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Teaching Fluid Mechanics and Mass transport to Biologists
Introduction:

Teaching chemical engineering to non-chemical engineers presents a myriad of challenges ranging from course development to delivery to evaluation. However, these challenges reflect the expanding scope of chemical engineering profession and as a consequence the chemical engineering education. The American Institute of Chemical Engineers Centennial report in 2008 noted that “Chemical engineering today is a field dedicated to the engineering of molecular systems, applying principles from underlying sciences (e.g., chemistry, biology, material science, and applied physics) and systems engineering (e.g., applied mathematics, operations research, and computer science)”\(^1\). This definition immediately implies chemical engineers crossing over to several other disciplines, and in reciprocity professionals from other disciplines crossing over into chemical engineering. This crossover is particularly true to the field of biotechnology which calls for an intimate partnership between chemical engineers and biologists. The explosive growth of biotechnology and related industries into an enterprise worth several billion dollars and the fact that about 50% of all drugs will be biologics by 2014 has persuaded many biologist and chemical engineers to migrate towards a career in biotechnology\(^2\). This migration is evident from the fact that employment of chemical engineers in biotech/pharmaceutical industry increased from 5.7% in 1996 to 11.3% in 2007 while employment in conventional chemical industries dropped from 33.3% to 25.5% during the same time period\(^1\).

To satisfy needs of the interdisciplinary biotechnology profession, several undergraduate chemical engineering programs have added at least one biology course to their curriculum. However, biology programs in the United States have yet to include a course of engineering nature to their curriculum. Nevertheless, several biologists work in the biotechnology profession thus interfacing with an increasing number of chemical engineers. Also many contributions of chemical engineering research to biological processes has made chemical engineering a ubiquitous part of the biotechnology enterprise. Thus biologists aspiring to succeed in biotechnology profession have a need to learn the basics of chemical engineering in order to communicate and operate effectively in a cross-disciplinary environment.

The course presented in this paper was developed and is being taught for biologists who aspire to start a career in biotechnology / pharmaceutical industry. This course has evolved over the past few years to satisfy two often conflicting pedagogical goals – deliver fluid mechanics and mass transport concepts without much diluting the ‘engineering nature’ of the subject matter, and at the same time ensure that the students who are not used quantitative instruction receive and adequately assimilate the course material. A few challenges, experiences, teaching methods, and assessment methods for achieving these pedagogical goals are discussed in this paper. There have been some previous efforts to teach chemical engineering to non-chemical engineers either in web format or in intense workshop/boot camp format\(^3,4\). While this paper uses some prior knowledge it will primarily focus on a biologist student group with special reference to the biotechnology industry. But, concepts presented here can be readily adapted to address the needs of other student groups.
The challenge:

Three major challenges can be identified in developing an engineering course for biologists:

i) Engineers and biologists have different styles of learning – engineers tend to learn through quantitative and analytical methods while biologists are more comfortable with descriptive and illustrative learning. Hence several well-known and established methodologies for teaching fluid mechanics and mass transport cannot be applied to the biologist student group.

ii) The non-existence of usual prerequisites among biologists - students usually have had very few (often just one or nothing) mathematics courses during their undergraduate study. Usually the class has a significant minority of chemists who have better exposure to mathematics and quantities problem solving. Students certainly did not have anything close to the usual prerequisite sequence that is typically required in a chemical engineering curriculum. This presents a challenge to teach fluid mechanics and mass transport in the absence of mathematics or basic quantitative problem solving abilities.

iii) Another critical challenge is the general unavailability of instructional materials to teach fluid mechanics and mass transport to non-engineers. All available textbooks cater to the needs of chemical or other engineers and assume some prior knowledge in engineering and also an extensive math prerequisite.

The discussion that follows will elaborate on the strategies used to meet the above challenges.

Course objectives and learning outcomes:

The first effort in developing this course was to determine and communicate the course objectives and the expected learning outcomes. The following are the listed course objectives:

• Introduce fluid mechanics and mass transfer, and establish its relevance to biological processes.
• Develop fundamental principles underlying the subjects of fluid mechanics and mass transfer.
• Demonstrate the application of fluid mechanics and mass transfer in design and operation of biotechnology unit processes.
• Prepare for productive interactions with chemical engineers and/or for upper level biological engineering courses.

A synchronous set of learning outcomes for this course is listed below. Students who complete this course will be able to:

• Apply concepts of fluid mechanics and mass transport to biological processes.
• Identify and solve fluid mechanics and mass transport problems as it relates to biological processes.
• Employ the right mathematical and quantitative methods for solving engineering problems.
• Attain sufficient understanding of subject and confidence to interface effectively with chemical engineers.
• Collaborate in teams.
• Prepare written reports and oral presentations.

Mathematics review module:

It is impossible to adequately teach fluid mechanics and mass transport without basic mathematics. The intent of this course is not to retrain biologists to make them chemical engineers but rather to equip them to effectively interface with chemical engineers in a professional environment. As a first step, a brief mathematics study/review module was developed in calculus, trigonometry and algebra. Both web-based resources and instructor-developed materials were used. Mathematics problems, theories and concepts included in this module had immediate relevance to various derivations and calculations in fluid mechanics and mass transport. Several example and exercise problems were supplied as a part of review module. It should be noted that no mathematics was taught in a formal lecture format. Review materials were made available to students for self-study and followed up with tutorial sessions conducted by either a teaching assistant or the instructor. The mathematics module was taught concurrently with the course.

An important aspect of teaching the mathematics module is providing a relevance to the subjects of fluid mechanics and mass transport. This was accomplished by recalling appropriate mathematical technique or theory when analyzing fluid mechanics or mass transport concepts during class. Handouts and lecture slides had a mathematics recall section in the footnote.

Homework assignments problems had hints to the use of right mathematical techniques for problem solving. Also students were allowed to bring a set of basic mathematics equations to the exams (such as standard integration tables, Taylor series expansions, trigonometric functions, etc.). The intent of this module is not to make students experts in mathematics but to make them efficient in recalling and applying mathematics principles to fluid mechanics and mass transport problems.

A picture is worth a thousand words:

Biology education is very much descriptive and terminology based with copious amounts of illustrations. Any typical textbook on a biology topic such as biochemistry, cell biology or molecular biology will make this evident. Usual chemical engineering textbooks with schematic diagrams and equations can be abstract and sometimes monotonous for biologists. Consequently, one can expect biologists to understand a concept better if it is presented as a picture rather than a set to sentences describing a scenario. This was in fact true based on classroom experiences. The value of learning through pictorial representation is well established at many levels of learning. However, several engineering problems and scenarios are often described in words
and not as pictures. Hence, this course emphasized pictorial representation of a scenario as an important part of learning fluid mechanics and mass transport. Students were required to translate every problem or scenario, however trivial it might be, to a hand-drawn picture followed by annotating the picture with notations, directions, vectors, and values. Such exercises provided an opportunity for the students to visualize and convey a complex scenario as a picture and helped them assimilate large amounts of information. A pictorial representation also helped to decipher the unknowns and provided leads on solution methods.

Students largely welcomed and appreciated this approach. For the instructor, this is a good opportunity to identify any lack of conceptual understanding and reinforce those concepts at an early stage. Students were initially required to make a pictorial translation of every problem or derivation they did. After doing this over a period of time, students were able to make some of this visualization in their mind and subsequently were able to solve problems without making a pictorial translation. Experience in this course showed that an initial training in problem solving through pictorial translation followed by its slow phase out helped biologists to embrace the quantitative learning style typical of engineers. This change is crucial for further learning of engineering concepts. Efforts will be made in the future to quantify and study the change in learning style through surveys and other assessment methods.

Smaller is better:

Lengthy problems and derivations in engineering can intimidate non-engineers. But problems in engineering often require lengthy solutions which call for several overlapping concepts and equations to be applied in a particular sequence. It is likely that non-engineering students will be lost in a maze of equations while trying to solve lengthy problems. This difficulty was solved by initially training the students to solve short problems which were at their desired comfort level. Homework assignments had several short problems rather than a few protracted problems. As described in the previous section, pictorial translation was a requirement. Students were then trained to break down a larger problem into several smaller ones and then proceed with the solution.

Creating relevance and a sense of belonging:

Students are most stimulated to receive and assimilate information when placed in an environment that provides an immediate relationship to what they know best\(^{10}\). Concepts are best learnt when students see an application in an area that is natural to them\(^{11}\). In the context of this course, the best subject area that biologist know is obviously biology. Hence it is logical to include biological processes while discussing fluid mechanics and mass transport concepts. Several such examples were included in this course and a few are listed in Table 1.
Table 1: Examples of biological process explained through fluid mechanics and mass transport principles

<table>
<thead>
<tr>
<th>Biological process and the relevant engineering concept</th>
<th>Engineering schematic and equations developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transvascular solute transport explained through combined diffusive (Fick’s diffusion) and convective mass transport</td>
<td><img src="https://example.com/schematic.png" alt="Schematic" /> [ J_s = J_s(1 - \sigma_f)C_m - D_{eff}S \frac{dC_m}{d\chi} = a_1, ]</td>
</tr>
<tr>
<td>Oxygen transfer to cells described through film theory</td>
<td><img src="https://example.com/schematic.png" alt="Schematic" /> [ \pi R_c^2(\nu z C_{B,T}</td>
</tr>
</tbody>
</table>

\[ \frac{dC_L}{dt} = k_L a(C^* - C_L) - q_{O_2}X \]
Besides examples in lecture materials, several fluid mechanics and mass transfer exercise problems that relate to biological processes were developed. Some examples are given below:

(i) Blood flow in the circulation system – Bernoulli equation.
(ii) Drug dissolution – diffusion in rectangular and spherical coordinates.
(iii) Liquid transport through a porous tissue – Ergun equation.
(iv) Rate of facilitated transport through cell membrane – mass transport coupled with reactions.
(v) Flow over an atherosclerotic plaque – Flow past a solid boundary.

To further enhance learning, students were required to do a term paper on a topic that demonstrated applications of fluid mechanics and mass transport in biology. Students were now able to apply concepts they had learnt in class to a biological topic that was of most interest to them. Term papers were evaluated through formal PowerPoint presentations and written reports. The term papers provided an opportunity for the class and the instructor to learn more about biological applications of fluid mechanics and mass transport. Examples of topics presented by students in this course include:

(i) Flow of cerebrospinal fluid and its impact in developmental disorders
(ii) Oxygen transport in tissues
(iii) Fluid mechanics of the vascular system
(iv) Impact of hydrodynamic stress on physiological state of cells
(v) Mass transport during drug delivery through a patch.

**Instructional resources:**

Instructional materials for this course were sourced from:

(i) Parts of Unit Operations in Chemical Engineering textbook by McCabe and Smith
(ii) Self-prepared materials, particularly those relating to biology examples
(iii) Web-based course modules and exercises.

**Course assessment:**

It is obvious that the traditional assessment methods and criteria cannot be used for assessing this course. However, some parts of the ABET “a to k” program outcomes were found to be relevant and hence were adapted for evaluation this course. A few criteria from biology education were included to evaluate the lesser quantitative aspects. A modified ABET ‘a to k’ outcomes for evaluation of this course is given in Table 2.

A few ABET outcomes could not be used for evaluating this course. Outcome ‘b’ can be added if a lab module (virtual or real) is included. Outcomes ‘c’ and ‘d’ are at present irrelevant to this course. Outcome ‘f’ is currently an incidental component, but in the future discussions on ethical responsibilities will be expanded. Biologists typically have had ‘adherence to ethical practices’
as significant part of their undergraduate education and this knowledge can be extended to engineering situations. Outcomes ‘i’ and ‘n’ were accomplished primarily through term paper which was done in teams.

**Table 2:** Modified ABET program outcomes used for evaluation of a fluid mechanics and mass transport course for biologists.

<table>
<thead>
<tr>
<th>Program outcome criteria</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. An ability to apply knowledge of mathematics, science and engineering</td>
<td>3</td>
</tr>
<tr>
<td>b. An ability to design and conduct experiments, as well as to analyze and interpret data</td>
<td>_</td>
</tr>
<tr>
<td>c. An ability to design a system, component or process to meet desired needs</td>
<td>_</td>
</tr>
<tr>
<td>d. An ability to function on multi-disciplinary teams</td>
<td>_</td>
</tr>
<tr>
<td>e. An ability to identify, formulate and solve engineering problems</td>
<td>2</td>
</tr>
<tr>
<td>f. An understanding of professional and ethical responsibility</td>
<td>i</td>
</tr>
<tr>
<td>g. An ability to communicate effectively</td>
<td>2</td>
</tr>
<tr>
<td>h. The broad education necessary to understand the impact of engineering solutions in global/societal context</td>
<td>1</td>
</tr>
<tr>
<td>i. A recognition of the need for an ability to engage in lifelong learning</td>
<td>2</td>
</tr>
<tr>
<td>j. A knowledge of contemporary issues</td>
<td>1</td>
</tr>
<tr>
<td>k. An ability to use the techniques, skills and modern engineering tools necessary for engineering practice</td>
<td>i</td>
</tr>
<tr>
<td>l. An ability to identify and use concepts and theories*</td>
<td>3</td>
</tr>
<tr>
<td>m. An ability to employ techniques and conduct analyses*</td>
<td>2</td>
</tr>
<tr>
<td>n. An ability to collaborate (team skills/self-regulation)*</td>
<td>2</td>
</tr>
</tbody>
</table>

A strike through indicates the ABET ‘a to k’ outcomes that were not used for evaluation of this course. 
* indicates outcomes which were adapted from biology education.
"3" = major component (>25%)  
"2" = significant component (10 to 25%)  
"1" = minor component (5 to 10%)  
"i" = incidental component (< 5%)
Future plans:

This course has been and will continuously evolve to satisfy instructional needs of non-chemical engineers. Immediate future plans are: (i) inclusion of a web-based virtual lab module to conduct experiments and analyze data, (ii) inclusion of CHE lab tours and mini field trips to give students a better perspective on engineering concepts, and (iii) expanding the ethics component.

References: