Int. J. Engng Ed. Vol. 23, No. 1, pp. 171–183, 2007
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Development of Challenge-Based Educational Modules in the Biotechnology Domain

GÜLNUR BÍROL†
Biomedical Engineering Department, Northwestern University, 2145 Sheridan Road, Technological Institute, E 310, Evanston, IL 60208, USA. E-mail: birol@science.ubc.ca

ANN F. MCKENNA
Institute for Design Engineering and Applications, Northwestern University, 2133 Sheridan Road, G 319, Evanston, IL 60208, USA

H. DAVID SMITH
Northwestern University, Evanston, IL 60208, USA

TODD D. GIORGIO
Biomedical Engineering Department and Chemical Engineering Department, Vanderbilt University, Box 351620 B, Nashville, TN, 37235, USA

SEAN BROPHY
Peabody School of Education, Vanderbilt University, Box 351620 B, Nashville, TN 37235, USA

Biotechnology is one of the active domains in the NSF funded Engineering Research Center VaNTH (Vanderbilt, Northwestern, University of Texas, and Harvard/MIT) where educational modules have been developed. These modules cover a collection of challenges designed around bioreactors, mass and momentum transfer issues, microbial kinetics, and downstream processing, which are among core biotechnology topics. The aim of this study was to design educational modules centered on challenge-based education and to implement them in classroom settings. This paper focuses on the design and implementation of such educational modules and provides an overview of the challenges and learning activities that were developed for three specific topics that have been implemented at Northwestern and Vanderbilt Universities.

Keywords: biotechnology education; mass transfer; microbial kinetics; bioreactors

INTRODUCTION

BIOENGINEERING lies within the intersection of biology with engineering, and the physical/chemical sciences and mathematics. During the 1998–99 academic year, Northwestern's (NU) and Vanderbilt's (VU) Biomedical Engineering Departments became part of the Vanderbilt-Northwestern, Texas-Harvard/MIT (VaNTH) Engineering Research Center (ERC) in Bioengineering Educational Technologies. The bioengineering faculty is currently working with learning scientists, learning technologists, assessment experts and bioengineering students to develop educational modules for bioengineering education. Such educational tools are intended to enhance the learning experience of students, support collaborative and reflective learning, and provide opportunities for students to practise skills expected in engineering practice. Aspects of learning science, learning technology and assessment are continuously being integrated into these modules [1]. In addition, new courses are being developed and integrated with new educational modules to provide students with a better learning environment.

Biotechnology continues to expand with the recent advancements in medicine, bioinformatics, proteomics, biomaterials, bioremediation and tissue engineering. Therefore, biotechnology is one of the first domains that the VaNTH ERC chose to develop using challenge based instruction. As the demand for biotechnology education continues to grow with these developments, the need for effective learning tools is also increasing. New approaches are being taken to teaching biotechnology and bioengineering to an interdisciplinary audience. An example of such a course is presented elsewhere [2]. Stemming from this observation, we developed three educational modules in the biotechnology domain. The focus of this paper is on the design process of these modules and related activities in the domain of biotechnology. It also addresses how the activities map to the learning goals of these modules.

* Accepted 27 April 2006.

† Current address: The University of British Columbia, Faculty of Science, Vancouver, V6T 1Z4, BC, Canada.

MOTIVATION

Microbial kinetics and mass transfer are two core topics that are taught in a typical biochemical engineering course and they take up a significant amount of class teaching time. Nonetheless, students commonly have difficulty writing the unsteady-state mass balance equations based on the bioreactor operation with an explicit kinetic expression. Furthermore, solving these ordinary differential equations becomes almost impossible for students since solving them requires synthesizing knowledge from different courses including kinetics, mass transfer, mathematical modeling and ordinary differential equations. The production of high value products from mammalian cell culture is also characterized by mathematical representations that are nonlinear and coupled. The interplay of cell biology and engineering principles of mass and momentum transfer is critical to successful mammalian cell bioreactor design, but represents knowledge integration that is not generally provided in any undergraduate curriculum. Previous experience suggests that learners demonstrate difficulty in conceptualizing the multiple relationships that control cell growth in mammalian cell bioreactors. We hypothesize that developing models that explore these relationships can overcome these difficulties, increase their understanding of modeling methods and when to apply these models. Therefore, we adapted a challenge-based approach to instruction for two courses in biotechnology.

MODULE DEVELOPMENT

Design considerations

Biotechnology modules were designed based on the How People Learn (HPL) framework by systematically linking learning resources together based on pedagogical principles defined by current learning theory [3]. Research on expertise and learning suggests that designs for learning environments should consider four primary elements. First, education research suggests that effective learning environments should be 'learner-centered'. That is, the materials and learning activities (both in and out of class) should take into account the knowledge, skills, preconceptions and learning styles of the learners. Second, a learning environment should be 'knowledge-centered' in the sense that clear objectives are defined and the core knowledge organized in a way to achieve curricular goals. This organization of the knowledge can facilitate students' learning with understanding. Knowledge is organized around key concepts and models are developed to aid in transfer to new contexts. Third, learning environments should be 'assessment-centered' such that they provide frequent opportunities for students to make their thinking visible to themselves and the instructor and receive feedback on their thinking. This can help students refine their understanding of the key concepts and how they can be transferred to an appropriate context. Finally the learning environment should be 'community-centered' in the sense that it fosters norms that encourage students to learn from one another, as well as encouraging faculty to do likewise [3]. This factor helps students learn more about the professional community of which they will some day be members.

Our desired outcome includes the construction of well-designed modules that increase students' motivation, establish a context for information to be learned, provide conditions for applicability of the knowledge, provide opportunities to make connections between ideas, and hence, promote learning with understanding [3–5].

The primary use of these modules presented here is in a biochemical engineering course. The student level can be anywhere from sophomore through graduate, provided that the students know basic aspects of material balances and mass transfer in bioreactors either from previous work or from lecture accompanying these modules.

The first step in creating these modules was to identify the taxonomy. As such, the topics to be included in the modules were carefully chosen to insure coverage of a significant portion of the biotechnology taxonomy and to address important problems in the area based on our teaching experiences. Biotechnology taxonomy can be found elsewhere [1].

The second step was to define the learning goals of these modules, which are summarized in Table 1. There were two sets of learning goals for each module. One set of goals was more general and considered core competencies. We were able to embody core competency skills in our modules, since one of the advantages of the HPL framework is to provide opportunities for students to master skills that are expected from an engineer. The second set of goals was more specific and directly related to the biotechnology content.

The third step in constructing these modules was to prioritize the topics to be covered. This was done by categorizing the items in the taxonomy by essential (E, these concepts are fundamental to the domain and the major learning goals), important (I, these are concepts that students should be able to recognize and use, but not necessarily be fluent in) and familiar (F, these are concepts that students should be aware of, but if they don't know them, then it won't limit their problem solving process of common problems) [5]. After putting all these elements together, challenge statements and related activities were designed around a learning cycle, as described below. Each challenge reflected a real life situation to motivate students and is presented in Table 2.

Iterative design process

To ensure the success of these modules, an iterative procedure has been employed as shown

Table 1. Learning goals of the biotechnology modules

Modules	Learning goals	
	Content	Core competency
M1 Microbial kinetics	• explain how and why cell, product and substrate concentrations change in batch cultures • describe specific growth and product formation rates • define rate expressions for cell growth, and for product formation • explain the differences in rate expressions for cell growth and for product formation • recognize the limitations of growth and product formation • write a rate expression for a given data set and solve it • write an expression that combines cell growth and product formation data to find substrate utilization	• apply modeling and design skills to open-ended biomedical problems • draw conclusions from data • recognize the importance of team work in biomedical engineering • apply effective written and oral communication skills
M2 Mammalian cell cultures	• explain the major differences among various bioreactor types • recognize the critical factors in bioreactor design • describe the types of cell cultivation recognize the factors associated with survival of a cell • recognize the constraints for cultivation of different cell types • qualitatively categorize possible solutions • differentiate among different bioreactor configurations for given cell culture conditions	• apply engineering principles and approaches to biological and medical problems • qualitatively categorize possible solutions
M3 Mass and momentum transfer	• explain the operation and analysis of bioreactors • identify the mass transfer limitations in bioreactors • quantitatively predict oxygen delivery and consumption in mammalian cell bioreactors • qualitatively assess cell damage induced by fluid forces in mammalian cell bioreactors • generate a near-optimal mammalian cell bioreactor design based on performance specifications	• apply engineering principles and approaches to biological and medical problems • draw conclusions from data • optimize solutions to address multiple criteria

in Fig. 1 that involved three main steps: classroom testing, evaluation, and refining of the modules.

From the beginning of the module development phase, *classroom testing* has been a central component of our efforts. For example, the first versions of the challenge statements were revised at least six or seven times before they took their final forms. The critical issues were to refine these statements to make them open-ended yet accessible to students and to highlight specific learning goals such that students were required to integrate several concepts from the course. In addition, the classroom environment was reconstructed to align with HPL principles and to make the tasks doable within a two week time period.

Evaluation of the modules also started from the beginning and included methods to measure both content understanding (pre- and post-module tests) and obtain student feedback about the challenges and course structure. An example of a questionnaire we gave students after completing the microbial kinetics challenge is provided in Table 3. Similar questionnaires were prepared for the other modules. These questionnaires provided valuable feedback to us for revision of the modules. Pre- and post-tests were also used to assess the students' learning gains, and these results are reported elsewhere [6].

Refining the modules required evaluating the data and adjusting the activities based on the results. For example, after implementing the modules we had a much better idea on how much classroom time was needed to address each module. Since the classroom environment is dynamic in nature, many adjustments had been made to accommodate the needs of the students and to minimize technical difficulties while maintaining the 'HPL-ness' of the classroom environment. These adjustments included, but were not limited to, arranging the distribution of the material (hard copy versus electronic copy), coordinating with the PC laboratory technician to make sure all the PCs contained appropriate software, and timely delivery of the material to avoid overlap or gaps between lectures and the module material. After the first iteration, we re-tested, reevaluated and refined the modules when necessary. Owing to the course schedule, the instructors only had one chance per quarter (or semester) per year to teach the course, as such, it took almost two years to finalize these modules for our team. Our modules are now ready for testing at other sites. In the implementation section, we describe how we used these modules in a biotechnology course.

STAR.Legacy Cycle for Microbial Kinetics Module

The sequence of learning activities is organized

Table 2. Challenge Statements of the Biotechnology Modules

Module 1 (M1):
The Board of Directors of Microbaway Antibiotics, Inc. has just voted on allocating funds towards construction of a new production facility to be used for the production of penicillin, a highly profitable antibiotic. As members of the Microbaway Antibiotics, Inc. Product Development team, it is your task to develop a mathematical model describing the microbial kinetics of penicillin production. This model will be used to maximize penicillin production at the new plant prior to production.

You will need to review production data in order to generate your model. Anne T. Biotic, a fermentation expert from SporeTech Pharmaceuticals, will help you run some experiments at one of SporeTech's penicillin production facilities, PenSim. Anne will provide you with the initial operating conditions from the last several production runs as a starting point in your analysis (we are also planning to run our plant at these operating conditions). Microbaway's management has requested that a preliminary report defining and assessing the kinetics of penicillin production be presented at the manager's meeting next week. This report should include the proposed model of the relationship between biomass, nutrients, penicillin and/or others as they are related, any assumptions, simplifications, etc. It is very important that you substantiate your proposed model via simulation results and support your findings.

After the development of this initial report, your team will need to test your proposed model based on a set of experimental data that will be provided to you by the fermentation expert. This will allow you to validate/invalidate your model. Your team will need to generate another report for presentation at the quarterly Director's meeting to take place in Maui, Hawaii, in November.

Module 2 (M2):
The production of therapeutic proteins from mammalian cells requires consideration of multiple, connected issues. The optimal conditions for cell growth depend of the cell type, the desired rate of product synthesis, bioreactor design and operating conditions. Commercial production of therapeutic proteins presents a particular set of challenges resulting from the large scale required. We will consider two cell types that could be used to support the production of rFVIII: '293 cells' and CHO (Chinese hamster ovary) cells.

We need to decide which one of these cells will be the best host for producing the product in terms of both efficient and correct synthesis. Our first challenge is to identify the conditions that will best sustain robust growth for each of these cell types.

Therefore, what is the best bioreactor design for growing the desired amount of each cell type?

Module 3 (M3):
CHO cells grown on 200-(m diameter microcarriers have been selected for the large scale production of Recombinate. Economic analysis suggests that the optimum production strategy requires recovery of 2200 liters of raw cell culture product per day. The resulting bioreactor volume is 2500 liters and three such bioreactors are required. For this production volume, and the specified use of microcarriers, the design must be a stirred bioreactor.

The goal of our challenge is to design the bioreactor to optimize Recombinate production. Therefore, you need to consider at least two important questions:

1. What physical and operating characteristics must be considered?
2. What additional data is required before the optimum conditions can be predicted?

around the STAR.Legacy Cycle shown in Fig. 2. STAR stands for Software Technology for Action and Reflect and has been used in a number of the inquiry-based learning environments that we want to emulate [7]. In order to demonstrate the mapping of each learning activity to the steps in the STAR.Legacy cycle (Fig. 2), we describe specific details of one module, microbial kinetics. Other modules were designed in a similar way.

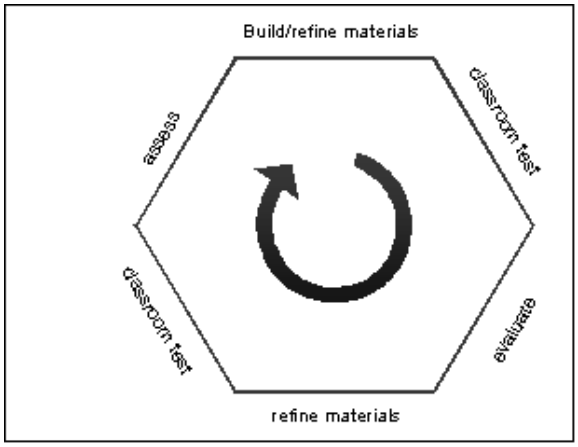


Fig. 1. After building the modules by domain and assessment experts and learning scientists based on the taxonomy and the needs of the course(s), they were delivered to learners for classroom testing and surveys were collected for evaluation. Then, the material was refined based on learner's input. This was followed by classroom testing again and more revision.

The Challenge

The challenge statement defines the problem to be investigated. This is usually a sophisticated problem, which covers a portion of content taxonomy and maps carefully chosen learning objectives with the subject matter, and its solution requires several steps. Since the purpose of the microbial kinetics challenge is to engage students to develop a mathematical model describing the kinetics of penicillin production, it was very important that students foresee the possible use of the mathematical model they would create in order to be engaged in the tasks. This was something we, as engineering faculty, would never predict, since the problem itself was interesting to us and the possible use was implicitly defined in the problem. As such, working with learning scientists helped us to identify and explicitly state the important points that otherwise would be assumed to be understood by students in the challenge statement. Another opportunity for us as domain experts was the

Table 3. Survey for microbial kinetics module. Eleven students completed the survey in Fall 2001 at NU

Part A	Strongly disagree		Somewhat agree		Strongly agree
1. The challenge was interesting.	1	2	3	4	5
2. Investigating the challenge helped me to learn about the assumptions and constraints in generating a kinetic model.	1	2	3	4	5
3. The challenge related to the course content.	1	2	3	4	5
4. Listening to the group presentations helped me to generate ideas about how to approach the problem.	1	2	3	4	5
5. The challenge was difficult.	1	2	3	4	5
6. Investigating the challenge helped me to learn about solving open-ended problems.	1	2	3	4	5
7. The challenge assignment was a valuable learning activity.	1	2	3	4	5
8. I found it difficult to make connections between the lecture material and the challenge assignments.	1	2	3	4	5
9. Listening to the group presentations helped me to interpret the data.	1	2	3	4	5
10. Adequate time was given to complete the assignments.	1	2	3	4	5
11. Listening to the group presentations helped me to think about how to generate a kinetic model of the system.	1	2	3	4	5
12. It was difficult to use PenSim.	1	2	3	4	5
13. Investigating the challenge did not help me to learn about penicillin production.	1	2	3	4	5

Part B. Please answer the following questions in detail.

14. The challenge we investigated in this class is just one of many possible questions relating to kinetics. What other questions would you suggest as interesting topics to investigate?

15. What was rewarding about investigating the challenge?

16. What would you change about the challenge assignment to make it better?

17. Do you think that the instructor gave enough explanation about the challenge? If no, what else would you need to know?

18. How much time did you spend on this challenge overall? (Select one.)

1–10 hours _____ 11–20 hours _____

21–30 hours _____ 31–40 hours _____ Other _____

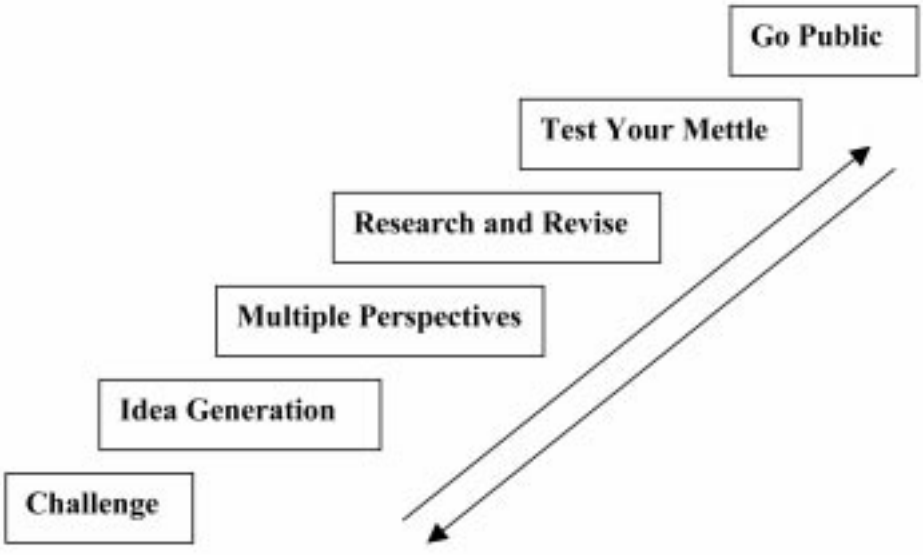


Fig. 2. A schematic representation of a Legacy cycle.

inclusion of an assessment expert in the team, who helped us integrating the assessment tools in our modules without disturbing the flow of the content.

Generating Ideas

The first step in problem solving is 'idea generation', where learners identify the influencing factors. In the microbial kinetics module, idea generation was facilitated in class by posing questions to students in an interactive small group activity. Students were asked to generate a legitimate and functional mathematical model to determine penicillin production. Although, this activity is intended to be open-ended, the instructor geared questions towards what variables must be considered and how to represent these variables in the model. The next step in problem solving is to identify what is to be found, that is, what is the goal of the solution. Thus, the students were also informed that data collection is not a random process but should be geared towards a purpose. The take home message of this idea generation session was the realization that the mathematical model should satisfy a purpose (e.g. Is this model going to be used to test the effect of environmental factors (pH and temperature) on penicillin production? Or is it going to be used to investigate the effect of glucose or oxygen or both on penicillin production? Or is it going to be used to examine the bioreactor's operation characteristics such as agitation rate?, etc.).

Multiple Perspectives

The second step in the Legacy cycle is 'multiple perspectives', which promote the identification by potential solutions. During this phase students begin writing the preliminary report by determining additional factors that affect penicillin production beyond initial idea generation. Students work closely with the instructor outside of the class to create a plan of action and the required knowledge should be identified after obtaining multiple perspectives on the subject matter. Here, students are given an opportunity to use an online simulator, PenSim, to run virtual experiments to aid them in understanding the effects of different variables on penicillin production [8]. Initial conditions for the process are given to them in the online PenSim software [9], which is introduced by a hypothetical person, Anne T. Biotic (the instructor or TA). This step is particularly important because the simulator will not produce physically meaningful results unless the range of variables is chosen within the limits of the software. This is a very good learning opportunity for the students if presented correctly by the instructor. That is, no model is valid for the whole range of variables, and that there is a limitation in modeling. Each model has a range of applicability. As such, there must be a set of assumptions and constraints when creating mathematical models to describe a physical phenomenon.

Since the students' task is to write a preliminary report, it is explicitly stated in the challenge statement that the report must propose the kinetics of penicillin production and a rationale for choosing that particular kinetic. The report should include the proposed model of the relationships between biomass, nutrients, penicillin and/or others as they are related, any assumptions, simplifications, etc. Students received some additional material to aid in the report writing process, such as report writing guidelines (to help develop written communication skills). Students are encouraged to substantiate their proposed model via simulation results to support their findings, which is a very important step in the problem-solving process.

Research and Revise

At this stage, students are ready to explore and investigate potential solutions under the 'research and revise' part of the cycle. The research and revise element contains content material and assigned problems designed specifically to help students apply their content knowledge to specific questions, thus promoting their learning. Students start building their mathematical model after completing careful research on penicillin production processes and kinetic aspects of it from the literature. Students combine this research information with the data generated from PenSim (an opportunity to improve competency to draw conclusions from data). At this point, they need to use a programming language such as Matlab, Simulink, C++, etc. They should also share their proposed model and preliminary results from the model with their peers by giving a short 3–5 minute informal presentation in the class (an opportunity to improve communication skills). This discussion determines whether more troubleshooting is required and if anything is lacking in the model. In this stage, the instructor should confirm that the students are heading in the right direction with regards to the capability of their model. It is crucial to discuss the practicality and need for certain variables in the model by asking why and how questions.

Test Your Mettle

Research and revise is followed by 'test your mettle' in which the students make use of their knowledge and experience gained through assignment questions to solve the challenge problem. If their solution is not complete when they reach this step, students go back to the appropriate step along the Legacy cycle and rebuild/refine their solutions. As such, this is an iterative learning process. In this stage, students finalize their models and prepare a mini report. Factors to consider prior to the formation of the mini report could include which variables were chosen and their effects when altered, as well as which kinetics rate expressions were chosen and why (assumptions, simplifications, etc). Upon the completion of this step, a final formal presentation

should be prepared that presents the mathematical model proposed, the methodology behind it and the results (an opportunity to improve communication skills). Oral presentation guidelines are also distributed to the students as part of the module materials. The instructor should make sure the students construct an effective argument as to why they did what they did.

Go Public

This part is the final, summative assessment of students' understanding of the material after the completion of the module. Here, students use the feedback and information they have gathered to finalize their model, validate it with experimental data and create a final formal report describing their method. This report must include all the elements of a formal report, i.e. an abstract, background, the model (similar to the mini report) and results. Students are encouraged to be creative and to focus on the premise of their model and how effective it was and explain why it was effective and/or how it could be improved to meet the goals of the initial challenge.

Elements of HPL

It is worth mentioning that each biotechnology module was created considering all the elements of HPL, which were embedded in specific tasks and activities. For example, providing students and faculty opportunities to generate ideas and gain multiple perspectives aligns with the HPL principles of learner- and community-centeredness. In this way, students hear different points of view, get feedback on ideas, and propose alternative solutions to the challenge.

The common themes of HPL elements among the modules were:

1. focusing on integration and application of concepts (knowledge centeredness);
2. bringing students' ideas to the forefront, creating engaging and motivating engineering problems (learner centeredness);
3. increasing dialogue between instructor and students (community centeredness);
4. students' reflecting on the problem solving process throughout the term (assessment centeredness).

IMPLEMENTATION

The biotechnology modules were used in two courses at each site (NU and VU). Each module required from three to five 75-minute classroom sessions and included several homework assignments between sessions. The topics covered in these courses and how the educational modules were embedded into class material is summarized in Table 4.

Example of implementation: bioprocess technology course at NU

The 10-week course (quarter system) consisted of two class meetings of 80 minutes per class per week. The first week of class time followed a traditional lecture format and focused on a general introduction of biology topics that included cellular biology and general characteristics of microorganisms. In addition, a related homework project was assigned. During the second week, types of bioreactors were introduced. This included different modes of operation and corresponding mass balance equations, a typical bioreactor configuration, and specific issues related to bioreactor operations.

After an introductory session to the bioreactors topic, the first challenge statement (M2) was introduced to students in class. The students read the challenge statement for about 10 minutes and wrote down their initial thoughts about the challenge. After this period, students made partners and shared their ideas with each other. All the generated ideas were collected by the instructor and posted anonymously on the course Web site right after the lecture period. Note that feedback

Table 4. Content of the courses where biotechnology modules were used (text in **bold** shows the topics that map to the content of these modules)

NU BME 395 Special Topics (in Fall 2001)	VU BME 281 Biotechnology (in Spring 2004)
1. Cell Biology	1. Biology of eukaryotic cells
2. Bioreactors (M2 and M3)	2. Manipulating the gene in cells
2.1. Cell cultivation	2.1 Gene cloning
2.2. Operation and analysis	2.2 DNA sequencing
2.3. Mass transfer limitations	2.3 Expression systems
3. Microbial Kinetics (M1)	3. Ethics of biotechnology
3.1. Stoichiometry of growth	**(M1)**
3.2. Biomass formation	**4. Mammalian cell bioreactors (M2 and M3)**
3.3. Product formation	**4.1 Mass transfer**
3.4. Substrate utilization	**4.2 Momentum transfer in mixing**
4. Product Recovery	**4.3 Fluid stress and cellular collisions**
4.1. Recombinant DNA Technology	**4.4 Scaling up the laboratory bioreactor**
4.2. Separation of insolubles	5. Mammals as bioreactors
4.3. Initial isolation	6. Hybridization for detection
4.4. Primary purification	6.1 Microarray technology
4.5. Final purification	7. Gene therapy
	7.1 Intracellular aspects of gene delivery

was an integral part of the teaching strategy and special care was taken to assure prompt feedback throughout the course.

Students were asked to review the posted ideas and generate any new ideas based on their review of others' comments. Each of these activities contributed to a learning environment that was learner and community-centered, and also followed the generate ideas phase of the Legacy cycle.

The next class began the multiple perspectives and research activities to help focus on specific content through a combination of class discussion, viewing video interviews with experts, and small group discussions. The class met in the PC lab of the Biomedical Engineering Department. The first half of the class time (approximately 45 minutes) was spent discussing different bioreactor configurations, including some carefully chosen examples from the Internet, and some instrumentation and their applications (e.g baffles, spargers, impellers, etc.) in a traditional lecture format. In the second half of the class time, students were divided into four groups (three groups of three and one group of two students). A short discussion on the ideas generated in the previous class was held in order to address possible pre-/mis-conceptions and highlight important issues that should be addressed in the remainder of the assignment. Then, the groups were assigned one expert from the software module to listen to and summarize what was said. Briefly, each expert (one graduate student specialized in T-flasks, two professors specialized in hollow fiber and roller bottle bioreactors and an expert from industry specialized in stirred tank bioreactors) introduces a specific type of bioreactor and talks about the pros and cons of that specific design. This activity took about 15 minutes. During this time period, the instructor walked around the groups and asked several questions to help them focus on specific issues and each group reported the important issues raised by the expert, including their own thinking about the process. During the reporting phase, the instructor raised questions about the topic to facilitate discussion. Research and revise activities were assigned as homework and were due the following class meeting.

'Research and revise' and 'test your mettle' activities were composed primarily of questions for discussion, and elements contained in the Web-based bioreactor module. One of the questions dealt with exploring cell growth, and the other was on bioreactor design. This was the formal mechanism of formative assessment. During the following class meeting, the instructor further discussed bioreactor configurations and introduced mass transfer in a single phase.

At the end of the class period, 'Test Your Mettle' questions of module 2 were assigned as homework, which comprised detailed analyses of cell requirements and bioreactors. In the next class meeting, the instructor reviewed the homework solutions and continued with mass transfer issues and correlations and also introduced power requirements in stirred tank bioreactors in a traditional lecture format. Students also engaged in a 'think, pair, share' activity during the class to help reflect and refine (self assess) their performance on the homework assignment.

At the end of the class, 'Go Public' questions of the module 2 were assigned as a new homework set, which comprised examining the drawbacks of a roller bottle bioreactor, choosing a suitable bioreactor configuration that serves as a bioartificial liver and investigating the operating parameters of a large scale stirred tank bioreactor. After each assignment, solutions were posted on the course Web page.

'Go Public' questions were administered as an on-line debate to promote synthesis and application of the lecture plus module material, to critically evaluate students' thinking, and to help them gain confidence on the bioreactors topic. Students were asked to post their solutions (these were multiple choice questions) by the end of the day with a clear explanation and reasoning about their choice. Then, they were expected to review each other's answers and debate their answers with a sound justification through the course Web site. At the end of the debate, they were expected to post their final answers, with detailed explanation and reasoning if their answers were different from their initial answers. After the debate, when the class met again, the instructor went over the solutions.

The second module (M3 in Table 2) was implemented in a very similar way to the first module (M2). The topics covered (Table 1) were momentum and mass transfer in bioreactors [10]. This material was covered in about two weeks. Again, extensive interaction between students and the instructor was encouraged. In the meantime, the instructor also covered scaling up of bioreactors topic. At the end of each module and the class material on bioreactors, a series of assessment techniques were implemented. These techniques are discussed later in this paper.

The implementation of the third module (M1 in Table 2) differed slightly from the first two modules. There were several goals in this first implementation of the microbial kinetics module. First, we wanted to investigate students' misconceptions about the topic of microbial kinetics. Second, we wanted to get feedback from students, which in turn helped us adjust the level of complexity of the final module and revise any technical problems for future implementations. The module was introduced relatively early in the microbial kinetics part of the course, right after one lecture on cell population kinetics, modeling, parameter estimation, and different models in biotechnology. Since one of the learning goals of this class was to promote and help students develop lifelong skills such as presentation and communication skills, it was critical that the structure of the course promoted group interactions throughout the

quarter. Thus, the homework assignments for the third module were designed to necessitate group work. For the rest of the quarter, the students worked with the same group members of their choice. There were four three-student groups and one two-student group. In order to make sure that group members were evenly distributed, the junior and the sophomore students were encouraged to form a group that had at least one senior student in the group. Each assignment (refer to challenge statement for M1) was followed by a presentation and a class discussion. At the end of each assignment, the students handed in a report. After every assignment (total of three), the instructor provided immediate feedback, since the next report would consist of a revised version of the previous one with additional requirements of that particular assignment. Between the two assignments, students met with the instructor individually to discuss their progress or problems, etc. At the end of three assignments, the students created one formal report per group. All the presentations were videotaped and a graduate student observed the session and took notes during the discussion. Documenting these events helped inform future development of the modules. This module was completed within a three-week time span and, during this period, the instructor introduced related course material (see Table 4) in a classical lecture format including extensive discussions with students. Two lectures were spent on presentations (about 12–15 minutes per group). At the end of the module, a series of assessment techniques were implemented; these are discussed in the following section.

Students contacted the instructor via e-mail or in person when they had questions. Whenever a student raised a question on a lecture topic or a homework, the instructor either sent an e-mail to the whole class or addressed that issue in class. In some cases, she posted the questions on the course Web site. Furthermore, all the solutions (e.g. homework, exam, other assignments, etc) were posted on the Web site right after students handed those in. This allowed maintenance of a good level of communication and continuity in the learning and teaching. The process also helped establish a community of learning where students could ask questions and receive feedback specific to their needs. These learner-centered/community-centered environments are often appreciated by the learners.

Some observations

The in-class activities were very effective in motivating students' interest towards the topics covered. Many times, the instructor introduced a question related to that day's topic and students generated ideas in a pair and share format. Then, students were encouraged to come to the blackboard and share their ideas with their classmates and the instructor. Usually, the blackboard was divided into sections and group members wrote their findings/ideas on that specific question. This activity was followed by a short discussion. Only once, one student, who did not wish to participate to this activity, was given the task of being a referee. The instructor provided the solution to the referee and asked her to lead the discussion. Since it is very common to see students' interests decline within 45 minutes or so, these activities helped bring students back in focus in an 80-minute class period. Assigning a weight to class participation (10% of the total grade) also promoted in-class questions and participation in class discussions and activities.

ASSESSMENT

Assessment was an integral part of these teaching and learning experiences. Although the focus of this paper is on development and implementation of the biotechnology modules, we briefly describe the various assessment techniques we used within these courses. Further elaboration of the assessment portion of these courses can be found elsewhere [6,11]. In order to assess the achievement of the learning objectives of these courses and hence the modules, a series of assessment methods were applied partly based on classroom assessment techniques for engineering courses [12] and partly based on our previous experience [6,13,14]. There were three levels of assessment:

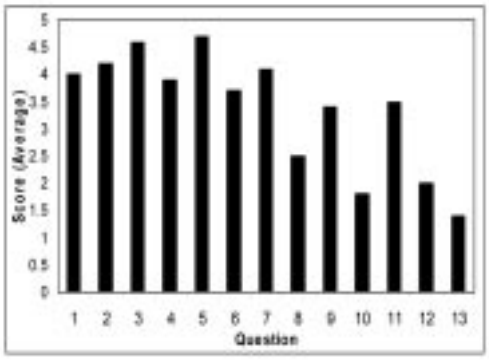
1. *Course as a whole,* which was achieved by pre and post tests (knowledge-based questions);
2. *Module specific* assessment, which included surveys and pre/post tests;
3. *Assessment of learning objectives,* which included homework, two take-home examinations and class participation.

Pre and post-tests were administered at the beginning and at the end of the quarter for the NU course and at the beginning and at the end of the module material at VU. These tests consisted of three parts: the first part was designed to capture general, 'adaptable' problem solving skills (e.g. students' ability to design a plan and identify necessary resources); the second and third parts were designed to gauge understanding of concepts covered in modules 1, 2 and 3. It also aimed to capture learning and potential 'value-added' of modules. A rubric to code the responses has been developed and is presented elsewhere [6, 11].

Surveys were targeted to obtain information on the effectiveness of the modules as an educational tool and were in the form of Likert-type questionnaires completed at the end of each module. The microbial kinetics survey is presented in Table 3. Figure 3 shows the student responses to questions in Table 3 (part A).

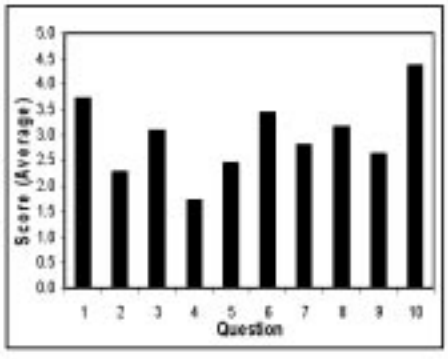
The survey results provided here were from the NU BME 395 class where the order of modules tested was M2, M3 and M1 (Table 4). In general, students thought the challenge assignments were

(A)



(B)

Statement
1. I didn't know anything about the factors that affect a bioreactor design before we started this lesson, therefore I found it difficult to Generate Ideas for Challenge 2
2. The experts' perspectives did not provide me with any new insights.
3. I could not predict the properties of cell growth demonstrated in t-flask simulation in Challenge 2's Research and Revise section.
4. I had difficulty understanding the challenge since it involves advanced biology concepts.
5. I did not find reading the resource on bioreactors in Research and Revise before class helpful in considering the differences in designing a bioreactor.
6. During the Test Your Mettle Questions in Challenge 2, I like having to explain my decision for a particular reactor design using logic.
7. I did not feel well prepared to answer the Test Your Mettle questions.
8. I found it easy to explain why the majority of people were right or wrong on the Go Public Questions in Challenge 2.
9. The technology problems interfered with my learning about bioreactors.
10. The challenge relates to the course content



(C)

Statement
1. When we generated ideas for this challenge, I was able to identify most of the operating conditions we need to consider before we talked about them in small groups or as a whole class.
2. The multiple perspectives for challenge 3 did not help me realize any additional conditions we need to consider in the bioreactor design with μcarriers.
3. I found it easy to make connections between the lectures and the problems we solved before class.
4. After listening to the lecture on fluid shear rates I was able to quickly solve the homework problems we did prior to the lecture.
5. I feel the class time we spent brainstorming about microcarriers in bioreactors was not important to learning about overall design.
6. I do not feel confident I could scale up a stirred tank bioreactor design from a small prototype to a large production model.
7. In Challenge 3, I found calculating oxygen delivery in the Test Your Mettle questions was difficult.
8. By the end of this challenge, I do not feel confident I can calculate the oxygen level in a bioreactor that uses convective methods of delivery.
9. I had difficulty understanding the challenge since the biology is involved.
10. By the end of this challenge, I feel confident I can calculate the amount of cell damage in a stirred tank reactor.
11. I found the challenge of microcarriers in a bioreactor very interesting.
12. The challenge relates to the course content
13. During the Test Your Mettle Questions in Challenge 3, I like having to explain my decision for a particular reactor design using quantitative methods.

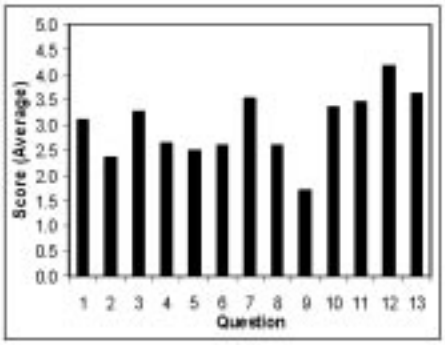


Fig. 3. Student responses to survey questions (example survey questionnaire is provided in Table 3 for Microbial kinetics module, other survey questions are placed next to the plots) from Fall 2001 BME 395 Course at NU. Number of students was 11. (A) Microbial kinetics module (M1), (B) Mammalian cell cultures (M2), (C) Mass and momentum transfer (M3).

interesting and a valuable learning activity, and found it highly related to the course content. They did not find it difficult to make connections between the lecture material and the challenge assignments, which proved the existence of a good alignment between them. It is interesting to note the progress of students' thinking about idea generation. The first time they were introduced to the module (M2), they found it difficult to generate ideas. But, their perception of difficulty decreased as they moved from one module to the next. This might be partly due to the fact that they got acquainted with the challenge-based teaching approach as the class progressed and were able to generate ideas more easily and more effectively. They found listening to experts useful and valuable for their learning and they felt well prepared for the 'test your mettle' questions.

The results of the open-ended part of the survey provided feedback to inform future module revisions. For example, we asked students 'What was rewarding about investigating the challenge?' Responses to this question, provided below, indicate that students valued the classroom interactions, and understood the context of the model.

'*You got as much out of it as was put in, proud that proposed model actually worked.*'

'It was rewarding to get some results from models we inputted.'

'Getting a decent model and seeing how it applied to extreme situations.'

'The group presentations were the most interesting because we were able to see how other groups approached the problem and it allowed us to determine if our assumptions and reasoning were justified and helped us to figure out where to go next or what we needed to go back and work on.'

'Learned about penicillin production, better understanding of modeling.'

In addition, we asked students 'What would you change about the challenge assignment to make it better?' to elicit feedback on how to improve the module. The excerpts given below indicate that perhaps more time would be helpful, and more help with computer programming.

'Do it over a longer period of time and give more direct examples in class'

'*More lectures prior to lab (simulation) time, this would facilitate research as journals would more easily be interpreted*'

'Give more time to complete it. Use some class time to work on MatLab programs or some outside help with MatLab. We couldn't model the process because our MatLab program took too long to run. We wasted time with MatLab rather than learn about kinetic Modeling.'

'Provide more code. Perhaps provide conditions to test the system under. Most of us do not know the possible range for the actual system so some settings may have been unrealistic.'

Finally, we asked students 'Do you think that the instructor gave enough explanation about the challenge? If no, what else would you need to know?' The following excerpts indicate that the explanations and lectures supported the module assignments but could benefit by providing more examples.

'She did a good job but time was definitely a constraint, more time would have allowed for more clarity and better understanding.'

'The mass balance lectures were excellent, specific growth rate model choice needed more theory though because choices were highly dependent upon empirical data.'

'An in-class example of the steps to take in Kinetic Modeling. Similar to the lecture on the steps taken to scale up a bioreactor.'

'Explanation was pretty thorough but a little more direction would be helpful.'

'Sometimes it felt like a little more if on how to choose out variables/which equations to use might have been helpful.'

'Generally yes, but it needed some clarification sometimes but that's analogous to real life.'

Homework and exam questions formed the formative assessment of these courses.

To sum up, student comments on the open ended survey items provided additional information about the specific aspects of the challenge assignment that were useful, and those aspects that could be improved. Students described an appreciation for the process of model construction and suggested that more time be provided for the tasks in the future. In addition, students requested some clarification on the assignment and the means by which proper variables should be chosen. This information, albeit anecdotal, aided in the improvement of the challenge and its implementation in future classes.

CONCLUSIONS

This paper presented three challenge-based educational modules that were developed and implemented in the biotechnology domain. These modules were based on HPL framework and were effectively integrated into class materials at two different universities (NU and VU). The topic choices challenged the students to think beyond the course material and apply their knowledge to new situations.

Some conclusions drawn from this work can be summarized as follows:

- The lecture material supports students in completing the module assignments but could be adjusted to avoid repetition and to provide more direction and/or examples.
- Integration of educational modules helped the instructors cover more course material than

would have been possible in a classical lecture format.
- Using formative assessment throughout the course helped instructors monitor student understanding and identify conceptual difficulties
- Formative assessment enabled instructors to correct problems as they arose, so that students made adequate progress on the assignments.
- Following the HPL principles enabled us to create an environment that more closely models professional practice such as solving open-ended problems, sharing and debating ideas, and presenting formal solutions.
- Continuous assessment helped instructors refine the modules.
- Although initial implementation of these modules takes significant amount of the instructor's time, subsequent offerings of the course with the modules is straightforward.

We believe that documenting our unique experience in designing and implementing challenge-based modules based on the HPL framework is a valuable contribution to the field of biotechnology education. The work presented here can serve as a model for other instructors who are interested in creating authentic learning experiences for their students based on a challenge-based format. In addition, the materials presented here can be used by other educators in the area of biotechnology, and the materials can also be extended into other related domain areas.

Acknowledgements—This work was supported primarily by the Engineering Research Centers Program of the National Science Foundation (NSF) under Award Number EEC-9876363. The Fall 2001 and 2002 students of BME 395 course are gratefully acknowledged. Special thanks to E. Budzynski, L. Crosson, M. Gonzalez, and Drs Suzanne Olds and Christopher Riesbeck of NU for their valuable feedback.

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Gülnur Bírol, Ph.D., currently holds a joint appointment as Research Associate with Skylight (Center for Science Learning and Teaching) and Biology Program of the University of British Columbia (UBC). Dr Birol has taught several courses at Illinois Institute of Technology and Northwestern University and has developed educational tools for engineering education. Before joining UBC, she was a project leader in NSF funded

engineering research center (VaNTH ERC) at Northwestern. Her recent research interests are twofold: post secondary science and engineering education and retinal metabolism. Dr Bírol received her BS, MS and Ph.D. degrees in Chemical Engineering from Boğaziçi University in Turkey.

Ann F. McKenna, Ph.D., is the Director of Education Improvement in the McCormick School of Engineering and Applied Science and the Associate Director of Design Education for the Institute for Design Engineering and Applications at Northwestern University. She also holds a joint appointment as Assistant Professor in the School of Education and Social Policy and Research Assistant Professor in the Department of Mechanical Engineering. Dr McKenna has extensive experience in engineering education research and curricula development and assessment. Dr McKenna received her BS and MS degrees in Mechanical Engineering from Drexel University in Philadelphia, Pennsylvania and her Ph.D. degree in Science and Mathematics Education from the University of California at Berkeley.

H. David Smith, Ph.D., is a Senior Lecturer in the Department of Psychology at Northwestern University. He received his BA in Psychology from Denison University, and his Ph.D. in Experimental Psychology from Virginia Commonwealth University. Dr Smith has a wide range of research interests including assessment and evaluation of educational interventions, judgment and decision making, and reasoning. Before joining the Psychology Department, he served as Associate Director of the Searle Center for Teaching Excellence at Northwestern. He has also served on the faculty of Middlebury College and the University of Michigan.

Todd D. Giorgio, Ph.D., is currently Associate Professor of Biomedical Engineering and Associate Professor of Chemical Engineering at Vanderbilt University. Dr Giorgio also holds an appointment in the Materials Science program at Vanderbilt and is a member of the Vanderbilt–Ingram Cancer Center. His research is primarily focused on the quantitative understanding of complex biological system interactions with gene and drug delivery systems. Professor Giorgio is active in educational research for biotechnology through leadership and participation in a NSF-supported ERC distributed among five academic institutions. He received his Ph.D. from Rice University and his BS from Lehigh University, both in chemical engineering.

Sean Brophy, Ph.D., is assistant professor of Engineering Education at Purdue University. Dr Brophy is a learning scientist and engineer conducting research with the VaNTH Engineering Research Center in Bioengineering Educational Technologies. His current research interests focus on developing learners' ability to solve complex problems in engineering, mathematics and science contexts. This research aligns with his work to develop effective learning environments using challenge-based instruction. Also, Brophy continually explore ways to develop and use technology to support learners' conceptual understanding of difficult concepts and support formative assessment methods through advanced learning technologies. As a graduate student in the Department of Teaching and Learning at Vanderbilt University, he worked on developing technology tools for projects ranging from young children's literacy to science and mathematics education for middle and high school students. He conducted his postdoctoral work at Learning Technology Center at Vanderbilt as a member of the Center for Innovative Learning Technologies (CILT.org).