Drawing the Connections Between ENGINEERING SCIENCE AND ENGINEERING PRACTICE

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Change is a fact of life, and engineers make their careers out of bringing about changes in their surroundings. In today's chemical engineering departments we hear of the need for changes in our institutions and methods. Alumni, employers, and researchers in the field bring back news of the need for new priorities for the curriculum—the need for students to have more teamwork experience, to develop better communication skills and critical thinking skills,[1] and to acquire specialized knowledge in emerging areas such as bio- and nanotechnology. In addition, there is continuing pressure for better preparation of graduates in each of the established, and diverse, fields in which chemical engineers find employment.

The passive approach to these demands would be to pack more and more into the chemical engineering curriculum, extending the undergraduate years and demanding more of the students. This runs counter to other institutional and national priorities, however, that demand high four-year graduation rates and low overall costs for undergraduate education.

Finding a solution to a problem amid seemingly contradictory requirements is the exact task that the practicing engineer faces on a daily basis. We can find a solution to the pedagogical dilemma posed above by following the same engineering problem-solving processes we seek to develop in our students. We should begin by defining the problem as we perceive it and exploring the context in which the problem presents itself. We then can bring our own expertise and experience and the expertise and experience of others to bear on the problem, seeking clarification and (hopefully) a solution. Finally, we test the proposed solution and evaluate its effects, feeding back our observations into a refined solution as we iterate and hopefully converge to the best solution.

What is the best way now and in the future to educate a chemical engineer? To address this question we need to reflect a bit on what a chemical engineer is—what abilities and expertise is a chemical engineer expected to have? How are these abilities different from those of other engineers and scientists? How has the field of chemical engineering survived throughout a century of tremendous change? What are the strengths and weaknesses of the chemical engineering education we currently deliver?

Before there were chemical engineers, there were mechanical engineers who worked in the chemical process industry along with industrial chemists who had become experts in large-scale production. The industrial need for individuals with chemical and engineering expertise suggested (to some) the establishment of a new discipline. Chemical engineering thus had very practical and industrial roots and an instant identity crisis—are the practitioners chemists or are they engineers? And, if they are something altogether new, how are they different from the chemists and engineers who have been doing the job up until now?

The answer for the early founders of our discipline was that chemical engineers were specialists in the chemical process industries—in particular, experts on unit operations. The

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> ***The key to the survival of the discipline [is] the ability to adapt to changing economies and technologies while retaining a fundamental, and valued, expertise . . . . Today's chemical engineering degree represents something of value to employers, but changing technologies and changing conditions in the workplace put new demands on the education of a chemical engineer.***

organization of chemical processes around a finite set of unit operations established both an identity and a pedagogy that could carry the new field forward.

The unit-operations paradigm served the field well through World War II, but the maturing of the commodity chemical industries through the 1950s led to some new challenges for the discipline. Faced with a dwindling need for chemical engineers to do classical chemical-plant engineering, the field adapted to new technologies (polymers, electronics, nuclear power) and claimed them as fields addressed by chemical engineering. This was possible because a new paradigm was adopted in engineering education—the engineering-science paradigm. By moving down in length-scale from the process-unit scale (unit operations) to the molecular scale (transport phenomena, chemical kinetics, thermodynamics), chemical engineers could broaden the number of fields to which they could apply their analytical skills and methods.

Fundamentals

- Physics, chemistry, math, liberal arts, general education
- Mass/energy balances
- Thermodynamics
- Transport phenomena
- Chemical reaction kinetics/reactor design

Practice

- Process Control
- Staged operations
- Unit operations
- Process design

One particular kind of practice (petroleum or commodity chemical processing)

Electives

- Technical (chemistry, biology), engineering

Figure 1. *Outline of the current chemical engineering curriculum, organized into fundamentals, practice, and electives.*

In the last 100 years, therefore, chemical engineers have established themselves as problem solvers in the field of chemical processes, including both large-scale chemical manufacturing processes and molecular chemical processes. The key to the survival of the discipline was the ability to adapt to changing economies and technologies while retaining a fundamental, and valued, expertise.

How do we currently educate a chemical engineer? While the chemical engineering curriculum varies from place to place, there is a general structure, shown in Figure 1. Industry-specific content is addressed in the practice courses (unit operations, design, controls) and is also addressed in the curriculum by including elective courses that allow students to follow their interests. These elective courses (*e.g.*, polymer engineering, environmental engineering, business, biochemistry, bioprocess engineering, etc.) are sometimes offered from within the chemical engineering department, but are often courses taught outside of chemical engineering. Within one of the fundamental courses there may also be some exposure to industry-specific content, depending on how the particular instructor implements his or her course. Many of the more recently published textbooks also go to some lengths to include individual problems or case studies that draw from a wide range of industries. Due to the emphasis of most textbooks, however, it is also possible (even probable) to complete an entire undergraduate chemical engineering degree without considering any chemical processes outside of the commodity-chemical or petroleum industries.

What are the challenges and changes that must be addressed? If technology and society remained stagnant, no changes in an effective curriculum would be needed. Two questions should be asked, therefore:

- *Is our curriculum effective as is?*
- *What changes in technology and in society have taken place, or are anticipated to take place, that might affect the chemical engineering curriculum?*

To address the effectiveness of our curriculum, we need to assess the experiences of our students, our alumni, and their employers. The good news is that chemical engineers are still in demand in industry, the current employment downturn not withstanding. Salaries for chemical engineers still top the list of engineering salaries, and employers have often shown a preference for classically trained chemical engineers over more specialized engineers (*e.g.*, environmental, biomedical, materials) because of the versatility of the chemical engineers.

There is room for improvement, however, as reflected in alumni surveys and in discussions with industrial advisors. At Michigan Technological University we have surveyed our alumni and industrial partners and some of the common concerns are given in Figure 2. High on the list of comments is that alumni and industrial partners would like to see an increase in teamwork experience and an improvement in communication skills, critical-thinking skills, and learning skills in chemical engineering graduates. Richard Felder has reported similar responses from NC State alumni.[2]

Changes in technology and in society challenge the curriculum as well. New technologies, including biotechnology and nanoscale engineering, are a vibrant part of chemical engineering research and a potential source for growth in chemical engineering employment. Fundamental changes have also taken place at colleges and universities in the last twenty years. Research is now a central activity at most universities, and for public universities the proportion of support coming from state governments has fallen to an average of only 32% of total expenditures.[3] The university degree has never been more popular, however—a fact that itself brings its own challenges since there are increasing numbers of underprepared students in need of remedial work and special attention. These changes at universities have been accompanied by double-digit tuition inflation, reflecting the broadened mission of the university and the decrease in state support for the universities' missions. Paradoxically, decreasing public funding for universities has been accompanied by calls for tuition controls, for sanctions for universities with poor four-year graduation rates, and for reduction or elimination of remedial programs.[4,5]

Thus, we face a dilemma. Today's chemical engineering degree represents something of value to employers, but changing technologies and changing conditions in the workplace put new demands on the education of a chemical engineer. In addition, our universities themselves have gone through a fundamental change, increasing their research emphasis, broadening their missions to include less-well-prepared students, all the while facing financial challenges. How can we preserve what is right about chemical engineering education while adjusting to these new realities?

CONTENT VERSUS PROCESS

At the end of the day, the chemical engineering curriculum is a list of courses (experiences) that are required by an academic department. These courses have content—subjects that are presented, explained, practiced, and mastered. Part of the educational process requires that the student master the content of the courses. Often this is the part on which we concentrate. The debates over chemical engineering curricula are usually discussions of content.

Another part of a student's education is the experience of confronting the material and structure of a course—the *process* of mastering the content. The educational process includes interactions with faculty and peers, managing time, working in groups, and developing and implementing a learning strategy for a course. We do not test on the mastery of process. Or perhaps we do, indirectly, since students who succeed in mastering content usually do so because they have mastered process—they are able to determine the goals of the course, and they plan their conduct to allow them to succeed. As the education scholar Jerome Bruner[6] notes, "To instruct someone. . . is not a matter of getting him to commit results to mind. Rather, it is to teach him to participate in the process that makes possible the establishment of knowledge."

As we assess and redesign the chemical engineering curriculum, we may ask ourselves, "Do we need to revamp the content? Or should we concentrate only on process and presume that whatever technical content is covered or omitted will be addressed in the graduate's subsequent career?" A graduate who has mastered the education process, in fact, sounds very much like the ideal engineer: a person who is able to learn new topics, work in teams, communicate effectively, focus on goals, and develop strategies to solve problems. To a certain extent, we have always relied on content not mattering too much, since it has always been important for engineers to be able to adapt to new technologies (lifelong learning).

Common Curricular Feedback

- Don't know bioengineering and other cutting-edge fields
- Don't use math after graduation
- Too much petroleum processing in curriculum
- Electives are taken for convenience instead of as part of a deliberate educational plan
- No time for undergraduate research
- Need more emphasis on
    - Teamwork
    - Communication skills
    - Critical thinking
    - Learning versus teaching
    - Lifelong learning

Figure 2. *Summary of some curricular feedback received from alumni and industrial partners.*

Shall we conclude then, that, within reasonable bounds, content does not matter? We can examine two case studies to explore these questions.

Case I

Is Content Important? Developing Writing Skills in Engineering.

I had been frustrated by the quality of unit operations laboratory reports, and I volunteered to teach the technical communications course to see what could be done to improve it. The previous instructors had shown the students how to write a proposal and then asked them to write a proposal of their own. The topic of the proposal could be anything they wished—it did not need to be technical. I wanted to see if this could be improved upon.

I formulated the hypothesis that the students needed more technical content in their writing exercises in order to gain proposal-writing skills. In my section of the course, I asked the students to write an essay on why fluid mechanics is important to chemical engineers. The results of this assignment were uniformly terrible. The students were unable to "find" the answer to the question, so they simply wrote appropriate-length texts consisting of paraphrases from various textbooks and submitted them as their essays. They appeared to not know how to write even cogent sentences.

Frustrated with this outcome, I gave them a focused lecture on a new subject and asked them to write an essay explaining back to me the content that I provided. Specifically, I gave a lecture on how to produce good technical writing and asked the students to write an essay explaining the important features of good technical writing. The results of the second assignment were uniformly excellent. Each essay began with the appropriate introduction and statement of the problem. The three key content components on which I had lectured were listed. A final paragraph was constructed that summarized the essay.

What was the difference in the two assignments? In the first assignment, I gave them an open-ended problem—they had to first find the content that they needed to report on in the assigned essay. The students did not know why fluid mechanics is important to chemical engineers, however, and *they did not know how to find out*. In the second assignment, I spoon-fed them the content ahead of time, and they repeated it back to me using writing skills that they possessed. For the first assignment, critical thinking and problem-solving skills were essential and apparently lacking in the class. What had looked like a writing-skill deficit had turned out to be a deficit in critical-thinking/problem-solving skills.

> **Conclusion:** *Content*—in this case the decision to confront the students with a *specific* question that required analysis, reflection, and discovery rather than simple disgorgement of presented material—can be critical.

We may be guilty of content errors in our chemical engineering curriculum. For example, we show students how to make tray-by-tray calculations on a distillation column. We then ask them to make such calculations. They succeed. When they arrive at their senior year in unit operations laboratory however, they may fail to recognize that the open-ended or ill-defined problem they have been asked to solve requires a tray-by-tray calculation on a distillation column. We may not have taught them how to determine what calculations are necessary.

Case II

Is Content Important? The Process of Problem Solving.

There was once a television commercial that touted the Internet as the place to find the answers to any questions one might have. In the advertisement they listed a question of fact that was quite obscure, and, using an Internet browser, they found the answer in seconds. The implication was that any question you might formulate could be answered easily if you have an Internet connection.

We all have enough Internet experience to know that this is not true. Going to an obscure site and formulating a question that is answered by that site is a far cry from having a specific need and actually finding a reliable answer to the question. In order to do the latter effectively, you need problem-solving skills and experience.

To find information effectively, one must learn the process of finding information. The process is something like the following:

A process for finding information or solving a problem:

1. Know where to start
2. Slog through unfamiliar nomenclature
3. Struggle with missing background (on your part) in the subject
4. Return to fundamentals for a refresher
5. Seek out experts – presuming you can determine what kind of expert you need
6. Postulate a solution (a location for your information)
7. Evaluate the accuracy of the solution, appropriateness of assumptions
8. Return to the appropriate step and repeat, depending on what you find and decide

In the case of the Internet search engine advertisement, they made finding something on the Web look incredibly easy because they skipped every one of these steps. They knew the answer they wanted ahead of time and went right to it. This is analogous to assigning homework or exam problems that are just like the examples in the book—students become accustomed to this practice and come to believe that the practice of engineering will be an exercise of finding a previously solved problem that is similar to the problem presented to them.

Conclusion: Skipping process prevents learning.

Returning to our topic, is content important? The answer we arrive at is yes. And no. Content is important (Case Study I) in that it must be real, open-ended, specific, and, although we did not discuss it, it must integrate physical and chemical principles that are fundamental to the types of problems that are faced by chemical engineers. Content is not important in the specifics, however (Case Study II), since problem-solving process is generic and common to all types of engineering (and nonengineering) problems.

We cannot teach chemical engineering without specifics, *i.e.*, without choosing content. But an engineering graduate who studies petroleum processes should be able to design a lysine fermentation process with recourse to additional materials and by consulting knowledgeable experts—if that graduate has mastered critical thinking and problem solving. And likewise, an engineering graduate who studied fermentation reactors should be able, with some backfilling of missing or forgotten techniques, to confront distillation-column design.

A PROPOSAL: RENEWED EMPHASIS ON INTEGRATION

There has been much discussion on improvements to engineering education in the last decade, including calls for more integration of engineering practice,[7] adoption of cooperative learning methods,[8] expansion of the engineering degree to a five-year degree,[9] changes in faculty reward structures,[10] and insertion into the curriculum of international experience and the studies of ethics,[11] government regulation,[12] and many other subjects.[13-15] These ideas have merit, but wholesale change is expensive, time consuming, and often unrewarded.

We have discussed the question, what is the best way now and in the future to educate a chemical engineer? In addressing this question we have found good things about the current method. We have also identified some challenges to maintaining the quality of the chemical engineering curriculum. Finally, we have discussed the curriculum as being composed of two components—content and process. Content and process are delivered together, and it is in the specifics of how this is done that we see an opportunity to address some of the challenges identified above.

The typical chemical engineering curriculum in 2005 requires roughly two years of science and mathematics study followed by a year of discipline-specific engineering science followed by a capstone senior experience. Engineering practice, therefore, is left until senior year (or late in the junior year), in large measure because of the need to build on the prerequisite material. To improve this curriculum we need to strengthen the exposure to engineering practice, make room for new subjects, and bolster teamwork and communication skills. These challenges can mostly be addressed by attending to the integration of chemical engineering practice into the delivery of the existing subjects.

All courses can strengthen students' mastery of chemical engineering practice by increasing attention to problem-solving process. While it is true that sophomores and juniors are not ready to tackle full-fledged engineering design, the problem-solving process used in chemical engineering senior design is the generic problem-solving process we discussed above. This process can be integrated into the first-year, sophomore, and junior courses by using open-ended problems and by assigning homework that stretches students beyond the "pattern recognition" response. Such problem-based learning methods[16,17] have been advocated by many on a wide scale, but it is also possible to implement it piecemeal to good effect.

Elective courses in engineering can broaden students' exposure to new fields while also strengthening their problem-solving/critical thinking skills. To do this, engineering/technical electives need to be designed to emphasize the problem-solving process. Engineering/technical electives need to make explicit the connections between engineering-science background material (math, sciences, introductory engineering subjects) and the types of problems that are tackled in the elective.

New textbooks that emphasize integrated problem-solving process can be written and adopted. An instructor's greatest ally when designing a course is a well-written textbook. The textbook is not just a compilation of notes on a subject, however. An instructor dedicated to integrating problem-solving process into a course may do so with almost any text, but the whole process is made much easier if the textbook is designed with the problem-solving process in mind.

Integration exercises can be added to all courses. Integration exercises[18] are activities or classroom exercises that serve to bring together subjects that have been studied independently. Classroom exercises could integrate mass and energy balance concepts, staged-operations concepts, and various mathematical and chemical concepts into one whole. The result will be a greater understanding of chemical processes and a greater appreciation of how all the pieces of a chemical engineering education fit together.

Co-ops and undergraduate research can be emphasized. Co-ops and undergraduate research are two classic ways in which students have gained exposure to engineering practice and problem solving. These are excellent sources of integration between engineering science and engineering practice and should be encouraged.

Academic advising can be recognized as an important piece also in integrating engineering science and engineering practice. Beyond helping students to plan their schedules, academic advisors can discuss with students the trade-offs of various choices for engineering/technical electives as well as the potential benefits to taking a minor or masters in a particular subfield. The discussion with the advisor is an integration exercise in itself. It can challenge the student as to what are his/her goals in making these choices, and it can challenge the student to articulate those goals effectively.

Finally, the senior design class, both traditional and nontraditional, can be retained and refined as the mainstay of integration of engineering science and engineering practice in the chemical engineering curriculum. Traditional senior design has students pulling together all their background studies to design chemical plants, typically in the commodity chemicals industry. More nontraditional approaches could range from choosing less classical design problems all the way to alternate design experiences such as working on interdisciplinary design teams with other majors, such as in the Engineering Enterprise Program we have at Michigan Tech.[19]

SUMMARY AND CONCLUSIONS

An engineering problem-solving approach has been applied to the problem of evaluating and seeking to improve the chemical engineering curriculum. Various demands on the curriculum may be seen as different views of the same desire: the desire for a chemical engineering graduate to be well-versed in the processes of problem solving that can be applied to any of the diverse fields employing chemical engineers. To educate engineers in these processes, we must use specific, real systems for study and calculation, and the need to specialize in this way may seem to narrow the education of the engineer. This need not be the case, however, if proper notice is taken of the processes used to solve the problem, and if the proper connections are drawn between the engineering science background common to all chemical engineering problems and the specific chemical engineering practice confronted in the classroom. As Bruner[6] notes, "To instruct someone. . . is not a matter of getting him to commit results to mind. Rather, it is to teach him to participate in the process that makes possible the establishment of knowledge."

Engineering graduates from Michigan Technological University have long been valued by employers for their ability to "hit the ground running." In the current decade, however, the number of fields in which a chemical engineering graduate can find employment is impossibly broad—our graduates cannot possibly "hit the ground running" in every field. We need to change our approach so that our graduates "hit the ground jogging"—no matter the field in which they land, they should land in motion, and they should be able to rapidly ramp up as they acquire the specific knowledge they need to succeed in their chosen field. The key to "hitting the ground jogging" is an education that emphasizes learning the process of engineering problem solving through a deliberate and widespread integration of fundamental knowledge (engineering science) with practical application (engineering practice).

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