Adapting Chemical Engineering Education to Increasing Job Diversity

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University of Notre Dame
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Future Directions in Chemical Engineering Education: A New Path to Glory

ADAPTING CHEMICAL ENGINEERING EDUCATION TO INCREASING JOB DIVERSITY

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Over the past few decades the job diversity for chemical engineers has dramatically increased. While the graduate chemical engineering educational experience has responded to the expanded diversity in the job market, the undergraduate curriculum has remained essentially the same. It is time to adapt the undergraduate chemical engineering curriculum to meet the needs of future graduates. Like other engineering disciplines that have experienced dramatic job diversity, for example, electrical engineering, one option to adapting the undergraduate chemical engineering curriculum to meet the increasing diversity without creating expanded requirements is to create a true track system. My colleagues and I at Caltech have created such a curriculum and have implemented it with success over the past two years.

Motivations for Changing the Undergraduate Chemical Engineering Curriculum

The chemical engineering undergraduate curriculum has changed little since I went through it in the 1970's. I must admit that my undergraduate curriculum was a bit different than the normal one at that time in that I fulfilled my chemical engineering requirements while simultaneously completing the requirements for entrance into medical school. At that time, a dual program was somewhat new in chemical engineering, but it gave me the opportunity to explore biology and medicine as an undergraduate engineer. For example, my undergraduate research project was conducted under the guidance of a professor of biology and involved understanding a neural network in sea clams. On the down side, I had to overload courses for most of my years of study and go to summer school in order to finish in four years. I mention this experience because it brings out two important points that I will emphasize here: (i) chemical engineering has provided a core program for the fundamental understanding of coupled chemical and physical phenomena that can be applied to any problems involving atoms, molecules or materials and its use in biologically-related problems is not new, and (ii) the curriculum has been and will always be a large and challenging one.

What has changed since the 1970's? First, in the 1970's the majority of the largest companies in the US (11 of the top 15) were based on petroleum and/or chemicals processing while in the 1990's, less than 20% of the top 20 companies were [1]. Today, companies like Microsoft, Cisco, and Intel, dominate global markets. Second, as expected from the first point, the diversity of jobs for chemical engineers has followed this trend away from the petrochemical industries. For example, in 1975 over 75% of the jobs taken by chemical engineers were with industries involved in fuels and/or chemicals processing [1]. By 2003, only 45% were initially placed in those industries while biotech and electronics/materials industrials employed approximately 15% and 10%, respectively (see Table 1 for recent data and Fig. 1 for the 2003 values) [2]. Third, the expanding job diversity now includes many opportunities on Wall Street, in Venture Capital Firms, in large consulting firms like McKinsey, and other opportunities that exploit the fact that chemical engineering students are typically some of the brightest on any campus rather than the specifics of their education. Fourth, there is a growing trend that chemical engineers will not work with the same company that they initially enter for their career. They will have several job changes over the lifetime of their career, and these will likely span several types of jobs in different types of industries. Fifth, undergraduate students now tend to compare and take into consideration the requirements and flexibility of a curriculum when choosing a discipline to a much greater extent than previous generations of students did. Not to say that in the 1970's we selected chemical engineering to prove that we could conquer the most difficult curriculum (as it was and still is the most difficult one on most campuses), but it was not such a determining factor as it is today.

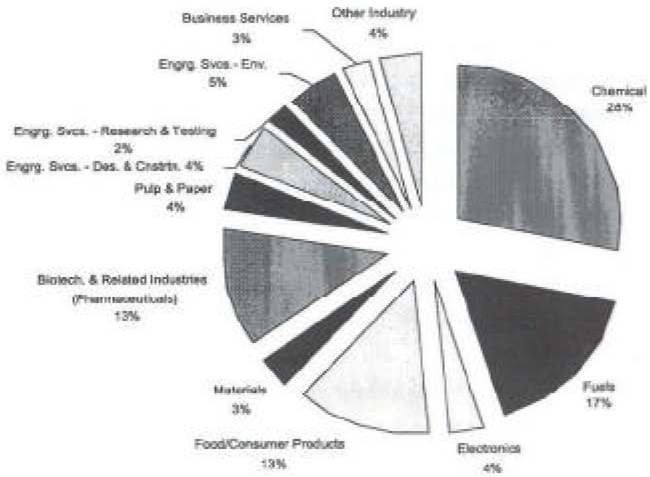
Given at least these five relatively recent changes, how should the undergraduate chemical engineering curriculum respond? I provide below one possibility that we have implemented at Caltech to address these issues.

Table 1. Breakdown of industrial employment for the 37.9% of Bachelors (B.S.) chemical engineering graduates who found work in industry [2].

	'01-'02	'00-'01	1999	1998
Chemical	30.8%	23.3%	26.7%	26.1%
Fuels	21.3%	15.7%	12.6%	10.8%
Electronics (e.g., computers, software development, chip manufacturing)	4.2%	15.9%	15.6%	11.4%
Food/Consumer products	11.2%	10.6%	11.4%	14.6%
Materials	2.3%	3.1%	3.3%	6.0%
Biotech & related industries (pharmaceutical)	10.3%	9.3%	6.9%	4.6%
Pulp & paper	1.1%	2.1%	2.4%	2.9%
Engineering Services : Design & construction	8.0%	5.6%	4.8%	7.2%
Engineering Services: Research & testing*	0.6%	1.8%	2.4%	
Engineering Services: Environmental engineering	3.9%	2.4%	2.6%	2.6%
Business Services*	2.8%	5.8%	6.4%	
Other Industry	3.5%	3.9%	4.8%	13.0%
Public utilities	-	-	-	0.8%

*Category added in '99-'00 survey

Figure 1. Breakdown of industrial employment of B.S. chemical engineers, 2003 [2].



The essence of chemical engineering

Chemical engineering is clearly a discipline with a lot to offer. The fact that graduates can find employment in such diverse industries attests to this statement. Thus, any curriculum for undergraduate chemical engineering must maintain certain qualities. In my opinion, the premise of chemical engineering education should be to clearly teach individuals fundamental science and engineering, and to do so in a manner that provides them with skills to continue a lifetime of self-education so that they can formulate solutions to whatever problems that they face. Given that motherhood statement, I also believe that the following specifics are the essence of chemical engineering:

1. The ability to understand coupled chemical and physical phenomena at all length scales from the atomic to the macroscopic
2. The ability to mathematically describe and predict coupled chemical and physical phenomena that normally lead to highly non-linear behavior

3. The ability to take a systems approach to a chemically-based problem
4. The ability to take an engineering approach to a chemically-based problem; that is to say that problems lacking a complete set of data are still approachable in the sense that a first approximate model is formulated and then refined into further more precise models as they are tested against an increasing amount of experimental data
5. The ability to provide a strong ethical profession that society can count on to do the right thing

A response to the challenges of modern chemical engineering education

Given the motives for change and the essence of what I believe is chemical engineering, how does one provide a solid undergraduate curriculum to satisfy the needs and balance the requirements? After quite some discussion on this, my colleagues and I in Chemical Engineering at Caltech decided to renovate our undergraduate curriculum in attempts to provide the best program for our students that will give them the skills they need for a career in the 21st century. Our solution is based on the following premises:

1. We must have a curriculum that is not overly burdensome in terms of required hours and lack of flexibility
2. We must provide the essence of chemical engineering and do so with increasing emphasis on atoms and molecules and on the translation of fundamental science to engineering principles
3. We must not ignore biology but not become bioengineering; bioengineering and biomedical engineering lack a strong fundamental core and an emphasis on molecular behavior; both are provided for in chemical engineering
4. We must not ignore materials and environ-

mental engineering but rather provide a different perspective on those areas; that is, a strong fundamental core with emphasis on the molecular-level phenomena

5. We must provide for the increasing diversity of employment

To satisfy those premises, we developed an undergraduate chemical engineering curriculum that is a true track system. The basics of this new curriculum are provided in the next section.

A new undergraduate program based on a track system – the Caltech curriculum and experience

While I was executive officer of Chemical Engineering at Caltech (equivalent to a chairman or head of department at other institutions), I was questioning the entire rationale for why undergraduate curricula were constructed as they are. We had just completed another ABET review and I was not in agreement with the suggested changes. Simultaneously, we were observing a decline in the popularity of chemical engineering at Caltech and hearing more and more complaints about the severity of the requirements and lack of flexibility in the curriculum from the students. In a chemical engineering faculty meeting, I stated my objections to the ABET suggestions and commented that we should build a new curriculum that would meet future needs and bring back excitement to the students. The chemical engineering faculty were extremely supportive of moving forward in this direction, if we could get Institute approval. I must say that I am proud of the Caltech administration whose response can be paraphrased as "do what is right for the students." Upon receiving Institute approval to completely re-do the undergraduate chemical engineering curriculum, the chemical engineering faculty as a whole developed a track system to satisfy what we felt were all the necessary needs.

The track system involves two key components; (i) a three year core of fundamental courses that all students must pass and (ii) a full year equivalent of an emphasis area. The emphasis areas or tracks are: (i) materials engineering, (ii) environmental engineering, (iii) biomolecular engineering and (iv) process systems engineering.

The core provides the fundamental background to all those who claim they are chemical engineers. Mathematics, physics, chemistry and biology are included in the core. At Caltech, undergraduate students take freshman and sophomore physics, freshman chemistry and one biology course (one biology course is required of all Caltech undergraduates independent of major). While Caltech has a greater emphasis on physics than most institutions, the remainder of these courses are not unlike those required of chemical engineering students at most universities. Our core involves a full year of organic chemistry because we believe that a solid background in organic chemistry is the springboard to all other areas. Additionally, the core has two quarters of physical chemistry: the quantum theory of atoms and molecules and then the practical application of this theory (spectroscopy). The students do not take the thermodynamics and kinetics portions of physical chemistry because these topics are taught in much greater detail in the chemical engineering courses. There are core requirements in business courses (economics or accounting) and the necessary humanities and social sciences. Finally, there are several chemical engineering core courses (see Fig. 2 for summary). In the freshman year, we conduct a one-quarter introduction to chemical engineering where we inform students about the exciting frontiers of chemical engineering. The sophomore year covers two quarters of thermodynamics, where we now even include statistical thermodynamics to further emphasize the molecular nature of our field, and a quarter of systems analysis. In the latter course, students begin to think about a systems approach to problems and how one might do synthesis of a product. In my opinion (and that of others, e.g., Cussler [1]), we need to think and teach more about synthesis whether this be of a molecule, a material, a process to make a molecule or material or a device. I recall in my own career, when I received the Presidential Young Investigator Award from the NSF in 1986, I was asked what type of research I was going to do with the $500,000. I mentioned that I was going to devote all of the funds to research on learning how to design the synthesis of new zeolites. I was told by a person at NSF that chemical engineers don't do synthesis but rather they do analysis. To that, I said that I could do whatever I wanted with the funds and that the future was in synthesis. It was fortunate that I did not listen to this person. Ultimately, we created VPI-5 in that program and now have gone on to show that synthesis is a key element of chemical engineering.

In the junior year of the core, there is a year long sequence of courses on the molecular basis of transport phenomena. Additionally, there is a quarter course on chemical kinetics and reaction engineering and a new course in the control of chemical systems where the emphasis is on the understanding of chemical networks whether they be of biological origin or not. In all of these courses the key issue is the strong emphasis on molecular-level phenomena and how to deal with it. Finally, there is a two quarter writing requirement for graduation where each student writes the equivalent of a Scientific American article on a scientific topic (I have mentored students on topics such as tissue engineering and advanced applications of zeolites).

The core is three years of full time study. We strongly believe that the engineering design component of the curriculum can be distributed within these core chemical engineering classes. Also, we have recognized that the movement of chemical engineering to the molecular level mandates that we provide more of the engineering fundamentals through science courses rather than courses with engineering labels.

Figure 2. Caltech chemical engineering core course contents.

ChE 10, Introduction to Chemical Engineering (10 wks)

- Weekly lectures from different faculty members
- Speakers from outside Caltech
- Overview of exciting areas of chemical engineering

ChE 63ab, Chemical Engineering Thermodynamics

a(10 wks)	b(10 wks)
• First and second law	• Chemical equilibria
• Phase equilibria	• Statistical thermodynamics

ChE 64, Principles of Chemical Engineering (10 wks)

- Mass and energy balances
- Equilibrium separation processes
- Numerical solutions to linear and non-linear systems of equations

ChE 103abc, Transport Phenomena

a (12 wks)	b (6 wks)	c (12 wks)
• Newtonian flow	• Heat conduction	• Mass transfer
• Complex fluids	• Heat convection (forced and free)	• Diffusion
• Colloidal suspensions	• Radiation	• Convective mass transfer
		• Diffusion - reaction
		• Dispersion - reaction
		• Transport based separation, e.g., membranes, chromatography

ChE 101, Chemical Reaction Engineering (10 wks)

- Homogeneous kinetics
- Heterogeneous kinetics
- Ideal reactor behavior
- Non-ideal reactor behavior

ChE 115, Dynamics and Control in Chemical Systems (10 wks)

- Principles of control
- Chemical systems
- Biological systems

Figure 3. Program for senior year of Biomolecular track in Chemical Engineering at Caltech.

	Topic	Fall Term	Winter Term	Spring Term
1.	Introduction to Biochemistry	Bi/Ch 110 (12)		
2.	Physiology for Bioengineers	BE 201a (9)	BE 201b (9)	BE 201c (9)
3.	Intro. to Bioengineering Design OR Cellular Engineering		BE/ChE 163 (9)	 ChE/BE 210 (9)
4.	ChE Lab OR ChE Lab/Senior Thesis	ChE 126a (9) ChE 126a (9)	ChE 126b (9) ChE 90a (9)	 ChE 90b (9)
5.	Bioengineering electives: BE 200a, 200c, and/or 240		(9)	(9)
6.	Humanities/Social Sciences electives	(9)		(9)
7.	Science/Engineering electives	(9)	(9)	(9)
	Total units per term	(48)	(35-45)*	(36-54)*

*Winter and Spring term total number of units must be at least 78.

The tracks are each the same number of credits and the total amount is one full year. What students have been doing thus far is to begin the track in the junior year and spread it out over the latter two years of the program. Each track has three features to it (see Fig. 3 for the biomolecular track). First, there are core courses that must be taken (items 1-3 in Fig.3). Second, there is a laboratory component (item 4 in Fig. 3). Third, there are track electives (item 5 in Fig. 3). All students are encouraged to do a senior thesis although it is not required (about half do it). As can been seen by the example in Fig. 3 of the biomolecular track, the track system provides a very rigorous emphasis and is definitely not a brief overview of the area. Since only those students who opt for the process systems track will experience a more traditional large scale design experience, we solved the issue of "engineering design" by bringing into the curriculum a one/two quarter open-ended problem. If students choose to conduct a senior thesis, then they address an open-ended research problem for two quarters. Numerous senior theses have led to research publications. If students opt for the second quarter laboratory course (in our denotation, ChE 126b; item 4 in Fig. 3), then they experience a one-quarter open-ended laboratory problem.

We have implemented this track system at Caltech and have gathered about two years of experience. First of all, the students have responded well to it. Our incoming classes have greatly increased in number. For example, our class sizes are now about 10% of the overall class at Caltech of around 200 per year while only having around 4% of the faculty size (around 275 faculty at Caltech). The current students like the program so much that they are helping us recruit new freshmen into chemical engineering each year. Second, although we do not yet have too many years of data, the numbers of students taking each track has been: (i) the materials track has the largest number, (ii) biomolecular and environment are about the same and slightly lower in number than the materials track and (iii) process systems is the smallest. At Caltech we decided to not change our name to reflect areas of biologically-related work. While many other institutions have modified their name, I think that it is important to do what is useful for the local situation at each institution. Personally, I am against name changes since they single out only one area. Given our recent history on the number of students going into each of the tracks, it clearly would have been a mistake on our part at Caltech to emphasis only biology in our name. I am also against the recent discussions on raising the level of biology to place it equal with chemistry. I agree that all students should be familiar with the basic molecular biology and its tools. However, what has given biology and medicine a real boost has been the molecular understanding of biological functions. The key is the chemistry of the molecules of life. Thus, I believe that the emphasis in chemical engineering should be chemistry and its application to other fields such as biology, materials science, electronics fabrication, etc. Finally, I caution against an overreaction to biology. As I mentioned in the beginning of this discussion, chemical engineering was being applied to biology back in the 1970's (and earlier). Additionally. the chemical engineering went through a build-up of bioengineering in the 1980's that ultimately produced too many students who then had to go to the more traditional jobs. The new emphasis on molecular biology is very good, but I caution on overextending chemical engineering once again. While there does appear to be a better job market situation when compared to the 1980's, there are still many parallels. I hope that we, as a discipline, emphasize what we do well and let the market decide whether there is a need. After all, I contend that what makes Bob Langer special in the area of bioengineering is his engineering skills, not his biology. In a book about Judiah Folkman who was Bob's post-doctoral mentor at Harvard's Medical School, Folkman brings this point out by saying "Langer attacked [the problem] with a chemical engineering approach, which is called working the problem, as Folkman recalls. That's fundamentally different from biology, where you discover phenomena, and you don't have many organizing principles. We have Darwin and the double helix. But in chemical engineering you have hundreds of principles and laws. So when you work a problem you pick out the best principle, and then it will explain everything" [3].

The textbook problem

While chemical engineering education is going through significant changes, one the most difficult problems to solve is the textbook problem. As chemical engineering is becoming more and more molecular and diverse, modern textbooks are needed to implement these new curricula. Why is there a problem? First, it is extremely time consuming to write a good textbook. Faculty are overextended as they attempt to meet their professional demands of teaching, research and service. In one survey from university administrators, the writing of textbooks was not included in the top 15 tasks that they viewed a university professor should be engaged in. While faculty normally do not write textbooks primarily for the monetary gain, there should be reasonable compensation. With the sales of books over the web, the whole publishing scenario is now changed. I illustrate this using my recent textbook (*Fundamentals of Chemical Reaction Engineering* by M.E. Davis and R.J. Davis) as an example. McGraw Hill publishes this book in hardcover in the US for approximately $120. The international edition is soft cover and sells for approximately $50. The international editions of books are now available on the web at many sites and students in the US can have the textbooks delivered to their dorm room. This practice raises many issues. First, the royalty income for the author on an international edition is far less than the hardcover. Thus, authors are not receiving compensations as they should when international editions are penetrating the US market. Second, why is the price differential so large between the two versions since the content is exactly the same? If this practice continues as I expect it will, there will be even less motivation for faculty to write new textbooks. One solution to this problem is to alert faculty to the fact that they can create new textbooks and sell them on their own. It is very straightforward to establish a web site and to have "print on demand" from pdf files. Chemical engineering is not a large field and authors could certainly publish their textbooks in this manner to provide adequate compensation for their efforts and provide lower cost textbooks for the students. My hope is that some type of new system evolves so that faculty will have the motivation to create the new textbooks that will be needed in the future.

Conclusions

Over the past few decades the job diversity for chemical engineers has increased and should be a driver for changing the undergraduate curriculum in order to meet the market needs. It is time to adapt the undergraduate chemical engineering curriculum to meet the needs of its future graduates. My colleagues at Caltech and I have created a new undergraduate chemical engineering curriculum and have implemented it with success over the past two years. Our experience suggests that this is one solution to meeting the demands of future students and providing highly educated chemical engineers for modern societies.

Acknowledgements

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