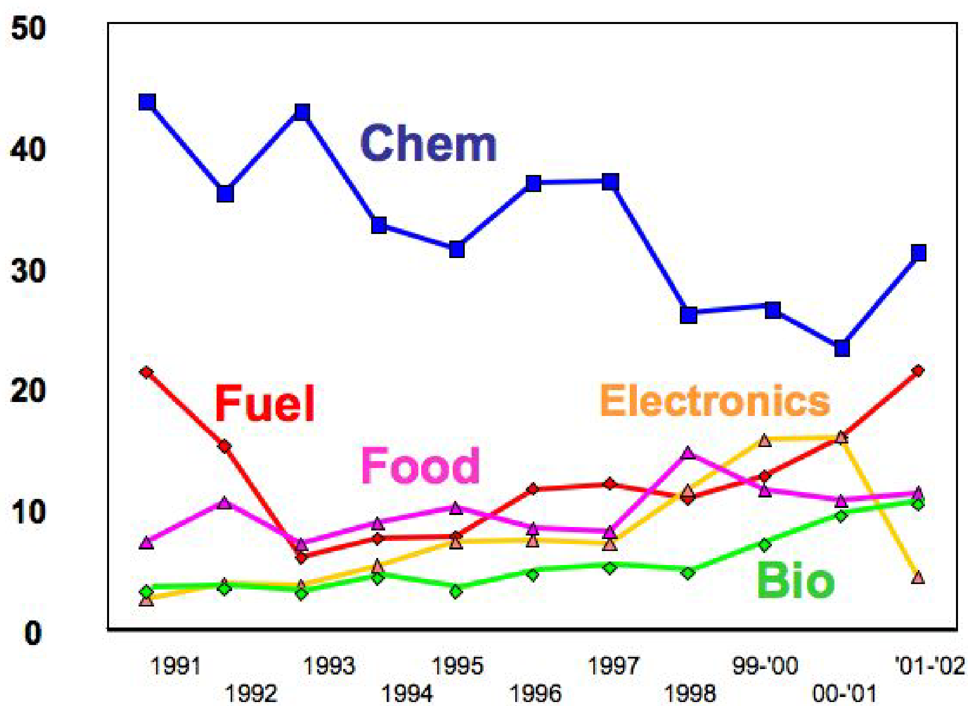
In this short essay, we want to make three points. First, we believe that the chemical industry is dramatically altered from that implied by our current curriculum. Second, we want to describe efforts to redress this imbalance by teaching chemical product design, in addition to process design. Third, we want to identify where teaching product design has been inadequate and to suggest ways in which we can be more effective.

An Altered Industry

The chemical industry today is completely different from the chemical industry of thirty years ago. The clearest evidence comes from the jobs taken by graduating chemical engineers graduating from U.S. universities. Twenty-five years ago, 80 percent of those graduating went to the commodity chemical industry exemplified by DuPont, Dow, and Shell. Occasionally they went to international companies like BASF and ICI. The remaining 20 percent was divided into two roughly equal groups. One group went to product-oriented businesses like Proctor and Gamble, 3M, and Pfizer. The other group went to everything else, including consulting, government, and academia.

As Figure 1 shows, the situation is different today. The percentage of graduates going to the commodity chemical industry has dropped dramatically, to about a quarter of the total. The percentage going to consulting has risen to about another quarter. However, the bulk of new graduates go to industries where products are central.

Figure 1:Where the Jobs Are



To understand this product-centered chemical industry, we must recognize three types of products, each with different characteristics. These characteristics are summarized in Table I. The first and most obvious type is commodities, the same products which used to dominate the chemical enterprise. The key for producing commodities is cost. Styrene produced by Dow and styrene produced by BASF are chemically identical: the issue is who can produce the largest quantities at the lowest possible price. The second and third types of products may be less familiar to chemical engineers. The second type of product involves molecules of molecular weights of 500-700 which have specific social or personal benefits. The most obvious examples are pharmaceuticals. The key to the production of pharmaceuticals is not their costs but their time to market: the speed of their discovery and production. These products are not made in dedicated equipment but in whatever batch reactors are available. Thus process optimization is likely to be less important than process scheduling.

The third type of product is those with a specific microstructure. The key to these products is not their cost nor their time to market, but their function. For example, I don't care why my shoes shine after I have applied polish; I only care that they do shine. Customers are willing to pay a premium for such a function, be it in a coating, a food, or a cleaner.

Table I: Three Classes of Products

	Commodities	Molecules	Microstructures
Key	Cost	Speed	Function
Basis	Unit Ops	Discovery	Trade
Discipline	Chemical Engineering	Chemistry	Materials Science

Current Teaching of Product Design

We teach about this altered chemical industry in one-semester senior-level course. In this course, we distinguish between process design and product design using the outline in Table II. In process design, we begin by asking whether the reactor will be batch or continuous. We almost always choose continuous. We then draw a block diagram, showing the input and the output of various chemical streams. We include chemical reactors at this point. We add recycles to avoid wasting any valuable materials, and we design the separation processes and the heat

Table II: Process vs. Product Design

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

integration. This general sequence, suggested by Douglas, organizes an effective chemical process design course.

In chemical product design, we start much earlier in the development. We begin by discussing a customer need, and then explore ideas which can meet this need. We must choose the best of a large number of possible ideas, typically around 100. We select the two to four best ideas, which often involves quick estimates. Finally, in chemical product design, we talk about the manufacture of the product. This manufacture step includes all of the steps of process design. Thus product design moves the engineers back further towards the decisions in product development which are based on marketing.

Our students are enormously interested and energized by the challenges of chemical product design. Individuals frequently say, "This is why I went into chemical engineering. This is what really interests me. Why on earth did I have to take all of that other stuff?" Of course, the reason is obvious: they couldn't make sensible scientifically based decisions using thermodynamics, kinetics, or unit operations before they understood these. They need most of what we already teach them in order to be effective with product design.

What Else is Needed

Our teaching of chemical product design has been uneven. It works well through the initial stages of needs and ideas. Students handle these topics well. However, when they get to the selection phase, they often stumble. We believe that they stumble because their education is missing technical topics which they need in order to be effective in these areas. It is these technical gaps that we want to address now.

These technical gaps can be identified under five headings. Each of these headings is drawn from the educational background of most chemical engineers. They are as follows:

1. Stoichiometry, including costs: Our students need to be reminded that a new product is likely to be unsuccessful if the ingredients cost more than the products.
2. Thermodynamics: Our students need to estimate how much energy is going to be needed for any given step and where equilibrium positions lie.
3. Reaction Kinetics: Our students need to think not so much about whether they have a first-order or a second-order reaction but simply about what the reaction half life is. For example, in the pharmaceutical industry, the important timescale is whether the half life less than eight hours so it can be handled within one shift.
4. Transport Phenomena and Unit Operations: Our students need to think beyond distillation and gas absorption about the way to treat and purify specific products.
5. Other Technology: Our students need to remember that all of the technology they need may not have come in their classes.

We need to identify educational gaps for each of the three types of products.

Commodity Products and Scaled-Down Processes

Our students are well prepared for commodity product design. We believe that they are also well prepared for making scaled-down processes. For example, we are intrigued with the possibility of making chemical fertilizers, like ammonia, on each farm.

We discuss these commodity products and scaled down processes in terms of the five headings above:

1. Stoichiometry: Students need to make the normal cost check.
2. Thermodynamics: Students need to remember the first law of thermodynamics, especially for flow systems. They need to be reminded of the concepts of enthropy and of Gibbs free energy. They need to remember chemical equilibria, including vapor-liquid equilibria.
3. Reaction Kinetics: Students should be reminded of why plug-flow reactors are often more effective than CSTRs. They need to review reaction mechanisms and chemical rate constants.
4. Unit Operations: The students need to review differential distillation and absorption.

All of this technology, readily available in simulation programs like ASPEN, does not require much additional teaching. We believe this review can be covered in a single lecture. As an example, we suggest considering air separation for patients with emphysema.

Molecular Products

Because the key in this case is time to market, the product design is dominated by chemistry. The role of engineers will be smaller than the role of chemists. Nonetheless, we review aspects that should make engineers more effective.

1. Stoichiometry: Students need to be reminded of chemical structures and of reaction sequences. They need to consider raw material sources, which can be scattered and difficult to locate.
2. Thermodynamics: Students must estimate solubilities and heats of reaction by group contribution methods. We are making new molecules which are potentially explosive.
3. Kinetics: Reactions making molecules of molecular 500-700 will be batch. They involve multiple phases, with several feeds. Their scale-up deserves review. Students should be reminded of how fermenters operate and of the importance of mass transfer.
4. Unit Operations: The important operations for molecular products are extraction, adsorption, and crystallization. Distillation and absorption are much less important.

We spend about two lectures on these products. One lecture emphasizes the chemical kinetics and the other discusses an example like taxol.

Microstructured Products: this area is where our students are most deficient. Our curriculum, with its emphasis on commodities and continuous processes, omits large amounts of known science needed to design microstructured products. The missing science is as follows:

1. Stoichiometry: There is nothing missing on this topic.
2. Thermodynamics: We need to discuss equilibrium and metastability. We especially need to distinguish between the spinodal and the binodal, because many microstructured products are metastable emulsions.
3. Kinetics: We need to talk about product stability and how it can be evaluated. Time-temperature superposition is one specific topic.
4. Unit Operations: We must teach incomplete mixing, where the goal is not a molecular mixture but a microscopic mixture. This is the key to product shelf-life.
5. Other Technologies: We need a review of physical chemistry, including osmotic pressure; surface tension; colloid stability; and possibly DLVO theory.

Examples illustrating these topics include engineered wood and synthetic crab meat. We cover these missing topics in four lectures.

Conclusions

We are still learning how to teach chemical product design. To be sure, we are convinced that the chemical enterprise has changed. We believe that the design experience of our students must be extended to reflect this altered enterprise. We can teach the chemical product design implicit in this altered enterprise by discussing consumer needs, ideas to meet these needs, selection of the best ideas, and manufacture of the resulting products.

We are not sure about how to go beyond this outline. We know that students are having trouble with product selection, and we can help by giving them technology missing in our current curriculum. We have suggested in this paper how to do this. However, we are not sure about what we are doing. We look forward to learning from you – each of you – how you are dealing with this effort to make chemical engineering relevant to more of the expanding chemical enterprise.