSION OF SPIRAL DEVELOPMENT AND IMPLEMENTATION

While the spiral development process worked pretty well for us, we did encounter challenges. One of the challenges was getting faculty to think about the bioprocess curriculum as a blank slate. It is difficult for many faculty members to let go of the existing curriculum, even figuratively. With time and effort, we were able to get most faculty members to embrace the clean slate idea and identify everything we thought the students needed to know without considering the existing curriculum. Yet, there were sometimes questions about something that is in the current curriculum that did not show up in the proposed curriculum. The idea of removing content from the curriculum was difficult for some to accept. Another significant challenge has been designing appropriate schemes for assessment that would allow us to collect appropriate data without burdening faculty and students in the data collection process. We have had assistance from our university academic assessment office, and are continuing to work on developing appropriate tools that the faculty are willing to take the time to implement on a consistent basis. Some aspects of the assessment process have worked very well, e.g., assessment related to individual modules and activities, while others are more difficult, e.g., overall spiral assessment.

We have conducted four hands-on workshops to share our spiral curriculum development process with educators within and outside the US (Table 6). The majority of those participants were enthused about the characteristics of a spiral curriculum and many expressed interest in implementing it in some way in their own program. They also expressed concern about the challenges we faced. Some wondered about difficulties in working across engineering departments and education. In our case such interdisciplinary collaboration worked very well. It is a matter of having people from each unit being fully committed to the process. We had no trouble having a fully committed core team; gaining the commitment from other faculty members was challenging at times. We tried to maintain the commitment from faculty by keeping the focus on the overall goal of producing better prepared graduates, which is a goal most, if not all, faculty members share.

Another challenge that we faced is that curriculum reform is not seen generally as a scholarly activity, particularly in engineering departments. This is an attitude that is changing in our CoE. The Department of Engineering Education was established at about the same time as this DLR project. The EngE faculty has grown and has been very successful in obtaining external funding, including CAREER awards, for engineering education research and scholarly activity. This is helping to change the attitude toward curriculum reform as a scholarly activity. As noted earlier, the development of learning modules for the bioprocess engineering spiral curriculum is ongoing and implementation of the full spiral is not yet completed. We learned that it takes considerable time to implement such a significant curriculum reform. It is challenging to sustain the effort now that the funding period is over. The committee structure and general attitude in the BSE department allows us to keep the spiral curriculum on the minds of everyone, however, the effort is more sporadic now than continuous, as it was during the funded project.

The spiral curriculum approach has been extended to several endeavors at Virginia Tech. In 2008, a nanotechnology option was developed within the Department of Engineering Science

Spiral Curriculum workshop venue	Participants
2007 ASEE Conference, June 24, 2007, Honolulu, Hawaii	Approximately 15 engineering educators including one faculty member from Korea
Univ. of Texas at El Paso (UTEP), August 24, 2007	Approximately 25 engineering faculty members and graduate students from UTEP
National Cheng Kung University (NCKU), Tainan, Taiwan, Aug. 05-07, 2008	Approximately 30 faculty members and graduate students from NCKU
Short Course organized by Indo-US Collaboration on Engineering Education, July 06-10, 2009, Mysore, India	Approximately 22 faculty members from various Indian engineering colleges

Table 6. Spiral Curriculum Workshop by DLR Project Investigators.

and Mechanics (ESM; www.esm.vt.edu) using the spiral curriculum approach. This effort is coordinated by nanotechnology and engineering education experts and is funded through the NSF Nanotechnology in Undergraduate Education (NUE) in Engineering program. A discussion of various learning modules that are being implemented to establish the spiral theory based nanotechnology option is provided in [49]. In addition, the DLR project investigators presented their spiral curriculum experiences at an ethics workshop that was organized in June 2009 on the VT campus as part of another NSF project under Ethics Education in Science and Engineering (EESE) program. The objective is to extend the ethics spiral approach from GE and BSE programs to other engineering programs [50].

CONCLUSION

The DLR project is the first collaborative project between two engineering departments and School of Education faculty members at Virginia Tech. This project enabled engineering faculty members to apply the well established spiral theory to rewrite the curriculum of the bioprocess engineering program within the BSE department. The reform efforts increased the dialogue among engineering and education faculty members. Further, it pushed faculty members to adopt student-centered methods, including teaming, interactive learning, and lectures integrated with team-based, hands-on exercises by encouraging risk taking in teaching. The GE program is better integrated with the curricula of engineering departments and assessment practices have become a norm within the program. Faculty members have a new found appreciation for collaborating with other disciplines, primarily education, and the spiral curriculum framework is extended to other engineering departments within the CoE to develop a nanotechnology option and integrate ethics across the curriculum. The lead author coordinated a graduate course on 'global and ethical impact of emerging technologies' in spring '10 and students are exposed to spiral curriculum theory in this course and are assigned to design ethics learning modules using spiral approach [51]. Further, new collaborative activities of the lead author with the director of a university level research institute (*Institute for Critical Technology and Applied Science*) led to his adoption of the spiral approach for promoting interdisciplinary research at this institute [52]. We describe lessons learned in three key words: (i) *Patience* – Reformulation results may take time to show up, (ii) *Diligence* – Assessment results are powerful, take these seriously, and (iii) *Awareness* – Students' perceptions may be difficult to interpret. Lastly, we recommend to the NSF that curriculum reform efforts like the ones targeted in the DLR program should be funded for at least six years. Also, NSF should consider developing follow-up programs that will enable investigators to seek funding for developing projects that will track the long-term impacts of such curriculum reform projects.

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