The Evolution of Engineering: 
Incorporating Biology into Traditional Engineering Curriculum 

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Abstract 
Technology is changing more rapidly today than ever before, and it is critical that engineering students are prepared to succeed in a wide variety of developing disciplines. Students should be prepared to apply fundamental concepts of engineering to nontraditional challenges. One emerging area in research and industry is that of biology: as this basic science evolves from being descriptive to quantitative and predictive, academic and industrial engineers are increasingly involved in addressing biological problems. Currently, large chemical companies are expanding in the biological sciences by exploring the genetic engineering of crops, use of bacterial catalysts, and “green” engineering. The engineering departments of universities are also involved by recruiting students and new faculty with an emphasis in environmental engineering and biotechnology. 

How can students be trained in biological topics without time consuming and controversial overhauls of the curriculum? During lectures, the instructor has a unique opportunity to expose students to current developments in emerging areas of research. Students can be trained to solve biological problems with mathematical solutions by incorporating biological applications, examples, and bench-top experiments into the traditional chemical engineering curriculum. Consequently, students learn to use engineering fundamentals to explain and control biological phenomena. 

This paper will discuss methods of incorporating biological applications into fundamental chemical engineering courses, such as thermodynamics, kinetics & reactor design, and transport in order to: 

1) teach students how to apply basic science and chemical engineering fundamentals to describe complex biological phenomena, 
2) help students understand chemical engineering concepts using biological examples, 
3) raise interest in chemical engineering by illustrating biological applications.

I. Introduction
The cover story of the November 23, 1998 issue of Chemical & Engineering News exposed the increased commitment to biology and the life sciences by large chemical companies such as DuPont, Dow, Monsanto, and Hoechst®. In this article, DuPont management states that biotechnology and the life sciences are “cornerstones” and “growth engines” that should coexist within chemical industries®. DuPont predicts that by the year 2002, the life sciences will represent a third of the company’s sales and earnings®. The trend in biological awareness is
also realized by many chemical engineering departments who are currently recruiting new faculty members conducting research in biotechnology. Scientists both in industry and academia are focusing on the economical use of existing biological systems for future, environmentally friendly applications. This need for engineers to adapt to the growth of biology in industry necessitates that all chemical engineering students be familiar with the union of chemical engineering with biotechnology.

Professors in engineering are confronted with the challenge of introducing students to emerging areas of research and development while fulfilling the core engineering curriculum. Bridging college courses with current events in industry prepares students to work on novel engineering applications and to succeed in the ever changing industrial environment. Equally important, introducing the industrial and practical relevance of basic theory and engineering fundamentals in the classroom will engage and motivate student to learn.

This paper discusses the incorporation of biology and biotechnology into the fundamental chemical engineering courses of thermodynamics, kinetics & reactor design, transport and unit operations. Biology can be effectively and rapidly incorporated into these courses by 1) introducing biological applications with respect to the subject matter, 2) solving bio-related problems using theorems taught in the course, and 3) designing simple bench top experiments to illustrate processes of interest and ease of working with biological systems. In this manner, engineering instructors can achieve the dual goals of teaching fundamental engineering principles while demonstrating their application to non-traditional problems encountered in industry.

An introductory course in biology typically involves intense memorization of vocabulary, classifications and processes. Thorough training in the life sciences, however, is not necessary for chemical engineers to understand and appreciate relevant biological processes. To begin, students can become familiar with biological terminology and overall processes by simply discussing biological applications in chemical engineering lectures. Second, biological processes are governed by the same laws of thermodynamics and physics that govern all basic sciences. For example, most of the unit operations in bioprocess engineering are the same as those in classical chemical engineering. Consequently, by including bio-related problems in lectures and homework sets, students will learn how to use the fundamental theorems of thermodynamics, kinetics, and transport to simplify and solve complex biological problems. Finally, bringing bench top experiments into the classroom allows students to see for themselves how the governing theorems do in fact predict biological behavior. Moreover, simple biological experiments demonstrate the ease and economic feasibility of using biological systems for large scale production.

This paper focuses on the incorporation of biology into the traditional chemical engineering curriculum in order to: 1) teach students how to apply basic science and chemical engineering fundamentals to describe complex biological phenomena; 2) raise interest in chemical engineering by illustrating biological applications; and 3) help students understand chemical engineering concepts using biological examples. The ultimate goal is to teach students how to apply their knowledge in engineering to not only biological phenomena but to any non-traditional problem of practical consequence.
II. Thermodynamics

Educators agree that changes must be made to update conventional thermodynamics courses by using examples and citing applications with respect to biology and biotechnology. Thermodynamics is central to theories describing many biological phenomena, including protein folding (the properly folded state is the thermodynamic minima), and the affinities of proteins for protein binding partners and small molecule effectors.

In biotechnology, thermodynamic principles are used to determine the affinities of protein receptors for their ligand binding partners. For example, the binding of erythropoietin (produced by Amgen®) to its cellular receptor was studied extensively prior to commercialization of this peptide hormone. The critical parameters in the analysis of protein binding events are the equilibrium binding constant and the stoichiometry of binding which can be calculated from simple calorimetry experiments. Previously, studies of protein binding reactions were limited by the inability to detect small changes in enthalpy due to binding. Isothermal Titration Calorimeter (ITC) is a micro-scale bomb calorimeter was developed to measure the enthalpy (∆H) of protein/ligand binding events. By titrating one binding partner to generate binding isotherms, kinetic constants can be determined with fair accuracy. Raw data from ITC experiments on receptor-ligand binding can be used to teach students how to calculate the change in free energy, the equilibrium binding constant, and the binding stoichiometry.

The figure above shows typical ITC data of a ligand titration curve presented as ∆H (µcal) as a function of injection number which corresponds to concentration of titrated ligand (M). As an in class activity, students can be provided with the above data, and guided through calculation of the enthalpy of binding, the equilibrium binding constant, and the binding stoichiometry. Equilibrium occurs at the inflection point of the titration curve. Thus, the ∆H can be read as the y-coordinate at that point and 1/ Kₐ is the ligand concentration at that point. The binding stoichiometry can also be determined by converting the injection number of the inflection point.
to the ligand/receptor molar ratio. The value of $K_a$ can then be used to calculate Gibb’s free energy according to:

$$\Delta G = -RT \ln K_a$$

Gibb’s free energy can be used to calculate enthalpy:

$$\Delta S = -\frac{\Delta H - \Delta G}{T}$$

III. Kinetics & Reactor Design

The chemical engineering course most easily modified to incorporate biotechnology is kinetics. At the present time, kinetics courses and textbooks include the topic of enzyme reactions. Moreover, the same reactor design fundamentals taught in kinetics courses are key to the operation of bioreactors in which the desired products are synthesized by living cells. Frequently, bacteria are used for easy, cost-effective synthesis of biological molecules. Students must be aware that in industry the goal is to minimize cost of production. For biological molecules, cost is cut most effectively by producing the desired products in bacteria. However, bioreactors differ from traditional chemical engineering processes in the sensitivity of living organisms, reactants and products to environmental conditions. The following example illustrates how bioreactor conditions such as the concentration of waste products and flowrate are critical for successful operation:

You are running a continuous-stirred tank reactor of volume $V$ with the goal of maximizing cell concentration. Accumulation of waste products in the reactor results in cell death. Production and consumption of cells, substrate, and waste are described by the following reaction network:

Substrate $\rightarrow$ cells + waste $\rightarrow$ cell death

$\text{r} = k_1 C_s C_c$

$\text{r} = k_2 C_w$

where $C_s$, $C_c$, and $C_w$ are concentrations of substrate, cells, and waste respectively; $k_1$ and $k_2$ are rate constants. What is the optimal residence time of the CSTR that maximizes concentration of cells in the effluent. What is the critical flow rate $Q$ that would result in “washout” of the reactor (when $C_c = 0$).

This example illustrates basic principles in reactor design such as residence time and flowrate. At the same time students are exposed to the use of bacteria in bioreactors and the nuances of working with living organisms.

Another subject covered in kinetics is the collection and analysis of rate data in order to calculate reaction orders and reaction rate constants. The empirical determination of the
reaction rate order(\(\alpha\)) and the reaction rate constant (\(k\)) can be illustrated in an experiment monitoring the growth of bacteria (an irreversible reaction) in a batch reactor (test tube) during the course of a lecture. A test-tube culture can be inoculated with bacteria prior to class (time = 0) and allowed to grow throughout the lecture. Absorbance readings using a spectrophotometer (\(\lambda= 600\) nM) can be taken at time intervals during the lecture and the data can be recorded in terms of absorbance of cell suspension versus time. Absorbance can be converted to concentration of cells according to 1 optical density unit = 0.3 mg dry cell weight / ml. During the lecture, students are instructed to plot the data according to:

\[
\ln \left( \frac{dC_A}{dt} \right) = \ln k + \alpha \ln C_A
\]

from the relationship

\[
- \frac{dC_A}{dt} = k C_A^\alpha
\]

where the slope of the line = \(\alpha\) and the intercept = \(k^\beta\). The reaction rate constant (\(k\)) in this case is the growth rate of bacteria.

This experiment can be made more interesting and visually stimulating by introducing a protein product synthesized in bacteria during growth that can be easily visualized. The \textit{lux} gene from the \textit{Vibrio fischeri} has been cloned into conventional bacteria (e.g. \textit{E. coli}) which consequently produce the luciferase protein. Luciferase is a luminescent protein that “glows in the dark”. Therefore, by having multiple test-tube cultures with different concentrations of cells, the concentration of protein produced by the cultures can be visualized by simply turning off the lights. This experiment visualizes accumulation of protein product in the batch reactor by bacteria over time while introducing students to the field of genetic engineering.

IV. Transport Phenomena

The fundamentals of momentum, heat and mass transport are central to not only chemical engineering but also medical and physiological studies. Blood flowing through the circulatory system delivers nutrients and removes waste products from tissue via diffusion. Similarly, the lungs remove carbon dioxide and oxygenate the blood by diffusion. Thus, there are many examples in the human body that can be used to conceptually illustrate key transport concepts. Physiological examples also can be introduced as simple problems that can increase in complexity to bring students to a sophisticated understanding of concepts.
For example, a common illustration of the Navier-Stokes Equation is that of a sphere in flowing liquid. The biological counterpart would be a spherical cell under flow conditions in a vein with blood flow of constant velocity. When the basic equations are understood, more realistic conditions can be implemented. For example, the cell is not spherical, but has the concave ellipsoid shape of a typical red blood cell; the cell is in an artery with pulsating flow patterns; the cell is an immune cell bound to a vessel wall receptor. In order to illustrate the effect of diffusivity constants, consider a cell with only a lipid bilayer as its boundary devoid of any pores or transport proteins. Potassium ions are critical to the cell’s survival, but the positive ion is very insoluble in the hydrophobic boundary layer. Diffusion can be modeled as:

$$\frac{\delta c}{\delta t} = D_{K^+, \text{lipid}} \nabla^2 c_{K^+}$$

where $D_{K^+, \text{lipid}}$ is very small.

The mammalian cell has devised a solution which takes advantage of the higher diffusivity of a potassium ion in aqueous solution, while maintaining most of the protective selectivity of the lipid bilayer. Proteins are introduced to span the cross section of the lipid bilayer to form aqueous channels through which potassium ions can diffuse. This can be modeled in a similar fashion as above, however now a fraction of the surface area has a very high diffusion coefficient,

$$\frac{\delta c}{\delta t} = ((SA_{\text{lipid}} * D_{K^+, \text{lipid}}) + (SA_{\text{pore}} * D_{K^+, \text{aqueous}})) \nabla^2 c_{K^+}$$

where $D_{K^+, \text{aqueous}}$ is large, and $SA$ represents the fractional surface area of the cell. Diffusion through channels can be visualized during lecture with a simple demonstration. Two dialysis bags filled with water and dye are placed in two beakers filled with water. One bag represents the cell without protein pores; the second bag represents a cell with protein pores created by poking small holes in the bag. This bench top experiment provides physical evidence of the increased diffusivity in membranes with the addition of aqueous pores.

V. Unit Operations

The chemical engineering curriculum culminates in the unit operations laboratory where all theorems and fundamentals are tested on hands-on experiments. Unit operations provides not only practical field training, but also an ideal forum for practicing inductive versus deductive teaching. Inductive learners prefer to see specific cases first (i.e. observations and examples) and work up to governing principles and theorems. The majority of lectures, however, are designed for deductive learners by introducing general principals followed by deduced consequences and applications. Interestingly, research proves that inductive approaches to education promote deeper learning and longer retention of information. With this fact in mind, a unit operations course can be easily transformed into an inductive learning experience by simply introducing the problem before the solution. Introducing a specific unit operation by first describing the process or operation, and then allowing students to induce possible mathematical and scientific explanations for that process renders lectures not only inductive but also interactive.
Traditional chemical engineering unit operations have equal counterparts in biotechnology as well as physiology. For example, after production, therapeutic proteins are subject to numerous purification steps, including ultra-centrifugation and column chromatography to separate proteins by size; anion and cation columns to separate by charge; affinity chromatography using antibodies which specifically recognize the desired protein; and ultra-filtration for concentration. Biological operations or physiological phenomena that parallel chemical engineering operations can be used as examples in inductive exercises. For example, a lecture on heat exchangers can begin by asking the class to figure out: "Why don’t penguins feet stick to ice?" Penguins feet are in fact counter-current heat exchangers. Warm blood leaving the body and traveling towards the feet is cooled by cold blood traveling from the feet back to the body and visa versa. In this fashion the penguins body remains warm while its feet are always cold thus minimizing heat loss to the ground. Penguins feet can be modeled simply as a counter-current heat exchanger composed of multiple arteries and veins with anti-parallel flow. Ironically, nature devised counter-current heat exchangers long before engineers. Ultimately the use of simple physiological examples to describe intimidating unit operations helps students understand and retain the governing fundamentals.

Conclusions

Although science and technology have changed drastically in the past thirty years, traditional chemical engineering courses have remained stagnant. For example, transport courses continue to use Bird, Stuart and Lightfoot’s text which was originally published in 1960. Older chemical engineering text-books are outdated because they rely on examples almost exclusively from the petrochemical industry. Focusing on a single field fails to inform students of the broad range of applications for chemical engineering principles. Engineering instructors must therefore take extra measures to prepare students for careers in modern-day industry and academia. Graduating engineers must have the skills to handle non-traditional problems and also be able to address emerging areas of research and development. One such emerging area within the chemical engineering giants is biology. The gap between the traditional chemical engineering curriculum and industrial awareness of biology and the life sciences can be bridged by simply incorporating biology and biotechnological into lectures using problem examples and laboratory demonstrations.

Bibliography


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