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by E. L. Cussler
University of Minnesota

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Chemical engineering provides useful skills for products with all levels of maturity: for commodities like Premarin, for rapidly developing products like Celebrex, and for inventions like tissue scaffolding. To illustrate the breadth of these efforts, look at the other topics covered at the Engineering Foundation meeting, which I organized. These topics are also summarized in Figure 3. Those appropriate for commodities include familiar topics like fluidized beds and optimization. They may also include interesting aspects of process intensification, like the HIGEE process using centrifugal fields to carry out distillation and gas absorption. The topics include interesting niche markets, like regeneration of the ion exchangers used to refresh the amines used for acid gas scrubbing.

In addition to topics useful for commodities, there are opportunities poised for rapid growth, like biocatalysis, where we can use enzymes to carry exquisitely selective chemical transformations impossible with more conventional catalysts. Most chemical companies have recent patents in this area. Another topic of rapid growth concerns installation of an entire hospital lab on a chip. Such a lab would mean that in a doctor's office, you give not tubes of blood but a single drop. The drop is analyzed in real time in the office as part of your physical. Topics of enormous potential but unproven value include chemical reactors with sonic velocities and microsecond resonance times, which can yield a million pounds of chemicals per year in a reactor no larger than a roll of paper towels. We can imagine exotic ways to kill that scourge of power plants, zebra muscles, by feeding small capsules, which the zebra muscles voraciously eat, only to be later poisoned. All of these topics are the targets of research by chemical engineers.

These targets for chemical engineers no longer exist only within traditional chemical industries. In this sense, I was impressed by the four business models suggested at the World Congress of Chemical Engineering for chemical companies by Prof. U.H. Felcht, the president of DECHEMA and the CEO of Degussa. My interpretation of his models is shown in Figure 4. The four different kinds of chemical companies have four different key variables. First, there are the traditional commodity chemical companies. These companies, which include BASF and Dow, have cost as their key criterion. Second, there are specialty chemical companies like Albemarle and Novaris. These companies make products like furniture polish, lubricants, and adhesives, where the key variable is not cost but function. If the product works well, the customer, who may be an individual or a corporation, will be willing to pay a premium. Both commodity and specialty chemical companies are major markets for chemical engineering graduates.

The other two kinds of chemical companies shown in Figure 4 are less visible. For fine chemical companies like Sigma Aldrich and Chirotech, the key variable is speed. These companies use generic equipment and standard manufacturing processes to produce products as rapidly as possible, most often for commercial customers. Finally, there are companies whose business is innovation, who will depend most heavily on patents. Companies like 3M and Pharmacia are examples of this model.

1. Commodities Key: Cost BASF, Dow	**2. Specialties** Key: Function Albemarle, Novartis
3. Fine Chemicals Key: Speed Sigma-Aldrich, Chirotech	**4. Inventions** Key: Patents 3M, Pharmacia

Figure 4. Four Different Chemical Business Models. This chart is based on ideas of U.H. Felcht, the CEO of Degussa.

Product design is different. In many companies, it also follows a four-step sequence. We now begin with a customer need. This implies knowing who the customer is and being able to define the need in terms of quantitative specifications. To meet this need, we generate ideas, ranging from the routine to the bizarre. The number of ideas needed is generally felt to be a large one. While 3M says it needs 20 new ideas to produce a successful product, Dupont feels it needs over 300. Once these ideas are generated, we need a quick method to select the best ones. We are not going to be able to evaluate in detail the engineering design for even 20 possible ideas. Finally, we need to talk about the manufacture of the product. This manufacture, of course, includes the four steps that are the basis of process design.

I am not suggesting that we in chemical engineering should replace process design with product design. I feel that process design as a full semester course provides an invaluable capstone for the chemical engineering curriculum. I do feel that instead of repeating the process design experience with the design of a new chemical plant, we will do much better to turn the students loose on products like generic Prozac, a less permeable landfill barrier, an adhesive that works under water or a solvent-free ink which reduces pollution. Because I believe so strongly in product design, I wrote a book with G.D. Moggridge, which is really just an extended essay aimed at supplementing an existing process design class. If you don't like what we have done, consult the extensive product design materials available in other engineering disciplines.

Finally I want to talk about the stoichiometry course. To illustrate my point, I want to refer to a Whistler etching which hangs near the front door of my house. The etching called "The Old Tenement" shows a sleeping dog, a pitchfork, and a small girl in the front of a half-timbered house falling to the ground.

The fascinating part about etchings is that the artist normally makes a fairly large number of proofs while he is scribing the etching. As a result, you can go back afterward and see exactly how the different parts of the drawing were put together. With this particular piece you can see when the little girl was etched in, when the pitchfork appeared, or how other artistic mistakes were blotted out as the artist continued to refine his vision. You can tell almost from the beginning that the picture is going to be of a house, a broken down house at that.

Now the chemical engineering curriculum is the antithesis of drawing a picture as a series of approximations. If we started in the lower left-hand corner of the etching and drew everything in completely before moving on toward the middle, we would have stoichiometry, which is like that lower corner. Then we do thermodynamics in the middle of the picture. Then, we do fluid flow, which is a patch completely unconnected from the first two. Each time we introduce a topic, we do so in almost as much depth as we will ever expect the students to have.

This is absurd. It is as if we expected to teach students French by having a first course that consists of nothing but verbs, and then a second course that deals exhaustively with nouns, and then a third course on adverbs. If we taught French that way, students would have no overall picture and no general idea about what was going to eventually occur. In the same sense, I believe our students have little perspective on chemical engineering because we never give them an early overall picture.

I suggest that what now is presently the stoichiometry course can serve as the vehicle for such an overview. I believe that we can teach mass and energy balances but within a context of an overall chemical process. I believe that we should introduce some synthesis into the course by asking students to calculate the amount of sulfur dioxide produced by a process with an ore feed and an absorption system for removing the sulfur dioxide, rather than roasting the ore.

What Happens to Chemical Engineering Education?

E.L. Cussler
Chemical Engineering and Materials Science
University of Minnesota
Minneapolis, MN 55455

The last time I was in Oklahoma, a curious thing happened. I was there to talk to a local section of the American Institute of Chemical Engineers, and I was waiting in the hotel to be picked up. When the phone call came, I went down into the lobby. But it was not my host for the talk. Instead, it was a very big, very old man wearing a broad-brimmed hat and a belt buckle the size of a salad plate. He came over rather stiffly:

"You Ed Cussler?"
"Yes sir."
"Your father Ed Cussler?"
"Yes sir. I am Ed Cussler, Junior."
"Well sir, then I am glad to meet you. I went to school with your father and he was good to me in 1926."

Now this type of introduction is an invitation to further conversation. This man, a native of Oklahoma, had been sent east to school because "my mother was from Boston". After the man finished, he returned to Oklahoma, received a degree in chemical engineering, and enjoyed a satisfying career with Phillips. My father, a New Yorker, stayed out east to become a chemical engineer and had a career with Dupont.

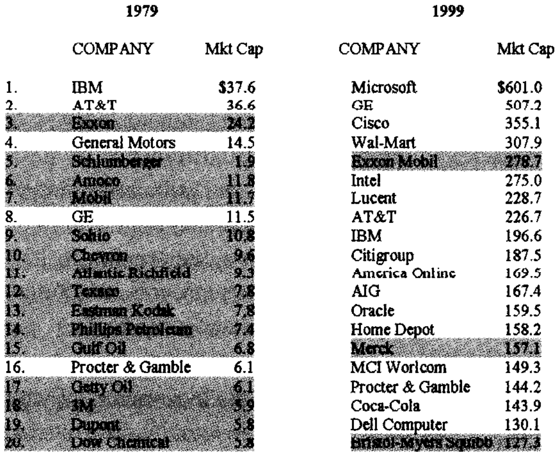
In preparing for this talk, I was reminded of this encounter because of how much the chemical industry has changed since these men graduated 70 years ago. In college, each of them saw his profession as a pioneering field, and both benefited from the field's enormous growth. This growth showed sharply in the 1970s. By 1985, both men felt that the good years were over.

My dad and his schoolmate each spoke of the core ideas in the chemical engineering practice. This core hasn't changed. I can still take problems from my father's class notes — from a course in 1930 taught by Barnett Dodge — and give them to my current students. Without hesitation or question, they get the answers correct.

Today I want to review with you both the core ideas and the changes in the chemical industry. The changes in industry are huge, especially in the last twenty years. These industrial changes imply a broader intellectual effort for chemical engineering. After discussing this broader effort, I will consider the implications for chemical engineering education.

The Changed Chemical Industry.

As an example of the altered chemical industry, consider the largest U.S. companies based on their market capitalization, as shown in Figure 1. On the left is the ranking of the companies 20 years ago. On the right is a more recent ranking. Those companies with an interest in the chemical industry are shaded and those without a strong presence are unshaded.



	1979		1999	
	COMPANY	Mkt Cap	COMPANY	Mkt Cap
1.	IBM	$37.6	Microsoft	$601.0
2.	AT&T	36.6	GE	507.2
3.	Exxon	24.2	Cisco	355.1
4.	General Motors	14.5	Wal-Mart	307.9
5.	Schlumberger	1.9	Exxon Mobil	278.7
6.	Amoco	11.8	Intel	275.0
7.	Mobil	11.7	Lucent	228.7
8.	GE	11.5	AT&T	226.7
9.	Sohio	10.8	IBM	196.6
10.	Chevron	9.6	Citigroup	187.5
11.	Atlantic Richfield	9.3	America Online	169.5
12.	Texaco	7.8	AIG	167.4
13.	Eastman Kodak	7.8	Oracle	159.5
14.	Phillips Petroleum	7.4	Home Depot	158.2
15.	Gulf Oil	6.8	Merck	157.1
16.	Procter & Gamble	6.1	MCI Worlcom	149.3
17.	Getty Oil	6.1	Procter & Gamble	144.2
18.	3M	5.9	Coca-Cola	143.9
19.	Dupont	5.8	Dell Computer	130.1
20.	Dow Chemical	5.8	Bristol-Myers Squibb	127.3

Figure 1. The Largest U.S. Corporations. Chemical companies, which are shaded, no longer have the strong position that they had 25 years ago .

The difference is dramatic. Twenty years ago, a majority of the largest companies in the United States, 11 of 15, had a basis in petroleum or in chemicals. Now, the only ones that have sustained their position among the largest have done so as the result of mergers. The chemical industry simply does not have the commercial clout that it had 20 years ago.

When I show these lists to engineering professors, they react in two ways. First, they complain that my classification is inexact, that a company like General Electric does have a significant polymer business. They also carefully scan the new companies to see how savvy they have been as investors. But that is not the point; the point is that the impact of chemicals, which existed 20 years ago, is no longer there.

There is considerable evidence, detailed in Peter Spitz' book *Petrochemicals: The Rise of an Industry,* which suggests that the growth in chemicals had stopped about 1970. One consequence of this is the stagnation in the salaries paid to chemical professionals. Between 1940 and 1970, those salaries rose in even when corrected for inflation. Since 1970, salaries of chemical professionals have remained remarkably constant when adjusted for inflation. We can be proud of the high salaries paid to chemical engineers, but those salaries are not increasing in real terms.

Moreover, there have been enormous changes in the companies who are employing our students. As shown in Figure 2, over 75 percent of our graduating students in 1975 went to work for commodity chemical manufacturers. In 1995, only about a quarter did. In 1975, only about one in six students went to work in a product-oriented business. Now half of our students do.

Now you can react to these data in a variety of ways. First, you can ask exactly where I got the data, because you may feel they are not accurate. I got the 1975 data directly from the alumni list at the University of Minnesota. I received the 1995 data by sending postcards to our 1995 graduates four years after they graduated. I didn't use our more recent graduates because so many go to work in one job and then switch to another. I also wasn't sure of my own classification of jobs, so I asked some of my colleagues to make their own assignments. While their individual assignments differed, their overall conclusions were the same. The commodity chemical industry is not the focus of most of our graduates, and product-oriented industries definitely are.

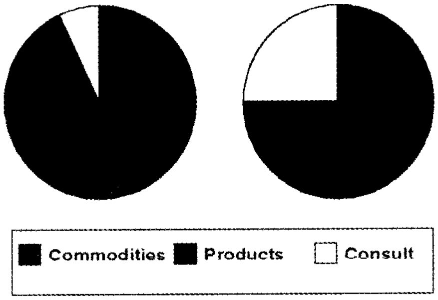


Figure 2. Where the Jobs Are. The domination of chemical commodities has been eclipsed by an emphasis on products.

The Changed Chemical Objectives

As a teacher of chemical engineering, I was concerned that I am not preparing my students for the jobs that they would face, but rather for jobs that my father and his Oklahoma friend had faced. To investigate this, I organized an Engineering Foundation meeting to explore those topics that had current emphasis both in industry and academia. While I will give you a larger list of the topics discussed later, I want to focus for the moment on only three. They are all pharmaceuticals: generic Premerin, the anti-inflammatory Celebrex, and human tissue scaffolds. I want to describe each in some more detail.

Premerin, the most prescribed drug in the United States, is an extract of pregnant mares' urine taken to alleviate the symptoms of menopause. The process for making

Premerin, described in patents which expired over 20 years ago, involves the familiar four-step bioseparations sequence. The first step is the removal of insolubles, usually by filtration. The second step, most frequently called isolation, aims at concentrating the active components in the biological feed stock, in this case, the urine. This second step commonly depends on liquid-liquid extraction. The third step, purification, often involves adsorption, though in the case of Premerin, solvent washing is used. The fourth and final step, called polishing, achieves additional purification, often by crystallization or drying.

Such a four-step process depends on classic chemical engineering, on unit operations in their most familiar form. Unit operations like extraction and drying are the common knowledge of any qualified chemical engineering graduate. The production of Premerin presents no unsolved chemical engineering problems, and its success depends on the efficient and inexpensive preparation of the final extract.

The second example is the new drug Celebrex, an anti-arthritis medication that is now the best selling drug in the United States. While its manufacturer also uses standard chemical engineering techniques, the goal in this manufacture is speed, not efficiency. After all, if a drug has sales of $1 billion a year, then each working day that can be saved in the development process is worth about $5 million in sales. Under these circumstances, there is no strong drive for optimization, continuous processing, or even dedicated equipment. The challenge of this type of product is first to make enough drug for the clinical trials, and second to repeat that manufacture for commercial sales. Because the Food and Drug Administration insists that the process used to make the drug for the trials not be significantly altered in order to make the drug for commercial sales, there is a regulatory caution against later chemical engineering development. In the production of Celebrex, conventional chemical engineering is useful but the details developed for petrochemicals are irrelevant.

The third example, human tissue scaffolding, concerns material that might be applied to burns to allow the growth of new flesh. Such scaffolding might be seeded with liver cells to grow a new liver to replace one that was not functioning well. After the new tissue grows, the tissue scaffolding should slowly erode, leaving the regenerated flesh. The skills required to develop materials like this are not clear but will certainly include both biochemistry and polymer science. They will also include concepts like mass transfer and reaction engineering, which are skills normally taught in conventional undergraduate chemical engineering. Still, biochemistry and polymer science will become more important.

I find it useful to plot these three pharmaceutical products on an S-curve like that in Figure 3. The curve plots market size vs. the effort required to achieve increased size. For established products like Premarin, a major effort is needed for a small gain. For new products like tissue scaffolding, a major effort is needed to get started. For products undergoing rapid growth, a relatively small effort can produce a huge gain. Thus we must remember that the development of products of different maturity may require different skills at different times.

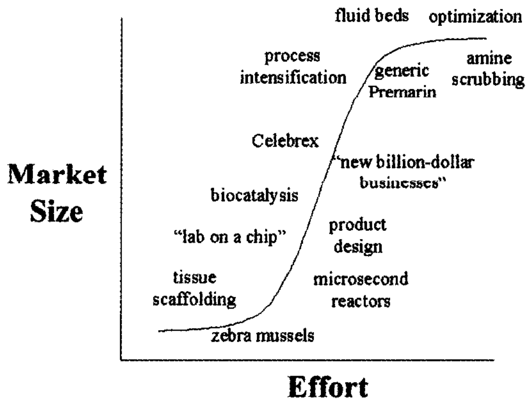


Figure 3. A Selection of Chemical Engineering Topics. These topics, discussed at an Engineering Foundation meeting, catalyzed discussions of the future of chemical engineering education.

In this limited space, I can only give the briefest of rationales for these changes. In most curricula in most universities, thermodynamics is taught twice, once in chemistry and once in chemical engineering. The rationale for this redundancy is that students do not master thermodynamics on the first try. This is true. However, they don't master it on the second try either. As a result, I am willing to trust the students to a greater degree, hoping that they will return to learn for themselves those parts of thermodynamics that they have not completely understood at first exposure.

I believe that biochemistry for our current students is much more important than quantum mechanics. To be sure, quantum mechanics provides the rationale for spectra, hence for chemical analysis, and can also be effectively used to calculate detailed thermodynamic properties. This calculation is now possible because of the enormous increase in computing power. However, for the foreseeable future, the properties calculated will probably be of molecules more closely akin to commodity chemicals than to the spectrum of products where our students are likely to get jobs. For example, I do not think it likely that in the time encompassed by our current students' professional careers, they will be able to calculate *a priori* the properties of a new adhesive. In the same sense, process control seems to me an artifact of the commodity chemical business, with its large established markets. It seems less important to new businesses where detailed chemical understanding is bypassed in favor of rapid development.

I would suggest that existing chemical engineering faculties have already made these revisions in terms of their own intellectual development. In a survey of six major chemical engineering departments, I discovered that less than 15 percent of the faculty publications are in chemical engineering. Moreover, only about 20 percent of these departments have faculty with more than one year's experience in what is commonly called "industry". Those with industrial experience are older. However, when I examine that industrial experience more carefully, I discover that it is almost exclusively in the commodity chemical business. Many young faculty have experience with start–ups and are much closer to the product orientation which most of our students will encounter. As a result, I would suggest that the changes in Figure 6, far from being revolutionary, are in fact already reflected in the research efforts of faculty.

Finally, I want to talk in a little more detail about the new courses in design suggested in Figure 6. The change from process to product design is detailed in Figure 7. In most process design courses, one uses an algorithm that can be idealized as four steps. In the first step, we decide whether the process will be batch or continuous. Since most of the examples we give to students involve manufacturing more than 10 million pounds of product per year, the choice is almost always continuous. We then make the input-output diagrams — the flow sheets — of the process. We add the recycles required to make efficient use of our raw materials; and finally, we design the separation trains and integrate the heat exchanger networks.

Process Design	**Product Design**
1. batch vs. continuous	**1. customer need**
2. input/output	**2. idea generation**
3. recycles	**3. selection**
4. separation/heat	**4. manufacture**

Figure 7. Process vs. Product Design. Product design involves deciding what to make, as well as how to make it.

Conclusions

In this talk, I have reviewed the large changes in chemical enterprise which have occurred over the last few decades. These changes imply a reduced emphasis on processes and an expanded interest in products. They imply demand for an expanded mix of chemical engineering skills. These skills suggest a somewhat different curriculum with the largest changes occurring in design.

I often think about how my father and his Oklahoma schoolmate would react if they were now miraculously young again and attending my chemical engineering class. Frankly, I think that they would be pleased, but not surprised. I believe that they would feel that our common profession could be poised for a new intellectual and business expansion, not unlike the one that they actually saw in their own careers, the one that produced today's commodities. I hope that we can all take part in the excitement of this educational evolution.

Further Reading

Calvin Cobb, "Prepare for a Different Future", Chemical Engineering Progress 97 (2) 69-74, (2001).

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E.L. Cussler, D.W. Savage, Anton Middelberg, and Matthais Kind, "Refocussing Chemical Engineering", Chemical Engineering Progress 98 (1), 26S-31S (2002).

Peter Spitz, Petrochemicals: The Rise of an Industry, Wiley-Interscience, New York, 1988.

U.H. Felcht, "The Shape of the Chemical Process Industries", paper presented at the Sixth World Congress of Chemical Engineering, Melbourne, Australia, September, 2001.

The Unchanged Chemical Engineering Curriculum

This brings me back to my original questions and the premise of this talk: What are the implications for chemical engineering education? How should changes in the chemical industry be reflected in changes in the curriculum? What are we professors doing well, and what can we do better?

Now, let me stress that I think the answer to these questions for some departments will be that no changes are needed. The basic ideas of unit operations, buttressed with concepts from reaction engineering and supported with the intellectual accomplishments of engineering science, may be all that we need for the future. We may simply have to respect the economic changes suggested by Figure 1 and fall back to a smaller but still important role. We may choose not to look at the development of new products until they have already obtained significant market size. We can argue, after all, that efficiencies provided by engineering only become valuable when the market size is significant. I think that this is a good argument.

I am also interested in the other option of revising the chemical engineering curriculum to provide a bigger tool kit for future chemical engineers. I recognize that the existing curriculum is full, so any broadening must result in teaching less material in some of the subjects. I understand that this is a traumatic enterprise. After all, Woodrow Wilson once suggested that "changing curricula is like moving graveyards".

I begin by asking how our present curriculum supports products like those shown in Figure 3. My tentative conclusion, shown in Figure 5, is that existing courses are good for big businesses but not so good for new businesses. They are effective for the production of the chemical commodities, which dominated financial markets twenty years ago. They are less useful for the more diverse chemical enterprise of the present. This chemical enterprise seems much less monolithic, but it still represents where the careers of many of our graduates will be.

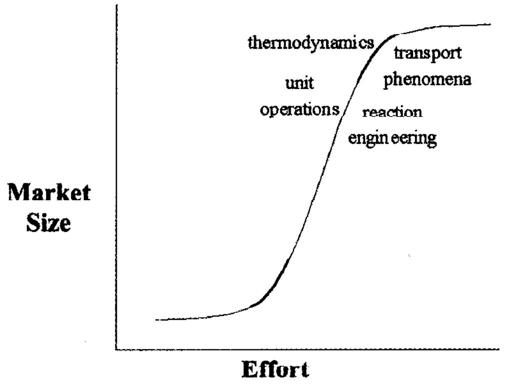

Figure 5. Current Chemical Engineering Education Stresses Larger Markets. It supports commodity chemical companies much better than other efforts.

At the same time, I am concerned that I am not preparing my students for new areas of higher growth, especially for higher value-added products. These concerns lead me to suggest modifications of the existing curriculum along the lines of those shown in Figure 6. Briefly stated, I would reduce thermodynamics, drop quantum mechanics, and make process control an elective. I would increase materials science for both polymers and inorganics. I would make biochemistry required, expand the design experience to include products, and add synthesis into the existing stoichiometry course.

Replace This	With This
1. Half of Thermodynamics	**Materials Science**
2. Quantum Mechanics	**Biochemistry**

Expand This	To Include This
3. Process Design	**Product Design**
4. Stoichiometry	**Elementary Design**

Figure 6. Possible Educational Changes. These changes reflect the belief that any new requirement implies changing an existing requirement.