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The Implementation of a Challenge-Based Curriculum into a Bioprocess Engineering Program*

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The newly created concentration in bioprocess engineering at East Carolina University was developed with a novel curriculum designed to engage the students and improve their mastery of concepts using proven pedagogical approaches. This study presents the development of nine instructional modules for three bioprocess engineering courses (three modules per course) and the assessment of the effectiveness of the instructional modules. Each module is initiated by presenting the students with a challenge question. The students work on the challenge by completing a cycle of exercises that are designed to engage critical thinking and self-assessment, and for making connections among concepts within the course. The module culminates with students presenting their 'answer' to the challenge through various means, such as a report, poster, video, exam, etc. Of the nine modules, three are integrated through the different bioprocess engineering courses. This integration provides a theme for the students to make connections among the different courses and to transfer concepts to new situations. Our work sought to provide the answers to two research questions: 1) Did the students master the facts, skills, and concepts of bioprocess engineering through the use of the modules? and 2) Did the use of the modules create an effective How People Learn (HPL) learning environment within the three bioprocess engineering courses? The results of the assessment indicate that the modules were effective in developing the students' mastery of the facts, skills, and concepts across all three courses and created a very effective HPL learning environment in two of the three courses.

Keywords: bioprocess; problem-based learning; challenge-based learning; legacy cycle; concept map; How People Learn

1. Introduction

There are many efforts underway within STEM education to move away from traditional lecture methods of delivery towards more novel methods designed to engage the students in the learning process [1–4]. In many cases, these methods are taking the How People Learn (HPL) concepts from theory to practice. The National Research Council [5] proposed four 'centeredness' aspects that, taken together, optimize learning: *knowledge-centeredness*, *student-centeredness*, *assessment-centeredness*, and *community-centeredness.* First, the learning environment must be *knowledge-centered*; that is, appropriate information should be presented in an appropriately sequenced and organized way. Second, the environment must be *student-centered*. Lessons should seek out students' prior conceptions and misconceptions, help students make connections with prior knowledge, and be relevant to students' own lives. Third, the learning environment must be *assessment-centered*; it should include opportunities for formative feedback for both students and instructors. Students benefit from opportunities to check their own understanding and instructors benefit from opportunities to assess the effectiveness of their teaching. Summative assessments must accurately reflect stated learning objectives and should be authentic. Finally, a learning environment must be *community-centered*, one in which students are provided opportunities to learn collaboratively. Studies show that when these four centeredness aspects are in place, students increase both their content knowledge and their ability to apply that knowledge in new situations—i.e., their *adaptive expertise* [6–11].

One particular approach to improve the efficacy of teaching STEM material is through the use of The STAR.Legacy Cycle (also called the Legacy Cycle). The Legacy Cycle was created as a means of implementing the HPL ideas in the classroom [12]. The Legacy Cycle incorporates the four centeredness aspects by providing a rich, contextually-based problem, relevant in some way to students' lives, and allowing students to engage deeply with that problem in ways that include opportunities for collaboration with other students and for self-assessment.

The Legacy Cycle consists of six phases; Challenge, Generate Ideas, Multiple Perspectives,

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Research and Revise, Test Your Mettle, and Go Public. In the *Challenge* phase, students are presented a problem that they are to solve. From the problem statement, the students are encouraged to generate ideas in a brainstorming session. During this *Generate Ideas* phase, the instructor accepts all ideas without criticism or comment. Following the *Generate Ideas* phase, the students are steered towards the desired path by receiving multiple perspectives on the subject. These could be pre-recorded opinions of known experts, excerpts from journal articles, or a quick visit to a website. In any case, the *Multiple Perspectives* phase is intended to be short and immediate, and requires pre-planning from the instructor. After the students obtain the additional insight and intended steering of the multiple perspectives, they move into the *Research and Revise* phase. This is the phase in which most of the teaching and learning occurs. This phase could consist of student-driven research and experimentation, passive lectures, homework assignments, or any other combination of concept delivery. During the *Research and Revise* phase, the students will occasionally test their mettle. In the *Test Your Mettle* phase, the instructor will implement formative assessment to evaluate the students' understanding of various concepts. The formative assessment provides the instructor the opportunity to revise the lessons and assignment to ensure any student misconceptions are resolved. Finally, the students answer the challenge through the *Go Public* phase. The *Go Public* phase is intended to provide summative assessment of the students' performance of the challenge. Table 1 provides a summary of each phase of the Legacy Cycle and examples of content and activities used to support the phase.

Engineering curricula utilizing the Legacy Cycle design have been successfully developed and implemented within the college engineering classroom [13, 14]. Roselli [15] and Pandy [16] have demonstrated the efficacy of the Legacy Cycle in biomechanics education. Upon implementing Legacy Cycles, Roselli's biomechanics class saw an increase in both student ratings of the course and instructor on evaluations as well as an increase in the under-

Table 1. Legacy Cycle Phase Summary and Examples [13]

Phase	Summary	Examples
Challenge	A question that causes students to wonder about the topic and become engaged with it. The question frames the module and requires students to bring to bear their current knowledge and preconceptions about the topic.	Examples (science): • Your grandmother is recovering from a broken hip. In which hand should she hold a cane to help her balance? • Assume you are a living cell in a bioreactor. What things will influence/determine how long you live?
Generate Ideas	A whole-class activity that causes students to display and compile their current knowledge/ideas/perceptions. Note that this can also be done in the form of questions: What things would you need to know to answer this question? What additional information would you like to have to help you answer this question?	Possible activities (all should include some type of written record): • Individually writing a narrative • Whole-group brainstorming • Small group brainstorming with public sharing • Think-write-pair-share • Think-write-pair-shared-squared with public sharing.
Multiple Perspectives	Two or more outside resources that provide information related to the topic of the challenge. (These tend to 'point students in the right direction' for further inquiry.)	Possible sources: • Outside expert (live, on video, or in transcribed paragraph[s]) • Web site(s) • Textbook excerpt • Magazine article • Clip from scientific video
Research & Revise	Additional information that students receive/seek. This may be in the form of lecture, readings, websites, etc. Students revise their original ideas based on new information (often includes students' journaling regularly).	Possible venues: • In-class lectures • Textbook and other readings • All others listed in Multiple Perspectives
Test Your Mettle	A set of activities in which students engage to help them explore their depth of knowledge. The goal is to create formative assessment situations that help them evaluate what they do not know so that they may return to the Research & Revise step again to learn more.	Possible venues: • Seek feedback from other students on product • Seek feedback from the instructor on product (poster, essay, game, practice test, role play, etc.)
Go Public	Final conclusion(s) that students display.	Possible venues: • Test • Oral presentation • Poster/Project • Role play

standing of difficult concepts. Others have successfully taught concepts such as Fourier analysis and signal processing through the use of Legacy Cycles [17, 18]. Greenberg [18] shows a statistically significant improvement in Fourier spectral analysis skills in a physiology course. These examples, along with studies at the high school level all illustrate a mastery of science or engineering concepts beyond that of control classrooms for concepts taught using the Legacy Cycle design [10, 11, 19–21].

This paper presents the results of the creation and implementation of a set of nine Legacy Cycle modules into three bioprocess engineering courses that partially make up a bioprocess engineering concentration of the general engineering program. In addition to helping in the achievement of an effective HPL learning environment within the three courses, the modules also provided common themes that integrated the three courses. The effectiveness of the modules was measured by three assessment tools: pre- and post-test, concept mapping, and an HPL survey.

Our work sought to provide the answers to two research questions: 1) Did the students master the facts, skills, and concepts of bioprocess engineering through the use of Legacy Cycle modules? and 2) Did the use of Legacy Cycle modules create an effective HPL learning environment within the three bioprocess engineering courses?

2. Engineering program description

The engineering program at East Carolina University was started in 2004 and provides students with a degree of Bachelor of Science in Engineering. Within the major, the students take a set of core engineering courses (40 semester hours) and a set of concentration specific courses (25 semester hours). Students select one of four concentrations: industrial and systems, mechanical, biomedical, or bioprocess engineering. Within the bioprocess engineering concentration, the concentration courses are: Chemistry II, Organic Chemistry, Microbiology, Bioprocess Engineering Systems, Bioprocess Validation and Quality Engineering, Bioprocess Separations Engineering, and Bioprocess Plant Design, Simulation and Analysis. The Legacy Cycle modules were developed and implemented into the Bioprocess Engineering Systems, Bioprocess Validation and Quality Engineering, and Bioprocess Separation Engineering courses.

The first course in the sequence is Bioprocess Engineering Systems (BIOE 3000). This course covers engineering concepts for biological conversion of raw materials to pharmaceuticals, biopharmaceuticals, fuels, biological products, and chemicals. The course includes enzyme, bioreaction and cellular growth kinetics, bioreactor stoichiometry, analytical characterization of biological products, and design, analysis, selection, scale-up, and control of bioreactors and fermenters. BIOE 3000 is a second semester junior year course.

The second course in the sequence is Bioprocess Validation and Quality Engineering (BIOE 4000). This course covers the bioprocess validation and quality control systems that ensure safe products, reduce the risk of adverse reactions, and avoid recalls and emphasizes cost effectiveness and level of validation required for different phases of development, license application, and process improvements. BIOE 4000 is a first semester senior year course.

The third course in the sequence is Bioprocess Separations Engineering (BIOE 4010). This course covers the mechanism and engineering analysis of downstream processing such as sedimentation, centrifugation, precipitation, extraction, adsorption, chromatography, and membrane separation. This course contains a laboratory component and is a first semester senior year course offered concurrently with BIOE 4000.

3. Module implementation

Three Legacy Cycle modules were developed for each course. The implementation of a Legacy Cycle module can be understood through examining the Challenge Question, Multiple Perspective, and Go Public. Tables 2–4 show the Challenge Question, Multiple Perspective, and Go Public for BIOE 3000, BIOE 4000, and BIOE 4010. All Legacy Cycles are shown to illustrate both the diversity and interconnection of the modules. In as much as possible, an effort was made to provide a variety of Multiple Perspectives and Go Publics so that the students would not feel as if they were doing the same assignment over and over. Each module has been assigned an identifying number that is referenced in the discussion that follows.

The Legacy Cycles thematically integrate three sets of modules across the three courses. Table 5 lists the integrated modules and the theme of the integration. The unique benefit of developing integrated Legacy Cycles is that it allows students to build upon the knowledge gained from the previous cycle, improving the efficiency of delivery of the second cycle, thus allowing more depth and breadth of coverage of the second cycle. The challenge of this approach is ensuring the ability to run the second cycle independent of the first cycle. In other words, the integrated modules must have the ability to stand alone to ensure portability to other programs and to allow for the case in which a student was not exposed to the earlier module within a series (per-

Table 2. Challenge Question, Multiple Perspective, and Go Public Descriptions for BIOE 3000

Module Number	Challenge Question, Multiple Perspective, and Go Public Descriptions
1	**Challenge Question:** *E. coli* is often used as a host organism to produce recombinant proteins of interest. How do you genetically engineer bacteria, such as *E. coli*, to produce a desired recombinant protein? **Multiple Perspectives:** Instructor guided. In the whole-class setting, have students share ideas from their journals. Record their ideas on the board. Break students up into groups and have each group review the ideas recorded on the board. Ask each group to categorize the ideas into about four categories. Have each group report and explain their categories. **Go Public:** Create an informative and visually appealing booklet style brochure providing a basic technical introduction on the processes of genetically engineering *E. coli* to express a desired protein, starting with the source DNA and finishing with the genetically engineered organism.
2	**Challenge Question:** Many protein production processes utilize bacteria as the host organism. How do you mass produce a recombinant protein using bacteria as the host organism? **Multiple Perspectives:** Excerpts from two journal articles serve to focus the students on the importance of considering protein quality, functionality, production speed and yield and using transgenic animals to express certain proteins. **Go Public:** Complete mini-project that analyzes cell growth kinetics and stoichiometry of microbial growth and product formation.
3	**Challenge Question:** The human plasma protein antithrombin is an anticoagulant that plays a key role in controlling clot formation. It is used as a therapeutic protein to prevent blood clots in patients who lack the natural anticoagulant protein. How do you mass produce this protein? **Multiple Perspectives:** Review excerpts from two journal articles that guide the students toward recognizing the need to develop and understanding of molecular biology of different expression systems, product quality and safety, levels of expression and yields, manufacturability, capital expenditures and production costs, downstream processing, and selection of ideal organism. **Go Public:** You work as a process engineer for a small bioprocess startup company. You have been asked to produce a therapeutic recombinant human protein. Select the appropriate production platform. Create a poster that illustrates your process design considering appropriate host organisms for post translational modifications, protein production, and downstream purification.

Table 3. Challenge Question, Multiple Perspective, and Go Public Descriptions for BIOE 4000

Module Number	Challenge Question, Multiple Perspective, and Go Public Descriptions
4	**Challenge Question:** In your hometown, a manufacturing plant makes the same pain-killer that your Dad takes for his bad back. Who is responsible for insuring that the pain-killer produced there is safe? **Multiple Perspectives:** Present an expert interview that will guide the students to see the need for inspection and auditing. **Go Public:** You are an FDA Director and have new inspectors to train. You must develop a presentation and train these inspectors based on the developed FDA inspection guide applicable to your assigned area, as well as the latest information on this topic area.
5	**Challenge Question:** Your sister has been diagnosed with asthma. Different types of medicines exist in order to both treat and maintain this disease, from steroid-based products to tablets. Thus, these are manufactured in different manners. Some of the equipment used to manufacture these different products may be shared. Your sister cannot take a steroid-based product. What should be considered by the manufacturer in establishing cleaning processes that help insure that the tablets she takes will not be contaminated by the steroid product? **Multiple Perspectives:** Present an expert interview that will guide the students to see the need for a cleaning validation program. **Go Public:** Develop a cleaning validation protocol for a cooking process considering equipment/containers/pots/pans/sinks/food contact surfaces in your kitchen. Use the cleaning validation procedure VAL-104 as your guide.
6	**Challenge Question:** Your aunt fell and broke her hip and has to have surgery. Due to her age, cigarette smoking habit, being overweight, and having been bed-ridden since the fall that caused the break, she is at risk for a pulmonary embolism. The hospital plans to give your aunt a recombinant therapeutic protein to prevent a pulmonary embolism. How does the pharmaceutical company that produces the protein insure that the protein is not only effective but safe for her to take? **Multiple Perspectives:** Present an expert interview that will guide the students to see the need for a process validation program. **Go Public:** Develop a Process Validation Protocol for the BIOE 4010 Ethanol laboratory (for which you prepared a laboratory procedure). Use the process validation procedure VAL-106 as your guide.

Table 4. Challenge Question, Multiple Perspective, and Go Public Descriptions for BIOE 4010

Module Number	Challenge Question, Multiple Perspective, and Go Public Descriptions
7	**Challenge Question:** As a newly minted bioprocess engineer, you have been asked to develop a process to produce ethanol using locally grown feedstock. How will you go about selecting and testing to determine the best feedstock? **Multiple Perspectives:** Interview from a biofuels expert that steers the students toward using a particular feedstock. **Go Public:** Create a laboratory protocol describing how to produce ethanol from sweet potatoes with an objective of determining the ethanol yield of the process.
8	**Challenge Question:** Many protein production processes utilize bacteria as the host organism. A new protein has been developed and will be massed produced using the bacteria *E. coli* in an industrial fermentation process. Determine the steps necessary to purify the protein. **Multiple Perspectives:** Review two journal articles that provide the two distinct separation methods for firefly luciferase. This steers the students toward using adsorption and chromatography for the separation processes. **Go Public:** Given a set of ten proteins and their properties, determine the process steps required to extract the proteins from the bacterial cells and purify the target protein. For each separation process step, describe the step, explain why you chose the particular separation process, and any possible alternatives and why you did not choose the alternative.
9	**Challenge Question:** The human plasma protein antithrombin is an anticoagulant that plays a key role in controlling clot formation. It is used as a therapeutic protein to prevent blood clots in patients who lack the natural anticoagulant protein. Transgenic female goats have been used to produce therapeutic recombinant human antithrombin (rhAT) in their milk. How can you purify a recombinant therapeutic protein from the milk produced in the mammary glands of transgenic animals? **Multiple Perspectives:** Review a patent that details the separation of therapeutic rhAT from milk. This steers the students toward using membranes for the separation process. **Go Public:** You work as the technical advisor for a small bioprocess startup company. Your company recently received the rights to process therapeutic rhAT produced in goat's milk. Your CEO has asked you to create a poster that he can use to explain the process to potential investors.

Table 5. Integrated Modules and the Integration Theme

Integrated Modules	Integration Theme
6-7	Production of ethanol. Create a lab manual in Module 7 and a validation protocol of the process in Module 6.
3-6-9	A therapeutic recombinant protein expressed in an animal's mammary glands. Used as the basis of the Legacy Cycles in all three modules, as the Go Public in Modules 3 and 9, and as a Test-Your-Mettle Exercise in Module 6.
2-8	Production and purification of a protein expressed in a bacterial cell. Understand the production of the protein in Module 2 and the purification of the protein in Module 8.

haps due to receiving transfer credit for the earlier course). To affect this end, the modules were loosely integrated so they can stand alone with only minor modifications.

4. Module assessment

There were two particular challenges with the assessment of the effectiveness of the Legacy Cycles, both due to the fact that the program is new. First, the Legacy Cycle modules were implemented with the first or second offerings of each of these new courses. This created a condition in which there was essentially no pre-implementation data in which to compare to the Legacy Cycles. Secondly, the program is still relatively small, resulting in small data sets and hence difficulty in determining changes. In order to overcome these challenges, the evaluation of the effectiveness of the Legacy Cycles on the ability to implement the four HPL centeredness aspects within a Bioprocess engineering curriculum was measured using three assessment tools: pre- and post-test, concept maps, and a 'How People Learn' survey. The pre- and post-test measured the student learning that occurred within a given module, the concept maps measured how well the students can integrate the material covered in all three courses, and the 'How People Learn' survey measured the degree in which the course was transformed into an effective learning environment through the use of the Legacy Cycles. The details of the assessment tools and results follow.

4.1 Pre- and post-test

Every module used a pre- and post-test to measure quantitatively the growth in students' knowledge of relevant basic terminology, problems and skills from the unit, as well as their ability to transfer this knowledge to a new, but related situation. Such questions are known as 'near transfer questions.' Pre-test and post-test scores were compared using a paired t-test. Figs 1–3 illustrate the pre- and post-test results for BIOE 3000, BIOE 4000, and BIOE 4010 respectively.

4.2 Concept maps

Concept maps have been used for assessing a variety of outcomes in instruction since the early 1970s. More recent studies have shown that concept maps can be used for assessing declarative knowledge ('knowing that'), procedural knowledge ('knowing how'), and implicit knowledge [22–24]. Because students develop domain expertise and their knowledge becomes more like their teacher's or the domain expert's over time, [25] concept maps could be used for monitoring learning outcomes and goals.

A teacher-expert map can be created by the method described by Gordon et al. [22] where the expert is first asked a question and that free response is recorded. This response is translated into nodes and rules. Question probes are used to complete the response along with observation and induction about the expert's implicit knowledge. Student maps can then be compared to the teacher-expert map using a scoring system that focuses on the

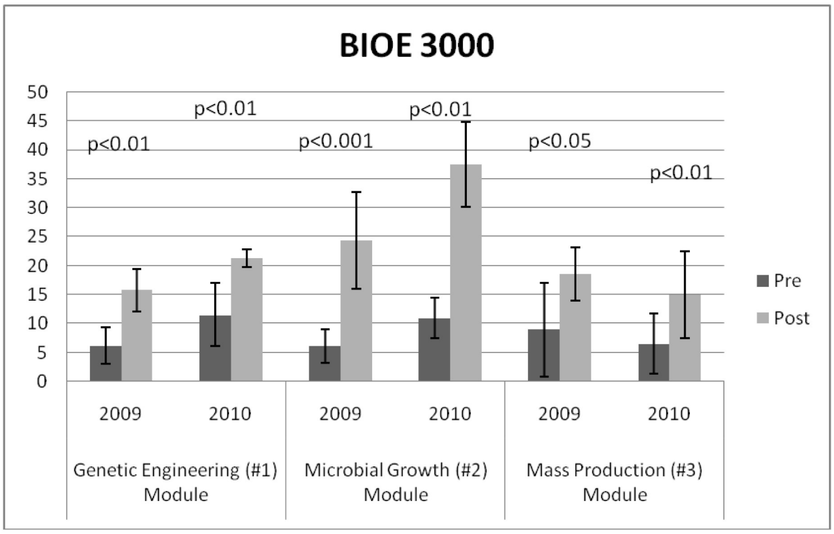

Fig. 1. Pre- and Post-Tests Results for BIOE 3000. N=6 in 2009. N=4 in 2010.

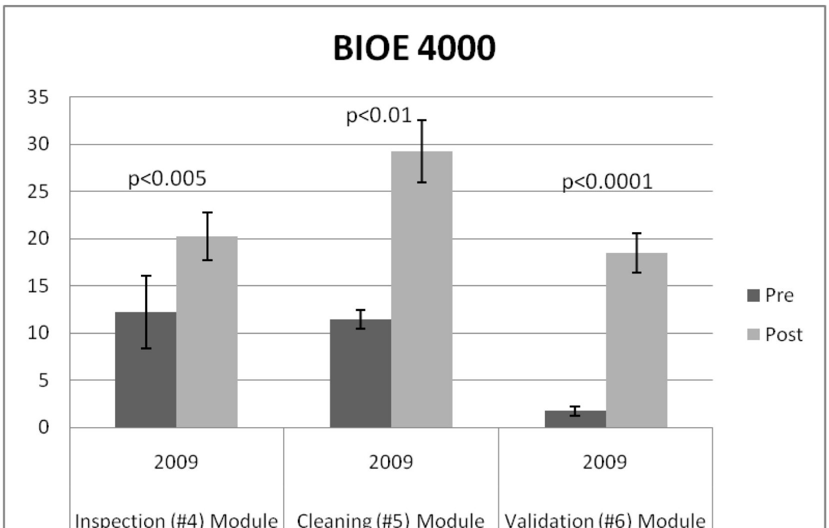

Fig. 2. Pre- and Post-Test Results for BIOE 4000. N=4 in 2009.

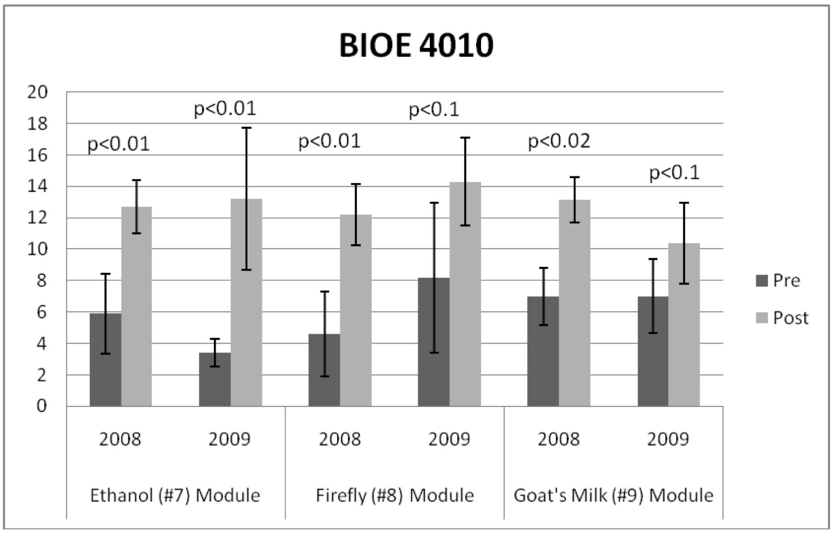

Fig. 3. Pre- and Post-Test Results for BIOE 4010. N=5 for 2008 and 2009.

degree of accuracy of the relationship described in each proposition, or pair of concepts, and is based on stated objectives of the course. [23, 26]. This analysis includes three rubric scores on each map: pertinent items found on the map, relationship between the concepts in the stem and the correct answer, and misinformation [23]. Previous studies such as Rice's [23] have shown strong inter-rater reliability measures for this scoring method as well as strong correlations to demonstrably reliable criterion multiple choice tests, suggesting that concepts maps are a reliable test method. Concept mapping can be taught quickly and easily to students and the technique can be used by large classes with minimal assistance from teachers, making it also a relatively easy method of assessment [24].

Using a concept map, the students were asked to answer the following question: 'How is a biologically based product produced and processed to ensure its safe distribution and use?' Students complete a new concept map during four points in the curriculum; 1) at the beginning of BIOE 3000, 2) at the end of BIOE 3000, 3) at the beginning of BIOE 4000/4010, and 4) at the end of BIOE 4000/4010. The purpose of the concept maps is to measure quantitatively the students' growth in basic terminology, problems and skills, and the relationship between these. In addition to the student generated concept maps, we generated a teacher-expert map utilizing inputs of the project investigators as well as three members of our industry advisory board. This teacher-expert map has been used as a basis in the development of an assessment rubric of the students' concept maps. An excerpt of the teacher-expert map is illustrated in Fig. 4.

Student concept maps were compared to the teacher-expert map. If a term on the student's map was an exact match or very similar match to a term on the teacher-expert map, the term was highlighted on the map and these highlighted terms were tallied. Additionally, if a linking word between two correct maps was found to be correct, it was highlighted and tallied. Because this two year curriculum design project was begun in the spring, data are staggered across three cohorts of students. Table 6 shows the results of the concept map evaluations with respect to terminology and Table 7 shows the results with respect to concept linkage. The low scores on the linkages are a reflection of the small number of terms found on the students' maps.

4.3 How people learn survey

The third assessment tool used was the 'How People Learn' survey developed by the VaNTH ERC [27]. The purpose of this assessment was to measure how well the new instructional materials met the areas of effective classroom instruction as proposed by the National Research Council [5]. These areas include knowledge, assessment, learner, and community-centeredness. This assessment was administered in all classes using the Legacy Cycle approach.

Table 8 shows the results of the 'How People Learn' survey for the first offering of all three courses. There are two indices utilized: HPL1, which focuses on the combined areas of knowledge-, learner-, and assessment-centeredness, and HPL2, which focuses on community-centeredness. Each student's survey was scored on a Likert scale from 0 to 4, and a class average was computed. The HPL1 index is comprised of twenty-two questions and thus the index has a mid-point of 44 on its scale. The HPL2 index is comprised of six questions and thus the index has a mid-point of 12. Appropriate questions were summed for each of the two indices

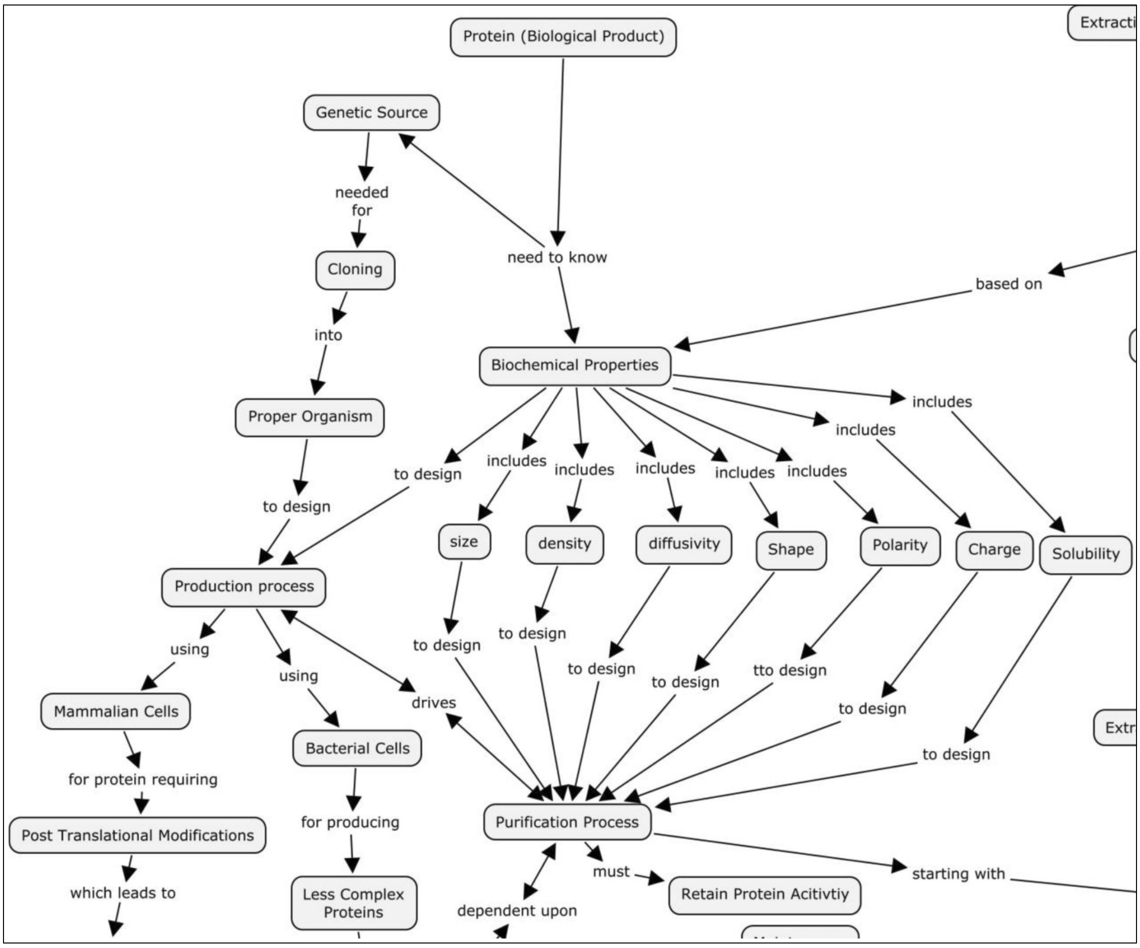

Fig. 4. Excerpt of the Teacher-Expert Concept Map.

Table 6. Number of correct terms found on student concept maps

	Pre-BIOE 3000 Average # Terms	Post-BIOE 3000 Average # Terms	Pre-BIOE 4000/4010 Average # Terms	Post-BIOE 4000/4010 Average # Terms
Cohort 1 (n = 5)			7.0	14.0
Cohort 2 (n = 6)	7.3	8.7	6.8	15.8
Cohort 3 (n = 3)	2.3	8.3		
Combined	5.6	8.6	6.9	14.9

Table 7. Number of correct linkages found on student concept maps

	Pre-BIOE 3000 Average # Linkages	Post-BIOE 3000 Average # Linkages	Pre-BIOE 4000/4010 Average # Linkages	Post-BIOE 4000/4010 Average # Linkages
Cohort 1 (n = 5)			0.2	4.8
Cohort 2 (n = 6)	2.0	2.3	2.6	7.4
Cohort 3 (n = 3)	0.0	1.0		
Combined	1.3	1.9	1.4	6.1

Table 8. HPL Survey Results for the ECU Data. HPL1 data focuses on the combined areas of knowledge-, learner-, and assessment-centeredness. HPL2 focuses on community centeredness

	BIOE 4010 Fall 2008	BIOE 4010 Fall 2009	BIOE 4000 Fall 2009	BIOE 3000 Spring 2009	BIOE 3000 Spring 2010
HPL1 (max = 88)	68.6	59.2	44.8	74.8	58
HPL2 (max = 24)	15.4	12.8	10.6	13.6	14.8

Table 9. HPL Survey Results from VaNTH ERC

	VaNTH HPL average	VaNTH non-HPL control average
HPL1 (max = 88)	55.7	45.8
HPL2 (max = 24)	13.8	11.6

and compared to other HPL and non-HPL survey results from the VaNTH ERC. The VaNTH ERC results reflect many years of data, both in HPL-based classrooms and non-HPL-based control classrooms and are shown in Table 9.

Referring to the VaNTH data in Table 9, the HPL1 index does discriminate between the HPL and non-HPL classrooms historically; however, the HPL2 index does not appear to be as discriminating historically. The VaNTH ERC data averages suggest that HPL courses use combinations of KLA (Knowledge, Learner and Assessment centered) instruction 'more than half the time' (the mid-point of the scale), whereas the non-HPL means fall below the mid-point of the scale reflecting 'some use' of these practices.

The HPL survey results for this project show that both BIOE 3000 and BIOE 4010 have been particularly successful in meeting the HPL goals, both in the KLA combination and the community-based score. The BIOE 4000 course is just at the mid-point on the KLA combination score and just below the mid-point of the community-based score.

5. Discussion

The first question of the study, 'Did the students learn the correct facts and concepts through the use of Legacy Cycle modules?' is answered through the analysis of the pre- and post-test and concept maps.

Test results indicate that students mastered the course content through the use of the HPL-based modules. Students in every module showed statistically significant improvement from their prior knowledge to the knowledge at the end of the unit. Though several units have higher pre-test scores in one year than another, t-tests comparing the differences in growth from pre- to post-test scores indicate no difference between the first and second offerings of the courses. In other words, the students do not appear to have come from different populations with differing backgrounds.

The transfer questions were structured to be fairly difficult in order to measure true adaptive expertise. The weighted average performance on the transfer questions was 34% correct. This performance is comparable to other results found in the literature for transfer questions [13, 28, 29].

The concept maps indicate that the courses are improving the correct usage of terminology and the linkages between ideas (terms) by the students. Some regression is seen over the summer between the end of the spring BIOE 3000 course and the fall BIOE 4000 and 4010 courses, as might be expected. The majority of correct student terms center on the course content of BIOE 4000. Students infrequently integrated knowledge from BIOE 3000 and 4010 into their maps, though when they did they did very well. It is believed that the question 'How is a biologically based product produced and processed to ensure its safe distribution and use?' inadvertently focused the students toward the regulatory content of the BIOE 4000 class and away from the technical bioprocess engineering content of the BIOE 3000 and BIOE 4010 classes. Students may have simply found it harder to structure their thinking about these technical courses in a concept map structure; perhaps additional practice in this skill within these courses would have improved the overall study results.

The second question of the study 'Did the use of Legacy Cycle modules create an effective HPL learning environment within the three bioprocess engineering courses' is answered through the analysis of the HPL Survey. The HPL survey results for this project show that both BIOE 3000 and BIOE 4010 have been successful in meeting the HPL goals, both in the KLA combination and the community-based score, whereas BIOE 4000 scored just below the mean. These results indicate that changes in the Legacy Cycles and the instructors' teaching style are still needed in order to meet the HPL goals. The HPL Survey also provided the instructors non-traditional (as compared to end of semester student surveys) feedback on the learning environment of each course and all of the instructors reported that the self-assessment of their teaching an delivery helped steer improvements in not only the courses of this study, but across all of the course that the instructors taught.

6. Conclusions

The results presented within this study show that the Legacy Cycle was effectively utilized to facilitate a move away from traditional lecture methods of delivery towards more novel methods designed to engage the students in the learning process within a bioprocess engineering curriculum. The results from the pre- and post-test and concept map assessments indicate that the students mastered the facts, skills, and concepts of bioprocess engineering through the use of the nine Legacy Cycle modules. The near transfer question results were comparable to other results found in literature and indicate that the students developed some adaptive expertise through the use of the modules. The HPL Survey shows that the use of the Legacy Cycle modules created an effective HPL learning environment within two of the three bioprocess engineering courses and that changes in the Legacy Cycles and the instructors' teaching style are still needed in order to meet the HPL goals within the third course. This work also adds supportive data to Legacy Cycle usefulness for teaching basic content and creating adaptive experts.

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