BIOCHEMICAL ENGINEERING

Taught in the Context of Drug Discovery to Manufacturing

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Biochemical engineering courses are an important part of the chemical engineering curriculum. They introduce students to the rapidly growing field of biotechnology and to the application of chemical engineering principles in the analysis of a nontraditional system.

Typically, biochemical engineering courses begin with the basics of the cell, followed by the basics of cellular machinery, and end with aspects of process design. In the course described here, these traditional topics and concepts in biochemical engineering are taught in a practice-oriented context, using the process from drug discovery to manufacturing as a framework and flowchart for the course. Therefore, each lecture's relevance to the drug-discovery-to-manufacturing process is presented. For instance, students learn how an understanding of the cell is essential for both developing a drug against a disease and for designing a cell-culture process.

The main goal of this biochemical engineering course is to provide a foundation and an overview of the fascinating field of biotechnology and of the role of a chemical engineer, as a scientist *and* a citizen, in implementing this technology. This paper presents

- *Activities for engaging students in learning the biological basics*
- *The drug-discovery-to-manufacturing process*
- *A description of two course projects*
  - *One designed to explore the societal and ethical issues involved in the application of biotechnology*
  - *Another designed to explore the scientific and business aspects of the biotechnology and pharmaceutical industries*

Providing an interesting, relevant, and connected framework for presenting the concepts, and engaging students in learning through in-class activities and projects, are guiding principles applied in the design of this course.[1]

DEFINING THE SCOPE OF THE BIOCHEMICAL ENGINEERING COURSE

At Northeastern University, our biochemical engineering course (CHEU630) is a senior-level, semester-based chemical engineering elective. A fraction of the students have taken high school-level biology but most have not taken college-level biology. As a result, a quarter of this semester-based course—six of 24 lectures—is devoted to covering biological basics, or an understanding of the cell and how it functions. These basics are detailed in the next section (as well as in the course-topic schedule found on the course Web site[2]). Throughout this course, chemical engineering principles such as material balances, transport phenomena, kinetics, and sepa-

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rations are applied either to analyzing biological problems or to designing a cell-culture process.

The scope of this biochemical engineering course is first defined and introduced to the students by using the definition of biochemical engineering found in Shuler and Kargi[3]: "Biochemical engineering has usually meant the extension of chemical engineering principles to systems using a biological catalyst to bring about desired chemical transformations."

In this course, the concept of a biological "catalyst" is interpreted in its broadest sense. For instance, the biological catalyst of choice can be a biological polymer, a cell, an organ, or a whole organism. The spectrum of biological catalysts and the basis for choosing the biological catalyst are presented using Figure 1.

Desired chemical transformations include

- *The production of useful compounds (e.g., vitamins, amino acids, antibiotics, other small-molecule drugs, enzymes, hormones, or antibodies)*

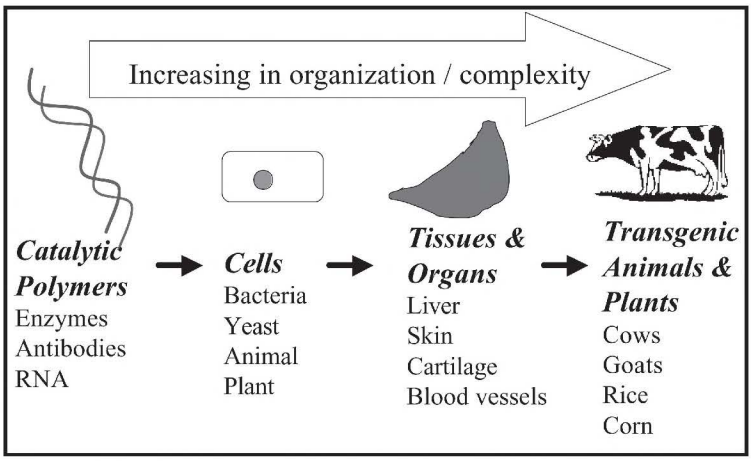


Figure 1. *Biological "catalysts" used for accomplishing chemical transformations.*

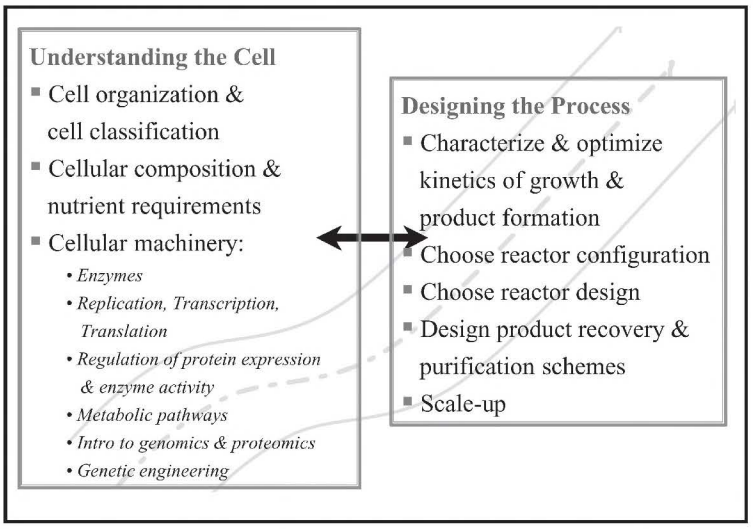


Figure 2. *Course topics taught in context of drug discovery to manufacturing.*

- *The utilization of alternative substrates (e.g., cellulose, lactose)*
- *The degradation of hazardous compounds (e.g., polychlorinated biphenyls or PCBs)*

The biological catalyst is chosen based on the complexity of the desired chemical transformation. In the simplest case, for instance, a chemical transformation can be performed using one or a few specific catalytic biological polymer(s) such as enzymes, catalytic antibodies, and catalytic ribonucleic acids (RNA) or ribozymes. For example, amylase and proteases—enzymes found in detergents—help break down starch-based and protein-based stains in clothing.

If a series of reactions is required to accomplish the desired chemical transformation, we can resort to the enzymatic network housed within a cell by using bacterial, yeast, fungal, animal, or plant cell cultures. Examples include the use of genetically engineered cultures of the bacteria *Escherichia coli* to produce human insulin (by Eli Lilly and Company), or the use of cell cultures of the Pacific yew tree to produce the anti-cancer drug paclitaxel from simple-media components (by Bristol-Myers Squibb Company).

With tissues or organs as the biological catalyst, different cell types are present which together perform chemical transformations (*e.g.*, in the liver) or provide physical structure (*e.g.*, cartilage and blood vessels) not possible with just one cell type.

In the most complex case, a collection of "unit operations" and "reactors" such as those found in a whole animal or green plant may be required. Examples include the use of transgenic cows to produce a therapeutic protein in their milk (by GTC Biotherapeutics), or genetically modified plants containing a vaccine (by ProdiGene, Inc.).

After the spectrum of biological catalysts is introduced through Figure 1, the course focuses primarily on the application of catalytic biological polymers and cell cultures to accomplish the desired chemical transformations.

With the scope of the course defined, a list of course topics and their relationships is then presented using Figure 2. A detailed course-topic schedule with the associated reading assignment is also given to the students and can be found on the course Web site.[2] Students are then introduced to the course flowchart (Figure 2) and shown how the course topics are taught in the context of drug discovery to manufacturing.

Emphasized in this overview and throughout the course is how the design of a process utilizing bio-

logical catalysts is intricately dependent on an understanding of the biological catalyst itself. For example, the activity of enzymes is sensitive to environmental conditions including temperature, pH, salts, and solvents. Cells are also not fixed but house their own process control that can change in response to the environmental conditions. As a result, the process design must cater to the needs and health of its biological catalyst for the process to be productive. Thus, a more comprehensive understanding of biological catalysts is necessary and is presented in the course first.

PRESENTING THE BIOLOGICAL BASICS

The biological basics, *i.e.*, an understanding of the cell and how it works, are divided into the following lectures in this course:

- *Cellular organization and cell classification*
- *Cellular composition and cell-culture nutrient requirements*
- *Cellular machinery*

Through in-class activities (presented below) students are involved in considering the impact of biology on the desired chemical transformations and the process design. These in-class activities are intended to help students *make connections* between information in order to draw out concepts rather than simply *memorize* seemingly "unrelated" information.

Cellular Organization and Cell Classification

The goal of this lecture and in-class exercise is to help students understand how the type of cell—*i.e.*, procaryotes vs. eucaryotes, Gram-positive vs. Gram-negative, bacterial/fungal/animal/plant—impacts the types of products formed as well as the design and operation of a process.

The professor can first set the context by discussing the types of cultures applied in industrial processes and the classification of these cultures as procaryotes or eucaryotes. Then an overview of the major differences between procaryotic and eucaryotic cells and the organization within the cell can be presented. The professor can note that choosing the cell-culture system is one of the first steps in developing a cell-culture-based process, thus establishing the relevance of understanding the differences between cell types before choosing an appropriate cell-culture system.

An in-class activity engages students in thinking about the characteristic differences between procaryotic and eucaryotic cells and the implications of these differences. Having read the textbook assignment prior to class, students are asked to make a table with one column listing the characteristic differences between procaryotic and eucaryotic cells, and a second column listing their implications (in terms of the ease of

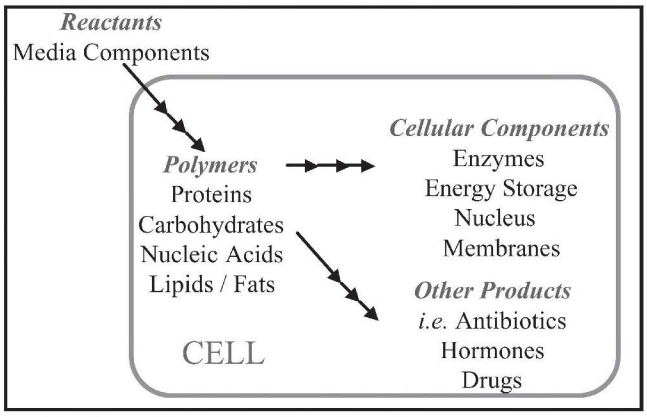


Figure 3. *The conversion of media components into cellular components and other products.*

TABLE 1
Differences Between Procaryotic and Eucaryotic Cells and the Implications of These Differences

	Characteristics	Implications
	Presence of nuclear membrane (only in eucaryotes)	Affects the ease and applicability of genetic engineering techniques
	# of DNA molecules (>1 for eucaryotes)	Affects ease of genetic manipulation since knowledge of gene's function is limited to certain organisms
	Type of cell membrane	Affects ease of protein secretion (*i.e.*, the difference between the membrane architecture and protein secretion characteristics of Gram-positive and Gram-negative bacteria)
	Cell size	Affects shear sensitivity of cells
	Presence of specific organelles (only in eucaryotes)	Allows localization of specific conditions and reactions; allows sequestration of molecules that are toxic to the cell
Specific Examples	*Vacuole*	*Sequesters ions such as H^+ and small molecules in plant cells; the recovery of molecules stored in the vacuole can be difficult*
	Lysozyme	*Houses digestive enzymes, away from other activities within animal cells*
	Chloroplast	*Forms glucose from CO_2 and H_2O in the presence of light in plants; has its own DNA and replicates independently of the cell*
	Mitochondria	*Breaks down carbon sources for energy; also has its own DNA and replicates independently of the cell*
	Endoplasmic reticulum	*Site of lipid and protein production*
	Golgi apparatus	*Site of glycosylation reactions and packaging of proteins*

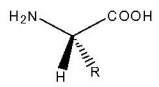
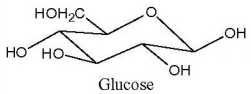
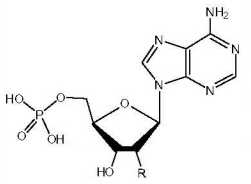
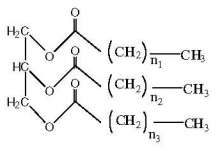
genetic engineering, ease of product secretion, shear sensitivity, or types of products made).

The professor can lead by giving one or two examples and then encouraging the students to work in groups of two to list other examples with the help of their textbook; a sample comparison is shown in Table 1. After about 10 to 15 minutes, the professor can review these differences using a completed table and elaborate on the implications, or the professor can ask students to participate by having them write and review one example on the board.

Specific examples explaining these differences and their implications are given below.

- *One main difference between procaryotes and eucaryotes is the absence or presence of organelles, i.e., specialized compartments with phospholipid membranes that confer selective permeability. These specialized compartments allow different environmental conditions (e.g., different pH, different enzymes, different ion concentrations) to be housed within the cell and hence different types of reactions to occur. For example, protein glycosylation reactions are required for producing an active protein with proper targeting and stability characteristics. These reactions take place in the Golgi apparatus and the endoplasmic reticulum after the initial protein is formed in the cytoplasm. Hence, the implication is that eucaryotic cell cultures would be the biological catalyst of choice if the desired product were a glycosylated protein.*
- *Another example of the importance of cell type on the process is the use of Gram-positive versus Gram-negative bacteria. Since Gram-positive bacteria have a single outer membrane, proteins are more likely to be secreted using this type of bacteria than with Gram-negative bacteria. Hence, the implication is that Gram-positive bacteria would be preferable since the recovery of a secreted protein is more cost-effective than the recovery of an intracellular protein.*
- *Differences in the size of the cell have implications on the operation and scale-up of a bioreactor. For example, due to their smaller size, bacteria are more resistant to shear than animal or plant cells and can be grown in a highly agitated, aerated stirred tank rather than requiring a specialized bioreactor.*

TABLE 2
Chemical Structure, Function, and Composition of Monomers/Polymers in the Cell

Monomer / Polymer	Chemical Structure (Elemental Composition)	Function / Localization in the Cell	% of Polymer[5]
Amino acids / Proteins (20 amino acids)	 R = functional group Illustrate primary, secondary, tertiary, quaternary structure (C, H, O, N, S)	Functions include physical structure, regulatory (as hormones), catalytic (as enzymes), transport (as membrane pumps), & protective (as antibodies); protein are localized in membranes & in the cytoplasm & throughout the cell	50% by dry wt
Monosaccharides / Polysaccharides or Carbohydrates	$C_n(H_2O)_n$  Glucose (C, H, O)	Functions as energy storage molecules, structural component of cell wall, component of DNA & RNA, component of glycosylated proteins which is important for protein targeting & stability	15 -35%
Nucleotides / RNA & DNA	 R = H → DNA R = OH → RNA (C, H, O, N, P)	Functions as molecules for energy storage (ATP), for encoding the cell's characteristics (DNA), for encoding instructions for protein production (RNA); localized in the nucleus, in organelles such as mitochondria & chloroplasts, and in the cytoplasm as t-RNA, mRNA, r-RNA.	10 – 20%
Fatty acids / Lipids or Fats	 (C, H, O)	Functions as energy storage molecules, regulatory molecules (hormones), and components of the cell membrane (composition affects the membrane's permeability characteristics)	5 – 15%

Cellular Composition and Cell-Culture Nutrient Requirements

The goal of this lecture and in-class activity is to help students link the cell-culture nutrient requirements to the cellular composition and to the desired products formed. Figure 3[4] is first used to depict the cell as the ultimate alchemist: It begins by transforming simple raw materials in media such as sugars and amino acids into biological polymers (*e.g.*, proteins, carbohydrates, nucleic acids, lipids, and fats); those polymers then either make up the cell (*e.g.*, phospholipid membranes, enzymes, nucleus, and energy storage such as glycogen and starch) or are converted into valuable complex bioactive molecules/polymers (*e.g.*, vitamins, amino acids, antibiotics, other small-molecule drugs, enzymes, and antibodies). Stated simply, the student's role as the biochemical engineer is to maintain healthy cell cultures and coax them to make the desired product.

The optimization of growth and product media is therefore one aspect of process development for maintaining viable and productive cell cultures. With this context, students are then asked to consider the monomers/polymers that make up the cell and deduce the nutrients in the medium needed for making these essential monomers/polymers.

For example, students are asked to make a table with headings shown in Table 2, listing the major monomers/polymers that make up the cell, their

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chemical structure and elemental composition, their function or localization in the cell, and their percent composition in the cell.

Similar to the previous in-class exercise, students should have read the assignment prior to class and are then encouraged to work in pairs to complete the rest of the table with the help of their textbook. Again the professor can lead by giving one or two examples first. After about 10 to 15 minutes, the professor can either review and elaborate on this material using the completed table, or have each pair of students participate by writing and reviewing one example on the board.

Based on the composition of these polymers in the cell (Table 2), students are then asked to determine the important elemental macronutrients—*e.g.*, C, H, O, N, P, S, etc.—and to order the expected prevalence of these macronutrients in the culture medium. Students can then confirm their answers by studying the medium compositions of bacterial, yeast, animal, and plant cell cultures,[6] *i.e.*, that the carbon source is supplied at the highest concentration. They can also compare the differences in the medium compositions of these cell cultures, and learn about the appropriate form to supply these nutrients. For instance, sulfur is fed as a sulfate salt in plant cell culture medium, but in animal cell cultures it's in the form of amino acids (cysteine and methionine).

Two points should be emphasized and connected:

- *The main media components provide the carbon backbones, or skeletons, for making the main cellular polymers, the product of interest, and the energy sources for the desired chemical transformations.*
- *The media also contains micronutrients (e.g., various metal ions, hormones, and vitamins) and inducers which are critical for maintaining the culture health and for inducing or directing the cellular activities toward growth or product formation.*

Hence, medium optimization involves more than just closing the material balance between inputs (media components) and outputs (cellular polymers, desired products). It requires an understanding of the cellular machinery involved in these chemical transformations and the application of that knowledge (such as by the addition of hormones or inducers) toward directing those cellular processes appropriately.

Cellular Machinery

At this point in the course, students have gained an understanding of: (1) how the selection of cell type/culture affects the kind of product made or the design of the process, and (2) the importance of the medium composition on growth and product formation. Next, the course addresses (3) how the cell makes the biological polymers and the desired products, and (4) how the cell regulates which and how much of these products to make. The inner workings of the cell, *i.e.*, its cellular machinery, are then covered in the order shown in Figure 2 (or see the more detailed course-topic schedule). The tools used in genomics and proteomics are then presented as the current approach to probing and expanding our understanding of the cellular machinery. Once the basics of cellular machinery are covered, the tools of genetic engineering are introduced as a means of altering the native, existing cellular machinery to either: produce a new protein previously not made by that cell culture, or enhance or inhibit the production of an existing protein.

Examples from the biotechnology and pharmaceutical industries are used to show the application of these topics to understanding disease mechanisms, to discovering and designing drugs to target a disease, and to enhancing the production of biological compounds from cell cultures. Examples are drawn from various sources such as those noted in the following sections on the drug-discovery-to-manufacturing process and on the survey of a biotechnology or pharmaceutical company.

PRESENTING AN OVERVIEW OF DRUG DISCOVERY TO MANUFACTURING

Before embarking on the engineering aspects of designing a cell-culture process, the path from drug discovery to manufacturing is presented in one lecture. Although the course is taught using the drug-discovery-to-manufacturing framework, a greater understanding of its overview was achieved when it was presented *after* covering the biological basics. This lecture also illustrates the multidisciplinary effort involved in discovering and bringing a drug to market—highlighting the role and contribution of chemical engineers to this endeavor.

The topics covered include

- *Ways that drugs intercept the biochemical pathway of the disease (e.g., by interfering with such biochemical steps in the cell as receptor-ligand binding, signal transduction, transcription, translation, or enzyme activity)*
- *Ways that drug hits are discovered or screened using whole-cell assays or target assays*
- *Sources of these drug molecules (e.g., natural-product libraries, combinatorial chemistry libraries, targeted synthesis, drug modeling)*
- *The goals and steps involved in the initial testing of a drug's effectiveness or safety (e.g., characteristics such as adsorption, distribution, metabolism, excretion, and toxicology)*
- *The goals of the new investigational drug application (IND), the new drug application (NDA), and the different clinical trials (e.g., Phase I, II, III)*
- *Steps involved in developing a cell-culture process*
- *Cost and time associated with the drug-discovery-to-manufacturing process and the likelihood that a drug hit becomes a prescribed drug*

Web sites for the Food and Drug Administration (FDA),[7] the Pharmaceutical Research and Manufacturers of America (PhRMA),[8] and various pharmaceutical/biotechnology companies provide publications, examples, and resources for these lectures. For example, an FDA publication, *From Test Tube to Patient: Improving Health Through Human Drugs*,[9] presents an overview of the drug-development process.[10] In addition, the FDA Web site provides drug information such as a drug's chemical structure, the mechanism of the drug in targeting disease, use of the drug, and its side effects.[11] A final project on surveying a pharmaceutical or biotechnology company (covered later in this paper) also provides examples of how specific drugs work and how they are made.

PROJECT ON SOCIETAL AND ETHICAL IMPACTS OF BIOTECHNOLOGY

Project Description

Scientists and engineers need to understand the impact of their discoveries and technologies on society. Our students are the future scientists and engineers who will be involved in determining the policies that regulate (*i.e.*, promote and restrict) these discoveries and technologies for the benefit and protection of society. In this project, students choose a contemporary bio-related technology under debate, and evaluate the issues regarding the application of this technology. Serving as an advisory board, students weigh the societal and ethical impacts of a specific biotechnology and then propose their recommendations on its appropriate use in written form. Contemporary biotechnologies that have raised concerns regarding safety and/or ethics are

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listed and can be introduced using Table 3. References from news and popular-science magazines such as *Time* and *Scientific American* are also listed in Table 3 and can serve as a starting point for this project.

Project Specifics

Students, working in groups of two or three, research, brainstorm, and debate the issues behind the use of their chosen bio-related technology and then present their evaluation in written form as an editorial (five pages maximum). In evaluating the technology of interest, they are first asked to (1) briefly explain the science behind the technology, and (2) summarize the benefits, risks/drawbacks, and other issues, noting if these issues are hypothetical or real. Finally, they are asked to synthesize their proposal on the application of this technology by (3) presenting an argument for or against the application of the technology of interest and the conditions under which the technology should be limited, and (4) formulating their recommendations on the application of this technology. Posted on the course Web site[12] are sample student reports exploring the societal and ethical impacts of two such technologies: genetically modified crops and cloning.

Several ABET criteria[13] are covered through this project: Students investigate a contemporary issue (Criterion 3j); evaluate the societal and ethical impacts of biotechnology (Criterion 3h); work in a team consisting of members with potentially different views (Criterion 3d); and practice communicating their evaluations effectively and logically (Criterion 3g).

TABLE 3
Topics for Exploring the Ethical and Societal Impacts of Biotechnology

Debated Biotechnologies	References
Human cloning Since the cloning of Dolly (the sheep), society has speculated that the reproductive cloning of humans was just a matter of time. While many are opposed to the reproductive cloning of humans, the use of therapeutic cloning remains highly debated. The goal of therapeutic cloning of human cells is to generate stem cells, *i.e.*, cells which give rise to new tissue and organs. Both types of cloning utilize a similar technique which starts with an egg and the replacement of its nucleus. Will therapeutic cloning yield replacement parts for damaged organs or serve as the precursor to reproductive cloning?	[17, 18]
Genetic alterations in human embryos The science fiction movie *GATTACA* portrays a society where genetically engineered babies are the norm while babies born by natural means become the discriminated, or the untouchables, of society. With the human genome already sequenced, gene sequence(s) which code for a devastating disease can potentially be corrected. Could this lead to the elimination of diseases or the age of designer babies?	[19 - 24]
Genetically modified crops (GMCs) Crops such as rice, soybeans, corn, and potatoes have been genetically engineered to enhance their yield, nutritional content, resistance to diseases or pests, or tolerance to specific environmental conditions such as drought or soil salinity. Crops have even been genetically engineered to produce therapeutics such as vaccines. Could this be the solution to world hunger or to the high cost of pharmaceuticals and biological compounds?	[25 - 30]
Transgenic animals Animals such as cows, goats, or chickens have been genetically engineered to produce therapeutics in their milk or eggs. It has been suggested that producing therapeutics through animals may be far more economical than through cell cultures in bioreactors. Fish such as salmon have also been genetically engineered to be fast-growing to satisfy the growing appetite of consumers for fish. Could transgenic animals be the solution to the high cost of pharmaceuticals and biological compounds?	[31]
Availability, patent, and ownership of genetic sequences The genome of several organisms has been sequenced. Determining what each gene codes for is the next task. Who has the right to own or benefit from these gene sequences? Should genetic tests be required or elective? Particularly with the human genome, should the genetic sequences of individuals be made available and if so, to whom?	[32 - 36]
High cost of pharmaceutical drugs The high cost of some pharmaceutical drugs has made them unaffordable to those in the U.S. and in Third World countries. What contributes to the high cost of these drugs? How can these drugs be made available to those who need them without crippling the companies that discover and produce these drugs?	[37 - 39]

The scope of this biochemical engineering course is first defined and introduced to the students by using the definition of biochemical engineering found in Shuler and Kargi[3]: "Biochemical engineering has usually meant the extension of chemical engineering principles to systems using a biological catalyst to bring about desired chemical transformations."

This project is assigned on the first day of class since students are already acquainted with these debated issues in the news. The project is only to be completed after the biological basics have been covered in class (see course-topics schedule). The project comprises 10 percent of the course grade and is graded equally on two components:

- *The quality and completeness of their evaluation of the technology (i.e., in terms of the science and the issues pertaining to this technology)*
- *The support for and the logical presentation of their recommendations for the application of the technology of interest*

PROJECT SURVEYING A BIOTECHNOLOGY OR PHARMACEUTICAL COMPANY

Project Description

Students survey a company of interest—potentially a company in which they are seeking employment—to learn more about the scientific and business aspects of the biotechnology and pharmaceutical industries. The goals of this project are

- *To illustrate that a company has an underlying scientific platform or approach for targeting a disease*
- *To demonstrate how an understanding of biology is critical to determining a treatment for intercepting a disease*
- *To gain a sense of the time and resources invested in researching a disease and in developing a drug or treatment for that disease*
- *To prepare students for a job interview*

Resources for this project include company Web sites, company annual reports, *Chemical & Engineering News,* news periodicals, technical journals, and the FDA Web site.[11] Other references such as medical dictionaries, biology textbooks, or anatomy and physiology textbooks, will be useful for understanding and addressing the question of how the drug targets the disease.

The company surveys from individual students can then be compiled in a notebook or file for the entire class to use in their job searches. An example of one student's survey on Genentech has been posted on the course Web site.[14]

Project Specifics

In surveying a company, students research the following questions (presented in a handout):

- *What is the company's mission or approach? For instance, does the company target specific diseases such as cancer or those that affect the immune system? What is the company's platform or technology for targeting diseases or for discovering drug leads?*
- *List examples of research areas. Are they related? Generally, a great deal of research in the basic sciences is required to understand a disease or develop a drug compound for targeting that disease.*
- *List the important accomplishments in the company's history that may have helped them become established as a biotechnology or biopharmaceutical company.*
  - *For example, companies may start as drug-discovery companies and license their discoveries to another company for manufacturing. As more of their drugs make it to market, these companies evolve into bigger entities and eventually build their own production facilities. Genentech is such an example.[15]*
  - *Another example is Pfizer, a company that was not initially involved in fermentation. Before 1939, Pfizer was producing citric acid from lemons.[16] When the price of lemons increased dramatically, it was no longer economical to extract citric acid from lemons and Pfizer pursued an alternate means of producing citric acid using mold. By turning "lemons into lemonade," Pfizer became well-positioned for the large-scale fermentation required to produce penicillin from mold during World War II.*
- *List two products that are already being marketed by the company. What is each product used for? How does each product work, i.e. its mechanism for targeting the disease? What type of drug is it? How is it made, i.e. from genetically engineered*

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bacterial or mammalian cell cultures, from extraction of a natural source, or from chemical synthesis?

► *List two products in the pipeline. What stage are these drugs at, i.e. Phase I, II, or III clinical trials, or approved by the FDA for production? What is each product used for? How does each product work? What type of drug is it? How is it made?*

This project is assigned on the first day of class to help students initiate their job search. It is due after the lecture on the drug-discovery-to-manufacturing process, in which specific examples are presented. The project comprises 10 percent of the course grade and is graded based on the quality and completeness of the answers to the above questions; for instance, do the answers demonstrate an understanding of the mechanism of the drugs' actions?

CONCLUSION

The following are student comments from teaching evaluation forms of this course:

- *Gave us an understanding of how every lecture would be used and how it fits in with the rest of the quarter.*
- *Activities in the course encouraged the student to learn and apply the material.*
- *Made the class fun and informative.*
- *Outside assignments were relevant and took a reasonable amount of time to finish.*
- *The material was an excellent overview of what is needed to work in biotech.*
- *I really strongly consider this as a potential career field.*

Through this course, students see the connection of each lecture to the drug-discovery-to-manufacturing process. In-class activities such as those presented in this paper were effective in communicating biological fundamentals and their implications. In addition, students were engaged in two projects designed to

- *Explore the societal and ethical issues involved in the application of biotechnology*
- *Explore the scientific and business aspects of the biotechnology and pharmaceutical industry*

The course covered the basics required for working in the area of cell-culture process development in an interesting and fun way without overburdening last-semester seniors.

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