PEDAGOGICAL APPROACHES TO TEACH FLUID MECHANICS AND MASS TRANSFER TO NONENGINEERS WITH A BIOTECHNOLOGY FOCUS

P. Arthur Felse
Northwestern University • Evanston, IL 60208

Biotechnology uses the principles of chemical engineering and biological sciences to create new products using living organisms.[1,2] Genesis of the biotechnology industry was catalyzed by rapid advances in molecular and cell biology, particularly in the areas of gene manipulation and animal cell culture.[3] Translating new discoveries in biology to an industrial enterprise requires the development of reliable, robust, and scalable bioprocesses. Predictably, chemical engineers took the lead in developing and commercializing biotechnological process. The positive synergy between chemical engineering and biology has existed for several decades such as in the development of submerged culture processes for antibiotic manufacture and immobilized enzyme processes for high fructose corn syrup production.[4] This was later followed by the development of processes for recombinant protein production in bacteria, large-scale mammalian cell culture for therapeutic antibodies, and most recently for the mass production of virus-like vaccine particles.[5,6] Future discoveries in genome sequencing, cell therapies, and regenerative medicine will demand an even closer interaction between biologists and chemical engineers.

Several chemical engineering programs in the United States responded to the interdisciplinary needs of biotechnology by requiring biology courses in their curriculum. About 30% of chemical engineering programs require at least one biology course, 27% require at least one bioengineering course, and 7% require both. Thus, more than 50% of chemical engineering programs require some biology exposure in their undergraduate curricula.[7] In contrast, biology undergraduate programs typically don't require a course of engineering nature in their curriculum. However, 49% of biology undergraduate programs in the United States require at least one calculus course and 42% require at least one statistics course.[8] Notwithstanding the lack of exposure to engineering, biologists routinely work with chemical engineers in the biotechnology industry.[9,10] Therefore, biologists aspiring to succeed in the biotechnology profession have a need to learn the basics of chemical engineering in order to communicate and operate effectively in the cross-disciplinary environment.

A limited number of precedents have been reported for teaching chemical engineering to nonengineers. Two web-based courses on the fundamentals of chemical engineering for nonengineers that satisfied the requirements of a certificate program in Foundations of Chemical Engineering were reported.[11] A sophomore-level course on chemical engineering for nonengineers was taught using active-learning exercises for liberal arts students.[12] This course had a unit operations approach to teach chemical engineering principles using indigo manufacture as a case study. AIChE's three-day classroom course on Essentials of Chemical Engineering for Non-engineers has been offered for more than 25 years and has been completed by lawyers, business managers, and process technicians.[13] Absi, *et al.* described a fluid mechanics course for nonengineers taught through atypical experiments using a play-based pedagogy.[14] This course was offered to undergraduate students in a five-year M.Sc. program in applied industrial biology.

The Master of Biotechnology Program at Northwestern University prepares biologists and engineers for careers in the biotechnology industry. The program offers two bridge courses to introduce nonengineers to the fundamentals of chemical engineering. First in this series is a course on balances and kinetics followed by a course on fluid mechanics

P. Arthur Felse *is a lecturer in the Master of Biotechnology Program and in the Chemical & Biological department at Northwestern University. He also serves as the assistant director for research in the Master of Biotechnology Program. His research interests include engineering education, diversity in engineering, and biotech regulatory sciences.*

and mass transfer. After completing the two bridge courses, students move on to take three graduate-level courses in bioprocess engineering. Presented in this paper is the fluid mechanics and mass transfer course offered to nonengineers. This course is designed specifically to meet the learning needs of nonengineers progressing to cross-disciplinary careers in biotechnology. Course development strategies, pedagogical methods, course assessment, and future initiatives are discussed. Details of a previous version of this course along with a discussion on course development challenges and course assessment using ABET guidelines were presented at the 2011 ASEE annual meeting.[15]

LEARNING OUTCOMES OF THE COURSE

By completing this course, students will be able to:

- *Explain the fundamental principles of fluid mechanics and mass transfer.*
- *Remember, recall, and use notations and terminology in transport processes.*
- *Perform numerical calculations related to solving quantitative problems in fluid mechanics and mass transfer.*
- *Relate and apply the principles of fluid mechanics and mass transfer to various bioprocess and physiological systems.*
- *Get the required prerequisite knowledge to take graduate-level courses in bioprocess engineering.*

STUDENT PERCEPTIONS AND LEARNING PREFERENCES

Students generally have a positive opinion about engineering, but it is often perceived to be difficult and overwhelming along with a rigorous course load.[16,17] To better understand the preconceived notions of students taking this course, they were asked to complete a short entrance survey on the first day of classes. The intent of this survey was to understand student perceptions and expectations, and to gain insights on their learning preferences. The survey had four questions: one each related to students' preconceived notions; the learning outcomes that students expected; their specific perceptions on the challenges in this course; and their preferences for activities that will make them feel confident in the classroom. Students provided free-style responses to survey questions, but they were prompted to use short, thematic phrases in their responses. Examples of thematic phrases were provided with survey questions. Students were informed that they should provide original responses, and the examples were solely meant to demonstrate the brevity and clarity of responses. Responses were processed using an open source phrase-frequency counter to quantify the frequency of any particular thematic response (<http://www.writewords.org.uk/phrase_count.asp>). In cases where the frequency counter was unable to identify thematic responses, a manual count was employed. When asked about their overall perceptions of this course, 72% of students thought the course would be challenging and 70% thought it would be rewarding and interesting as well (Table 1). About 62% of students reported that the course will involve a lot of math and quantitative calculations, which is conceivable for an engineering course. About 25% of students held no preconceived notions. This data indicates that students generally enter this course with a positive attitude expecting the course to be rewarding and interesting, while recognizing that it will be challenging as well.

When asked about the learning outcomes that students expect from this course, about 88% wanted to gain competence in performing engineering calculations and 78% expected this course to set them up for success in future engineering courses (Table 1). These two expectations match the stated learning outcomes of this course. A significant number of students (~ 64%) wanted to apply transport principles to physiology. This course was initially developed with a bioprocess perspective. Based on this feedback, physiology examples of fluid mechanics and mass transport were included in the course. About 24% of students expected this course to be useful in their careers, which is not the intention of this course. Students were informed that taking the graduate-level bioprocess engineering courses will help them in their careers, but the fluid mechanics and mass transport course itself is not directly correlated with career opportunities.

TABLE 1

Student perceptions and expected learning outcomes based on entrance survey responses.

Student response	% of students
What are your overall perceptions of this course?	
Challenging/rigorous	72
Rewarding/interesting	70
Lot of math/calculations	64
No preconceived notion	25
What learning outcomes do you expect from this course?	
Competence in engineering calculations	88
Success in future engineering courses	68
Apply transport to problems in physiology	64
Useful in career	24
What do you perceive as specific challenges in this course?	
Time commitment	90
Math/calculations	78
Paying attention to long lecture	62
Understanding concepts	24
What makes you feel confident in the classroom?	
Contribute to class discussion	78
Cheerful class environment	64
Success in problem solving	62
Come prepared for the lecture	42

Students perceived that time commitment and performing math calculations will be the major challenges in this course (Table 1). Since students perceive that this course will have a lot of math calculations, they might also perceive that a larger amount of time will need to be invested in this course. Many students observed that paying attention to a two-hour lecture on an unfamiliar topic will be challenging. Based on this student feedback, the course format was modified to shorten the lecture to about 50 minutes and include hands-on, student-centered learning activities for about 50 minutes of a 110-minute class period. These nontraditional pedagogical methods are discussed later.

The last question on the survey related to understanding what made students feel confident in the classroom. Being able to engage and contribute to classroom discussions was the top response (78%), followed by a cheerful class environment (65%), and a sense of success in problem solving (62%). Based on this student feedback, active learning and other pedagogical methods were applied to advance student contributions during class and to increase student self-efficacy.

DEVELOPING QUANTITATIVE PROBLEM-SOLVING SKILLS FOR NONENGINEERS

To familiarize students with quantitative problem solving, a math review module covering topics in calculus, trigonometry, and algebra was developed. Online learning platforms such as Khan Academy (<https://www.khanacademy.org>) were particularly useful since the modules are customized to students' mastery level that is determined using a pre-test. Several example and exercise problems were supplied as a part of the math review module. Review materials were made available to students for self-study and followed up with tutorial sessions conducted by either a teaching assistant (TA) or the instructor. Homework assignments and exams in the math review module ensured adequate mastery in quantitative problem-solving skills required to learn fluids mechanics and mass transfer topics.

An important aspect of teaching the math review module is providing relevance to the subjects of fluid mechanics and mass transfer. This was accomplished by recalling the appropriate math technique or theory when discussing fluid mechanics or mass transfer concepts during class. Handouts and lecture slides had a math recall section in the footnote. Homework assignment problems had hints to the use of right math techniques for problem solving. Students were allowed to bring a set of math tables to the exams (such as standard integration tables, Taylor series expansions, trigonometric functions, etc.). The use of online resources saved lecture time, and homework hints eased students into quantitative problem solving.

COURSE CONTENT AND FORMAT

The fluid mechanics and mass transport course was structured in modular format. The course had one module that was one week long and four modules that were two weeks long, each with their own homework assignment, problem-solving clinic, and exam. The class met for two 110-minute class periods each week. Each 110-minute class period had a 50-minute lecture followed by a 50-minute problem-solving session or active-learning exercise. The course outline and progression of modules are given below:

Module 1: Introduction to the course, and review of basic concepts in physics and math (two class periods).

Module 2: Fluid statics and its applications to manometers, decanters, and centrifuges (one class period); rheological properties of fluids, the concept of turbulence, and flow in boundary layers (one class period); macroscopic momentum balance, continuity equations, and Bernoulli equation and its applications in physiology and bioprocess systems (two class periods).

Module 3: Incompressible flow in pipes and estimation of friction losses during pipe flow (one class period); motion of particles through fluids under gravitational and centrifugal fields, Stokes' and Newton's regime for particle settling, and hindered settling (one class period); Ergun equation and estimation of pressure drop in packed columns (one class period); flow profiles in stirred tanks, impeller systems for agitation, heterogeneity in mixed vessels, estimation of power requirements, and scale-up of agitated systems (one class period).

Module 4: Fick's first law of diffusion, estimation of diffusive and convective mass transport rates, and prediction of diffusivities in gases and liquids (two class periods); film and penetration theories, mass transfer coefficients, and estimation of mass transfer coefficients (two class periods).

Module 5: Gas-to-liquid mass transfer in stirred tanks (one class period); principles of equilibrium stage operations, operating line and equilibrium relationships, and analytical and graphical estimation of number of stages (one class period); concentration profiles in solids during mass transport in spherical, rectangular, and cylindrical geometries, mass transfer with chemical reactions, and external and internal mass transfer (two class periods).

Topics covered in this course were chosen based on their relevance to biotechnology. For example, there was a strong emphasis on topics such as Newtonian fluid flow, energy balance equations, flow of incompressible fluids, flow past solid boundaries, mixing and agitation, diffusive mass transfer, equilibrium-stage separations, mass transfer in solids, and mass transfer in agitated vessels. Topics that had only marginal relevance to biotechnology such as flow of compressible fluids, non-Newtonian fluid flow, gas absorption, distillation, and drying operations were not included in this course. The course was taught using instructor-developed materials that included lecture slides, reading notes, and a glossary of terms. Problem sets were developed by the instructor as well. The course had a unit operations approach. Enrollment in each class offering varied between 20 and 30 students, and this course has been

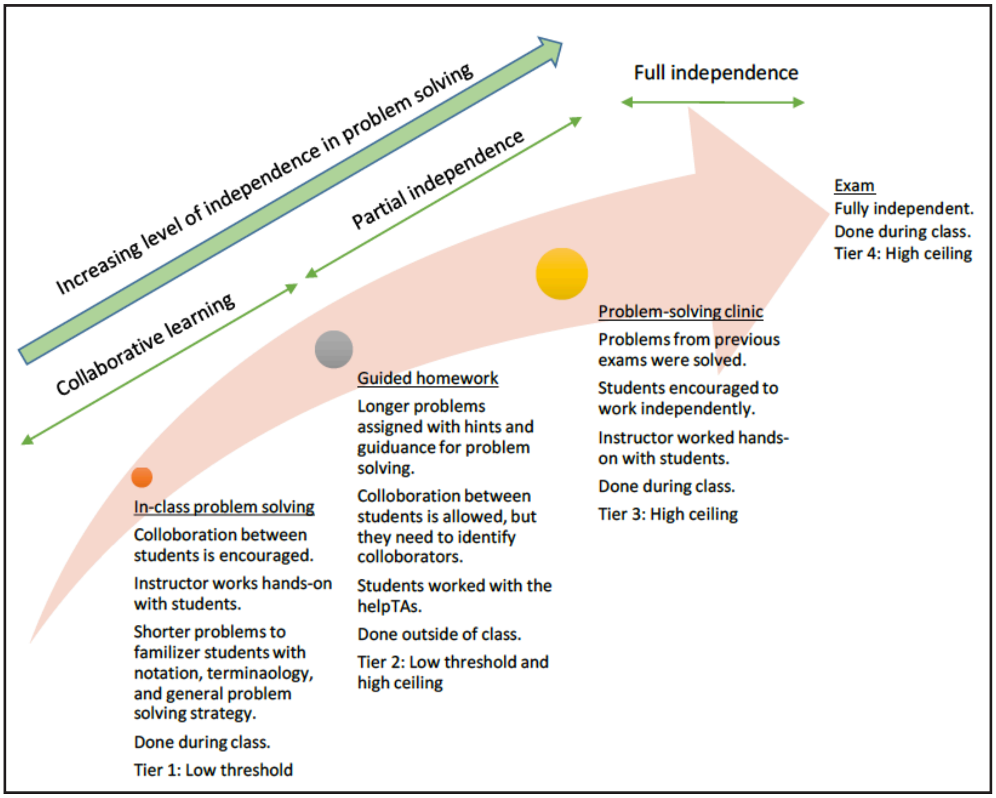
TABLE 2

Select examples of applications of fluid mechanics and mass transfer principles in physiology and bioprocess.

Transport principle	Applications presented in class
Fluid statics	Pressure vs. liquid height profiles in a bioreactor, centrifuge operation
Fluid flow phenomena	Blood flow in arteries and capillaries, differential separation of cells
Bernoulli equation	Blood flow in the circulation system, fluid flow in a bioreactor piping systems
Flow past packed solids (Ergun equation)	Flow in tissues, flow in chromatography columns
Motion of solids in a fluid	Settling velocities in a centrifuge, dispersion of virus particles in air
Mixing and agitation	Flow patterns and power requirements in bioreactors
Convective mass transport in liquids	Transport in blood dialyzer, artificial kidneys, oxygen transfer in bioreactors
Diffusive mass transfer in solids	Drug transport in tumors and in transdermal patch, transmembrane cellular transport
Equilibrium-stage operations	Extraction processes, chromatography (adsorption)

offered in its current form for the past four years.

Since the entrance survey results indicated that students wanted to apply fluid mechanics to physiological systems, several applications in physiology were included along with bioprocess examples. Table 2 provides a representative list of applications covered in this course. Several problems and exercises (in-class problems, homework, problem solving clinic, and exams) were related to either bioprocess or physiology. These problems and exercises demonstrated to students the relevance of fluid mechanics and mass transport to biotechnology.



In-class problem solving
Colloboration between students is encouraged.
Instructor works hands-on with students.
Shorter problems to familizer students with notation, terminaology, and general problem solving strategy.
Done during class.
Tier 1: Low threshold

Guided homework
Longer problems assigned with hints and guiduance for problem solving.
Colloboration between students is allowed, but they need to identify colloborators.
Students worked with the helpTAs.
Done outside of class.
Tier 2: Low threshold and high ceiling

Problem-solving clinic
Problems from previous exams were solved.
Students encouraged to work independently.
Instructor worked hands-on with students.
Done during class.
Tier 3: High ceiling

Exam
Fully independent.
Done during class.
Tier 4: High ceiling

Figure 1. The four-tier collaborative learning approach for progressive independence in quantitative problem solving.

TIERED, COLLABORATIVE LEARNING FOR PROGRESSIVE INDEPENDENCE IN QUANTITATIVE PROBLEM SOLVING

Quantitative problem solving in fluid mechanics and mass transfer can be daunting for nonengineers. To ease students into independent problem solving, the new four-tier sequential approach developed by the author in this work was used (Figure 1). The first tier is the in-class problem-solving exercise embedded in every lecture. In-class exercises were shorter problems or parts of larger problems, and were directly related to the lecture material. The instructor worked with students to solve in-class problems. Students were encouraged to collaborate and help each other in solving problems. Benefits of collaborative problem solving are well documented in the literature.[18,19] In-class exercises helped students in getting used to notations, nomenclature, and units, and it helped the instructor to identify gaps in conceptual understanding of the material. Since students were able to complete solving problems during class, it gave them a sense of accomplishment and improved their self-efficacy. As a result, there was greater engagement from students during class. The association between higher self-efficacy and improved academic success is widely reported.[20] Higher self-efficacy is also known to improve cognition and motivation for learning.[21]

Problem statement:

Fermentation media is pumped out of a large tank at a rate of 100 L/h. The media level in the tank is constantly maintained at 0.5 m. Determine the horizontal distance between the tank outlet and the pipe outlet. The pump is located immediately after the tank outlet and delivers 50 J/Kg of energy. The pipe delivering the media is angled at 30° positive vertical and is 2-in diameter. Assume 100% pump efficiency and no friction losses. Media tank and the pipe outlet are open to the atmosphere. $\mu_{media} = 0.89$ cP, and $\rho_{media} = 990$ kg/m^3.

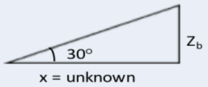
HINT: It will be useful to draw a pictorial representation of the problem statement and annotate it with known distances, pressures, velocities, and angles, and mark the unknown distance. ASSUMPTIONS: What assumptions can be made about liquid velocity on the surface of the tank, when compared to the velocity at the pipe outlet.	
This is a problem in energy balance. Set-up the Bernoulli equation between the two points – one at the top of fluid and the other at the pipe outlet.	**Write and substitute all terms in the Bernoulli equation**
Estimate pipe velocity using flow rate and cross sectional area of pipe	**$v_b = Q/A$, $v_b = ?$**
Rearrange Bernoulli equation to determine vertical height of the pipe outlet	**z_b = (rearranged expression), then z_b = ?. Use v_b from above.**
From the height and angle, use the appropriate trigonometric relationship to estimate the unknown distance.	 **Estimate x =?**
CAUTION: Use the right unit conversions, and use the appropriate correction factor for the velocity term based on Re in pipe.	

Figure 2. *Example of solution strategy provided to a homework problem to facilitate LTHC and progressive independence in problem solving.*

Second tier is the guided biweekly homework assignment with longer problems. To point students in the right direction, problem-solving guidance was provided. The guidance included solution hints, notes on potential mistakes, or solution templates that helped students to break down bigger problems into smaller, manageable portions. An example guidance is shown in Figure 2. With the help of written guidance, students were able to start working on the problems without getting stumped at the beginning. Students were allowed to collaborate in solving homework problems but were required to identify their collaborators. Homework was the most comprehensive problem-solving opportunity that involved collaboration and engagement from students, TAs, and the instructor. Homework contributed to 30% of course grade. Through homework, students were trained in extensive problem solving that is common in engineering courses.

Third tier is the biweekly problem-solving clinic after the homework had been completed. Problems from previous exams were assigned during the clinic. No guidance was provided and students were encouraged to work independently. The biweekly problem-solving clinic was not graded, but students were expected to participate. The clinic trained students to independently solve problems and prepared them for the exam. Nuances and tips for problem solving were discussed during the clinic. It also provided an opportunity for the instructor to address persistent gaps in students' understanding of the subject material. Due to close interactions with students during in-class problem sessions and the problem-solving clinic, the instructor was able to identify and pay attention to students who needed extra help.

Fourth tier is the biweekly exam that followed a few days after the clinic. The exams tested students' mastery in problem solving and conceptual understanding that were progressively developed through the first three tiers of the learning process. The students were comfortable and confident going into the exam because they were familiar with problems of various depth and rigor. Students worked independently during exams that contributed to 70% of the course grade. The first (in-class problems), third (problem-solving clinic), and fourth tier (exam) exercises were done during class time, while the second tier (homework) was done outside of class.

LOW THRESHOLD HIGH CEILING (LTHC) APPROACH TO TEACH FLUID MECHANICS AND MASS TRANSPORT

The number of math courses taken by students in the fluid mechanics and mass transfer course varied from one to six with a majority having taken two or three math courses. Their GRE quantitative reasoning scores varied from 40th to 99th percentile with a majority in 80th-99th percentile range. Thus, students enter this course with a diverse range of quantitative problem-solving skills. The LTHC approach was used to accommodate the significant diversity of quantitative problem-solving skills of students in this course. This approach has its origins in teaching computer programming skills to new learners, which was later adapted to high school[22] and college education.[23] LTHC refers to a course design where the initial tasks and topics are at a level where all students will be able to access them, followed by a progressive increase in the intensity of topics that are suitable for advanced learners. This course has an assortment of exercises that allow students to pick those that are at their comfort level. This allows students to work at paces and depths that are more suitable to them. In this approach, the work towards a solution is more important than the solution itself.

The four-tier approach to independent problem solving complements the LTHC method. Students start problem solving with solution hints and hands-on help from the instructor. Students also work collaboratively among themselves to solve problems. The in-class problem-solving exercise provides a safe environment for students to learn without the risk of judgement or critique. The entry threshold for this step is low and supportive for students of all quantitative abilities. Students can learn concepts and problem solving at their own pace and in groups. Students also use the in-class problem-solving sessions to ask the instructor about concepts they did not understand during the lecture. Quantitative problems and conceptual questions of various levels of rigor were assigned during the in-class problems, so students could start learning at levels that are comfortable for them and then progressively move to more advanced problems. The guided homework assignments were longer problems with solution hints and solution templates that provided a low threshold to start solving the problems. Students then progressed to advanced steps (high ceiling) with the help of the TA or instructor during office hours. The problem-solving clinic had a mix of mid-level and advanced problems. Students were encouraged to solve problems independently, and collaboration was allowed only with permission. The clinic was skewed towards the high ceiling of LTHC method due to the expected greater independence and rigor of problems. The instructor helped students as needed during the problem-solving clinic. Problem solving during the clinic was timed and it simulated the exam environment, which provided students with insights on the format and rigor of exams. In summary, the in-class problem-solving exercise was a low threshold activity with opportunities to go to high ceiling, the guided homework was a combination of low threshold and high ceiling activities, and the clinic was mostly high ceiling activities. All stages of the LTHC method fostered active student engagement and contribution during class that were indicated as an important attribute for successful learning in the entrance survey (Table 1).

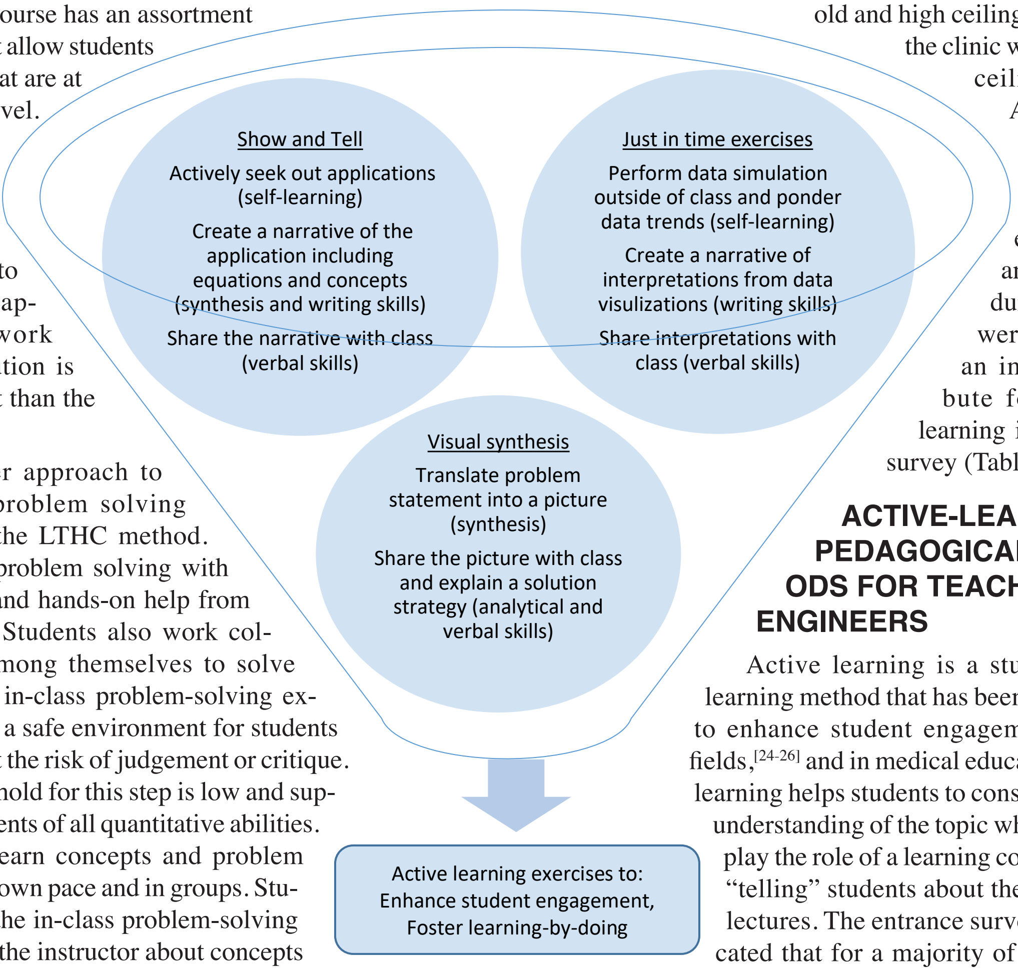


***Figure 3.** Active-learning pedagogical methods used in the fluid mechanics and mass transfer course and the skills developed through these methods.*

ACTIVE-LEARNING PEDAGOGICAL METHODS FOR TEACHING NON-ENGINEERS

Active learning is a student-centered learning method that has been demonstrated to enhance student engagement in STEM fields,[24-26] and in medical education.[27] Active learning helps students to construct their own understanding of the topic where instructors play the role of a learning coach rather than "telling" students about the topic through lectures. The entrance survey results indicated that for a majority of students, contributing to classroom discussions was important to feel confident in the classroom (Table 1). To enhance student engagement, active-learning exercises were developed and integrated in the fluid mechanics and mass transfer course. These exercises took about 15 minutes each and were done either during the lecture or in-class problem-solving sessions. Active-learning exercises were performed in informal teams, *i.e.*, teams that came together *ad hoc* for the purpose of active learning. The skills that students acquired through active-learning exercises are presented in Figure 3. Three active-learning exercises were used in this course.

Show-and-tell is an exercise where students display an item or exhibit and discuss it with the class. The display item could be an object, short piece of writing, picture, brief presentation, novel problem-solving technique, etc. The show-and-tell

TABLE 3
Representative examples of show-and-tell exercises presented by students.

Exhibit	Principles used to explore the exhibit
Pump energy required to deliver water from a nearby water treatment plant to a student's apartment	Pressure, height, velocity relationships explored using Bernoulli equation
Water pressure required to percolate through Keurig coffee machine K-cup	Pressure drop required for flow through packed bed explored though Ergun equation
Minimum air flow rate required for a paint sprayer to work	Pressure drop-velocity relationships explored using Bernoulli equation
Ground water contamination due to prolonged perchloroethylene exposure on soil surface	Diffusive mass transfer in solids explained using Fick's law
Deposition of DNA in microchannels	Buffer evaporation rates explored using principles of one-component diffusion flux
Bioreactor for cartilage regeneration	Substrate and oxygen transfer explored thorough principles of diffusion in rectangular and cylindrical coordinates

exercise typically explored the application of a topic that was recently discussed in class. Show-and-tell exercises were assigned a few days ahead of time to student teams chosen by the instructor. Students self-assembled in informal teams on the day the exercises were assigned. About 10-15 minutes of class time was set aside for active-learning exercises that included show-and-tell. The active-learning exercises were not graded. Due to time constraints, groups did not share or compare their show-and-tell exercises, but the assigned teams presented their work to the class. Representative examples of show-and-tell exercises presented by students are given in Table 3. Show-and-tell exercises presented an opportunity for the class to explore the applications of a particular topic, understand the limitations of theoretical relationships, and practice communication skills.

Just-in-time (JIT) teaching is an active-learning method in which students are assigned a piece of reading or an exercise to complete outside of class and discuss it during the class. When examining equations where several variables are related though complex mathematical relationships, the effect of input variables on the response may not be immediately evident. The effects become particularly puzzling when multiple variables are varied at the same time. The JIT method was used to visualize and analyze mathematical relationships through simulation of equations. Simulations developed in Excel were presented to students. Simulation results appeared as graphical visualizations that readily showed trends and patterns in variables. An example of a JIT data visualization exercise is shown in Figure 4. Students had the option to enter variable ranges or data into spreadsheet columns to visualize the responses. Students were assigned to generate data visualizations and then actively share their interpretations during class. JIT exercises led to vibrant explorations on the interpretation of data trends and the limitations of equations.

Visual synthesis is a pedagogical method that is known to enhance cognition and retention of knowledge.[28] The value of visual synthesis and pictorial representation in problem solving through improved organization and communication of ideas are discussed in the literature.[29] Active-learning exercises based on translating a problem statement into a picture were developed. In this exercise students were asked to represent a problem statement as a hand-drawn picture and then annotate the picture with input and output variables, notation, values, and vectors. Students did their own pictorial representation of the problem during in-class problems (collaboration encouraged) and the problem-solving clinic (solo work encouraged). The instructor assisted students with visual synthesis as needed. The pictorial representation helped students to identify the known and unknown variables and to determine the steps in problem solving. Beside active learning to understand the problem statement, this exercise provided an opportunity for the instructor to discover any lack of conceptual understanding and proactively address it during the in-class problem-solving sessions.

COURSE ASSESSMENT

After completing the fluid mechanics and mass transfer course, students progressed to take three graduate-level bioprocess engineering courses—bioprocess engineering 1, which covered upstream bioprocessing; bioprocess engineering 2, which covered downstream bioprocessing; and a bioprocess engineering lab course, which covered hands-on experimental methods in bioprocessing. Graduate-level courses had students with undergraduate degrees in both nonengineering (who took the fluid mechanics and mass transfer course) and chemical engineering. Comparison of grades secured by the nonengineer and engineer groups in graduate-level courses is presented in Figure 5. The nonengineer group performed reasonably well in graduate-level courses, but a modest difference in performance was observed between the nonengineer group and engineer groups in bioprocess engineering 1 and bioprocess engineering 2 lecture courses. These courses are quantitatively and analytically rigorous, and require fluid mechanics and mass transfer as prerequisites. It should be noted that in a typical chemical engineering undergraduate program, fluid mechanics and mass transfer subjects are offered as two full courses covering much broader topics, and

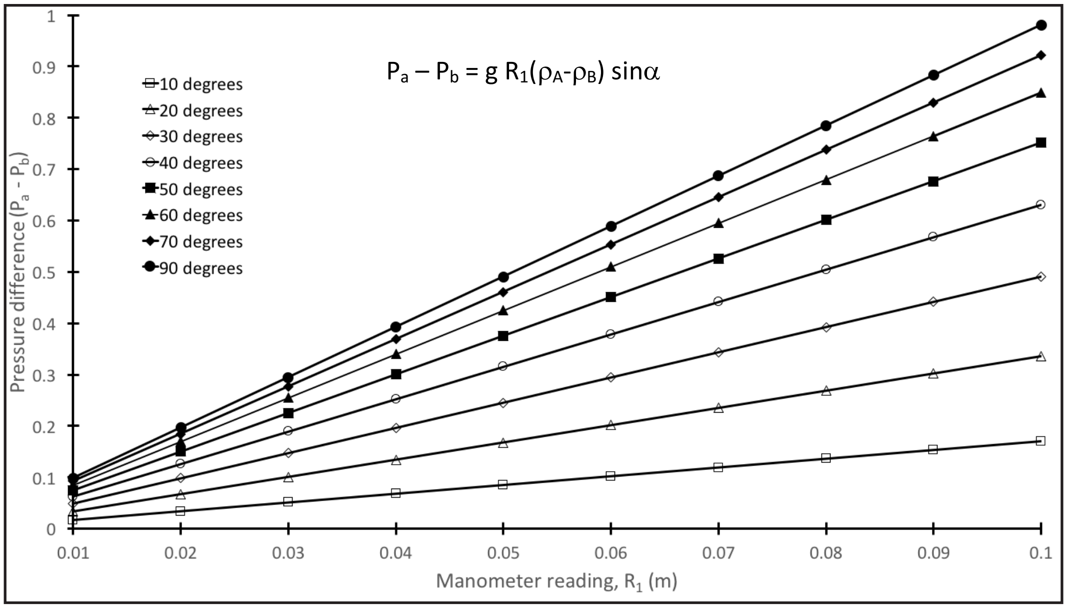


Figure 4. *Example of a JIT data visualization exercise. This exercise was used to visualize the effect of inclination angle on the relationship between pressure difference and manometer reading in an inclined manometer. The equation that was simulated to generate the data for visualization is included.*

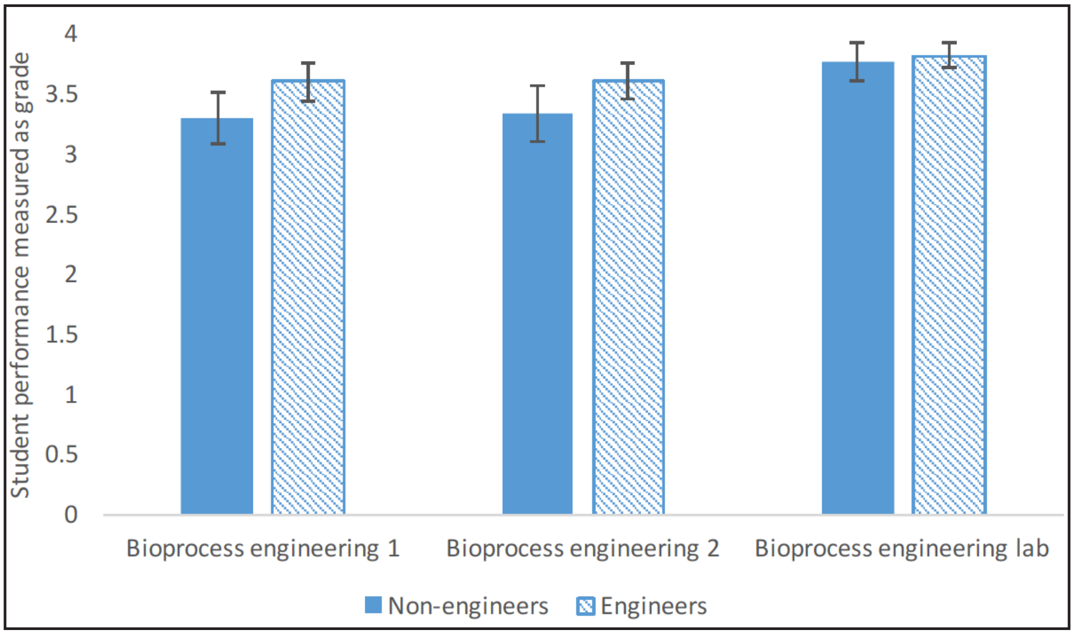


Figure 5. *Comparison of performance between nonengineer and engineer student groups in graduate-level bioprocess engineering courses.*

students are required to take many more quantitative engineering courses. Hence the engineer group can be expected to be better prepared to take graduate-level bioprocess engineering courses. Nevertheless, the nonengineer group performed close to the engineer group, indicating that the fluid mechanics and mass transfer course provided an adequate prerequisite to this group. In contrast, there was no difference in performance between nonengineer and engineer groups in the bioprocess engineering lab course. This is because the lab course has predominantly hands-on and data-analysis exercises and nominal quantitative problem-solving exercises. The nonengineer group was able to handle quantitative problem solving in the lab course with equal competence as that of the engineer group.

Pairwise correlation coefficients between student performance in the fluid mechanics and mass transfer course and graduate-level bioprocess engineering courses were estimated using JMP Pro13.0. Data presented in Table 4 (next page) indicate that student performance in the fluid mechanics and mass transfer course and bioprocess engineering 1 and 2 courses are highly correlated. Thus, student performance in the fluid mechanics and mass transfer course is a strong predictor of student performance in bioprocess engineering 1 and 2 courses. In contrast, there was no significant correlation between student performance in the fluid mechanics and mass transfer course and the bioprocess engineering lab course, indicating that the skills acquired in the fluid mechanics and mass transport course are not directly related to success in the bioprocess engineering lab course. Interestingly, student performance in bioprocess engineering 1 and 2 courses is not correlated with student performance in the bioprocess engineering lab course. Thus, the skill sets required for the success of nonengineers in the

TABLE 4
Pairwise correlation of student performance in fluid mechanics and mass transfer course with graduate-level bioprocess engineering courses.

	Fluid mechanics and mass transfer	Bioprocess engineering 1	Bioprocess engineering 2	Bioprocess engineering lab
Fluid mechanics and mass transfer	1	0.996	0.997	0.008
Bioprocess engineering 1	0.996	1	0.998	0.004
Bioprocess engineering 2	0.997	0.998	1	0.007
Bioprocess engineering lab	0.008	0.004	0.007	1

bioprocess engineering lab course are different from the skill sets required for success in bioprocess engineering 1 and 2 lecture courses, and these skill sets are not imparted through the fluid mechanics and mass transport course.

FUTURE DIRECTIONS

Course and teaching evaluations completed by students over the past five years were examined to identify directions for future course improvement. As a part of course and teaching evaluations, students were asked to offer suggestions for improvement. The following themes emerged after a manual analysis of students' narrative comments:

1. *Students formed* ad hoc *teams when working collaboratively on in-class problems and active-learning exercises. But students often self-selected into teams with individuals whose proficiency was similar to themselves. Therefore, the* ad hoc *teams had students with similar abilities and lacked intellectual diversity. As a consequence, students with a longer learning curve felt discouraged to work with advanced performers.*

2. *Classroom discussions provided a clear theoretical basis of the subject. But, an exposure to experimental methods and tools used in fluid mechanics and mass transfer would place the theoretical understanding in a practical applications context.*

3. *Theoretical concepts underlying the equations were not intuitive and were hard to visualize. It would be an improvement if the lectures and exercises can help develop a visual image of the process or the concept.*

Based on this feedback, new pedagogical methods will be implemented in the future. Students will be assigned to teams by the instructor based on their prior quantitative problem-solving skills. Teams having students with a wide spectrum of problem-solving skills and personalities will be formed. In the future, short experiential learning modules will be added to complement the lectures. Experiential learning modules will include table-top experiments and virtual lab modules available online. The experiential modules will be linked with corresponding lecture topics during the module period, and done in the teams that are formed for in-class problem-solving and active-learning sessions. To facilitate visual learning, video learning modules and animations available online will be used. YouTube videos on topics such as Pascal's law, particle segregation in fluid flow, friction factor experiment in horizontal pipe, and mixing in stirred tanks will be used to provide a visual description of theoretical concepts. Other sources for virtual learning modules such as the AIChE Concept Warehouse will be explored.[30]

CONCLUSIONS

Experiences in this course show that it is possible to successfully develop and deliver a fluid mechanics and mass transfer course for nonengineers. Designing the course based on a combination of traditional and student-expected learning outcomes, and the implementation of teaching methodologies guided by student feedback were immensely valuable. The online educational modules for math review saved lecture time and were an essential tool throughout the course. The newly developed four-tier learning approach and the complementary LTHC method fostered collaboration, improved student engagement, and increased student self-efficacy, all of which resulted in a better learning experience. The hands-on, active-learning exercises facilitated peer-learning and a greater interaction between the instructor and students. The pedagogical methods developed and used in this course can be readily adapted to other engineering courses for nonengineers, and to courses that introduce students to new subject areas.

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