

The OSU ConocoPhillips Lectures on Chemical Engineering Education: A Half-Century of Recollections, Opinions, and Wisdom

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I thank the faculty of the School of Chemical Engineering for putting at serious risk its reputation for good judgment by deciding that my name deserves addition to the list of distinguished persons who have spoken here in past years and who presumably have already said everything worth saying about chemical engineering education. Thus constrained to repeat what is worth saying or to give original voice to what isn't, I nevertheless press on undaunted.

So said Hendrick Van Ness in the 22nd Phillips lecture at Oklahoma State University on April 8, 1988. I feel as flattered as he did about being invited to be a part of this unique lecture series—maybe more so, since I've had the honor twice—only I can't express it as elegantly as he did and so I chose to salute him by plagiarizing his words.

The series began on May 11, 1967, when the legendary Olaf Hougen of the University of Wisconsin gave a presentation entitled “Progress and Future in Chemical Engineering Education,” and the Department subsequently published a monograph that elaborated on the content of his lecture. From then through 2013, 46 Phillips Lectures (later ConocoPhillips or CP Lectures) were given through 2013 by many of the most prominent figures in the history of chemical engineering education. I have been charged with the formidable task of reviewing and discussing the monographs. I've done my best, but there's no possible way I could do justice to that amazing body of history, practices, principles, and speculations about the future of our profession.

The monographs cover a wide variety of topics that cluster into a relatively small number of categories (see Figure 1). All reference citations will be to the monographs. A complete list of titles and authors with links to all but two of the monographs can be accessed at https://che.okstate.edu/content/ConocoPhillips_Lecture_Series.

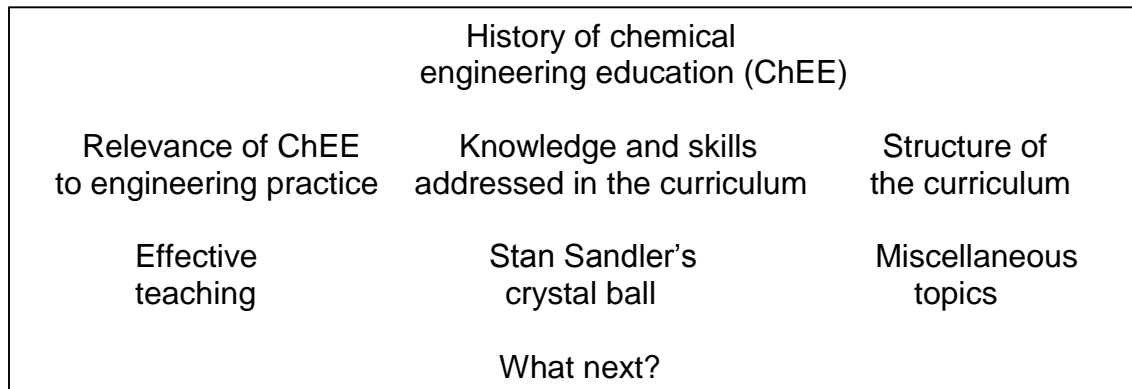


Figure 1. Themes of the ConocoPhillips lectures.

HISTORY OF CHEMICAL ENGINEERING EDUCATION

The English chemist George E. Davis coined the term “chemical engineering” in 1880, defined the discipline of chemical engineering in a series of lectures at the Manchester Technical School in 1888, and published *A Handbook of Chemical Engineering* in 1901. Davis’s definition essentially comprised the collection of current manufacturing practices in the British chemical industry. Prior to Davis, each branch of the chemical industry—acids, paints and dyes, alcoholic beverages, etc.—had its own set of references summarizing its manufacturing equipment, recipes, operations, and rules of thumb. Davis was the first to organize the field in terms of the different operations used across the branches, including transport of solids and fluids, heat transfer, distillation and crystallization, and combustion and other reactions. The first four-year undergraduate chemical engineering degree program was established at MIT by chemistry professor Lewis Mills Norton in 1888. (Varma, 2003, supplemented by Wikipedia entries on chemical engineering education and George E. Davis.)

Hougen’s inaugural lecture reads like a time-lapse photographic view of chemical engineering education, starting 23 years after that first ChE degree program was established and ending 56 years later with the discipline pretty much what it is today. Hougen became interested in chemical engineering as a high school student when he visited the 1909 Alaska-Yukon-Pacific Exposition in Seattle, and studied it as an undergraduate at Wisconsin from 1911 through 1915. The curriculum was mainly a hodgepodge of chemistry and mechanical engineering courses—nothing on material and energy balances, unit operations (a term that wouldn’t be coined by Arthur D. Little until 1915), mass transfer, reaction engineering, or process design. There were no textbooks and the slide rule was an exciting novelty. Quantitative approaches to chemical engineering problems were generally unheard of: the students instead tried to solve real industrial problems experimentally with not much more to work with than glass beakers and a few chemicals.

Here are some of the problems the Wisconsin undergraduates tackled between 1911 and 1915. *Why did the city’s water pipes corrode? How could acetone be produced from sawmill wastes? How could scale in the University boiler plant be prevented? What’s the alcohol content of Ranier Beer?* (Hougen recalled that very large samples were required for that last one.) Hougen had the boiler scale problem, and his solution was to throw some leather into the boiler water. Collagen in the leather formed a protective layer around the calcium precipitate, producing a soft scale deposit that could be easily dislodged.

A number of the CP lecturers offered perspectives on historical shifts and major events in chemical engineering education, including Hougen (1967), Wei (1979), Amundson (1985), Churchill (1990), Aris (1991), and Varma (2003). While acknowledging the tremendous progress that had been made in chemical engineering education since the first chemical engineering department was founded, some of the lecturers saw losses along with the gains.

James Wei (1979) commented on the curricular paradigm shift in the second decade of the 20th century when the pure empiricism described by Hougen gave way to unit operations. He noted that the change revolutionized the chemical process industry, but moved the curriculum toward “puzzle solving,” which “sometimes leads to logical and elegant results that are tidy and neat, eminently teachable, but give little additional insight or utility.”

Wei (1979) & Stuart Churchill (1990) discussed a second paradigm shift catalyzed by the 1955 Grinter Report to the ASEE that moved the curriculum focus from engineering practice to engineering science. Wei (1979) suggested that the new approach emphasized deductive elegance more than practical applications, stating, “By turning its back to comprehensive designs and operations of industrial processes, this new paradigm has serious drawbacks. It is sterile by itself and cannot stand alone. It may develop a set of tools without significant problems to solve.” Churchill believed that the change had its good points, but the accompanying reduction in credit hours led to the disappearance of most of the art of engineering from the curriculum and to students’ having low confidence in their engineering skills, which caused many of them to leave the field. The tasks Hougen and his classmates worked on are still prototypical real-world chemical engineering problems, but it would be a rare department that would dream of assigning them to undergraduates by the time Hougen gave his lecture. (He suggested that in 1967 the topics would probably be turned into subjects of doctoral dissertations.)

RELEVANCE OF CHEMICAL ENGINEERING EDUCATION TO ENGINEERING PRACTICE

The growing split between the industrial practice of chemical engineering and the content of the chemical engineering curriculum described by Hougen, Wei, and Churchill also concerned other CP lecturers. The problem was eloquently expressed by Robert Pigford (1981):

We teach in a scholastic environment in which everything real about engineering has to be imagined and accepted on faith. Students come to us full of curiosity about what engineering really is, yet we have very few ways to help them see that the practice of engineering can be very satisfying if it is done well.

We can't produce the result we're after in universities unless we bear down hard on principles and theories, but the fundamental subjects by themselves do not distinguish engineering clearly from chemistry, physics, or mathematics, and they don't relate to engineering unless we make them relate.

Engineering is of course different from science because its uses are so different. Its methods depend on the sciences, but without some understanding of the art of using science effectively our graduates will not know how to perform effectively on the job. Most important, they will not see while they're in the university that engineering after graduation offers a challenging career in which one can be very satisfied with the things he's accomplished.

Geoffrey Hewitt (1995) suggested that the content of an engineering curriculum should integrate instruction in four categories: *knowledge* (memorized factual information), *skill* (a sequence of actions so ingrained that they're done almost automatically by an expert), *know-how* (a problem-solving ability based on experience that combines knowledge, skills, and intuition), and *understanding* (a problem-solving ability based more on fundamental concepts than experience). What Hewitt found missing from modern curricula was instruction that builds know-how. CP lecturers reflected on two aspects of this lack—what is not being taught, and the qualifications of the faculty to fill in the gaps.

Gaps in the curriculum

- *Realistic methods and problems*

Hougen (1967) pointed out that industrial design and scaleup rely heavily on rules of thumb and educated approximations. He lamented, “*Today many young engineers are so insistent upon establishing the effects of all variables involved that the process becomes obsolete before the experimental program is completed.*” O’Connell (2007) observed that engineers invariably have to take action in the face of uncertainty, employing such principles as “optimal procrastination” and “optimal sloppiness,” and he suggested introducing these notions to the students.

Wei (1979) noted the need for empiricism when dealing with operations that still lack rigorous scientific foundation, such as solids handling, plant design and siting, catalyst preparation, and hazard control. He observed that medical school and engineering both focus the first two years of their curricula on scientific fundamentals, but in the next two years engineering mainly stays with the basics while the future physicians start getting a heavy dose of clinical practice. Wei proposed that engineering move closer to the medical school model.

Other CP lecturers bemoaned the heavy emphasis in the modern ChE curriculum on problems in which complicating factors such as non-idealities in system properties, complex or unknown relationships among system variables, significant fluctuations in operating conditions, and multidisciplinary considerations are all assumed away to make simple analytical solutions possible (Canjar, 1972; Pigford, 1981; Maddox, 1989; Churchill, 1990; Hewitt, 1995; Cussler, 2002). Their lectures called for including more realistic engineering problems in the curriculum.

- *Product engineering*

Commodity chemicals are almost always produced in large-scale continuous processes, and while they are subject to random fluctuations in operating conditions, treating their post-startup production as steady-state is generally a reasonable approximation. For the first half of the 20th century, most chemical engineers were engaged in such processes and focused their attention on process engineering. In the late 1970s, roughly half still were involved with commodity chemical production (Wei, 1979), but by 1995, only an estimated 25% of graduates went into commodity chemicals and double that number worked in the manufacturing of more specialized products (Cussler, 2002). Wei and Cussler both observed that product engineering was still largely absent from the chemical engineering curriculum when they gave their lectures, and that situation still prevails in 2015. The next item brings up a related issue.

- *Batch process engineering*

Unlike commodity chemicals, specialty products such as pharmaceuticals, paints and dyes, cosmetics, agricultural chemicals, food products, and microscale and nanoscale materials and devices are generally produced in batch processes that are subject to significant variations in operating conditions, processing times, and product quality. The manufacturing of those products consequently involves complex dynamic modeling and stochastic simulation of production planning and scheduling, inventory management, and quality control (Reklaitis, 2000).

Although specialized products account for an increasing percentage of industrial production tonnage, batch processes and their complications rarely show up in chemical engineering curricula (Edgar, 1999; Reklaitis, 2000; Rousseau, 2001; Cussler, 2002; Varma, 2003). Cussler (2002) suggested that the material and energy balance course be modified to include

the analysis of batch processes using a recipe rather than a flow chart, tracking of batches through a plant, and sharing of multiproduct facilities.

- *Statistics*

Hougen (1967) cited the eminent statistician George E.P. Box, who observed that without a knowledge of modern engineering statistics, the young engineer “becomes lost in a maze of misunderstanding and confusion.” The absence of a firm grounding in statistics in the chemical engineering curriculum still persists in 2015, which is unfortunate. Relatively few of our graduates will ever derive and solve differential equations, estimate physical properties, design separators and reactors and piping systems, or carry out many of the other tasks we spend so much time teaching them. If there is one thing most of them will sooner or later need in their professional careers, however, it is statistics.

Ronald Rousseau (2001) sounded an optimistic note on the topic of gaps in the curriculum, pointing out that our students have for many years been among the most highly sought after and highly paid graduates in any field. He suggested that as long as we continue to teach generalizable skills such as problem-solving and teamwork that equip our graduates to learn whatever they need to know on the job, we shouldn't be too concerned if we don't explicitly cover some industrial practices in the curriculum.

Declining faculty know-how

One of the main reasons for the growing gap between chemical engineering education and engineering practice is the decline of engineering experience on the faculty. Two phenomena have contributed to this decline. First, in the mid-20th century professors who had worked in industry or did extensive industrial consulting retired or died and were replaced by new Ph.D.'s with no industrial experience and no inclination to get any. You can't teach what you don't know. Robert Maddox (1989) observed that what is taught in many engineering design courses is not really engineering design, partly because the instructors have never done engineering design themselves.

The second phenomenon is the movement in the National Science Foundation in recent decades to funding almost exclusively pure scientific research rather than applied research relevant to the work environment most engineering undergraduates will enter. This trend has in turn motivated engineering departments to hire almost exclusively research scientists, further exacerbating the loss of faculty engineering experience and know-how.

Following are suggestions CP lecturers offered for increasing the relevance of the chemical engineering curriculum to industrial practice.

- *Engineering schools and departments encourage their students to participate in coop and internship programs, both of which give the students industrial experience early in their college education* (Canjar, 1972; Fair, 1975).
- *Department heads encourage and help their faculty members to engage in industrial consulting* (Fair, 1975; Tiller, 1977; Katz, 1978; Pigford, 1981). Besides increasing the industrial relevance of the curriculum, consulting can enhance the department's research funding. Donald Katz (1978) observed that of the 45 doctorates he directed, 26 stemmed from his consulting contracts and were funded by his clients.

- *Faculty members take industry internships, and practicing engineers serve as consultants and adjuncts to departments* (Fair, 1975). The mutual education that would result from such arrangements would serve the interests of both universities and companies.
- *Joint faculty-industry teams offer continuing education programs to faculty and industry personnel* (Fair, 1975). Most engineering graduates' knowledge is obsolete in 5–10 years, and chemical engineers increasingly have to work in areas in which they've had no training (such as safety and environmental protection, sustainable development, bioengineering, and advanced materials). Professional development is becoming more of a necessity than an option in industry (Sandler, 1993).
- *Departments open some permanent faculty positions to people who can effectively bridge the gap between theory and practice* (Fair, 1975; Pigford, 1981; Maddox, 1989). Many departments bring in experienced engineers to teach courses as adjunct professors. That option is certainly better than nothing, but it is clearly inferior to bringing the engineers onto the faculty as tenured professors rather than temporary employees, to teach courses and also to serve as advisors, mentors, and professional role models to the students.
- *Companies fund departments to support research in particular areas of interest* (Pigford, 1981), *and to provide research grants to individual professors and research assistantships to graduate students* (Fair, 1975). The growing dominance of the federal government over industry in funding research and moving academic research priorities away from engineering practice is a cause for concern (Sage, 1967).
- *Departments solicit and pay attention to input from industry personnel on curriculum content related to how operations and design are actually done, and invite them to participate in preparations for accreditation visits.* Departments should take industrial advisory committees seriously, as opposed to just considering them sources of financial support (Fair, 1975).

KNOWLEDGE AND SKILLS ADDRESSED IN THE CHEMICAL ENGINEERING CURRICULUM

Throughout the first half of the 20th century, the curriculum in most chemical engineering departments focused almost exclusively on a relatively narrow spectrum of practices in the chemical and petroleum industries. Over time, several trends arose that led to a need to integrate a much broader range of knowledge and skills. Surveys of employers of engineering graduates revealed that recent hires were well prepared in the technical skills that had been the focus of engineering curricula for decades, but they were seriously lacking in nontechnical (“professional”) skills such as communication and teamwork. At the same time, the list of fields that employed chemical engineering graduates expanded dramatically; problems facing society that required chemical engineering expertise in such areas as energy, sustainable growth, health, safety, and the environment grew increasingly serious; and a combination of globalization and incredibly rapid advances in computational technology began to change the job descriptions of engineers. Cussler (2002) noted that “As a teacher of chemical engineering, I was concerned that I was not preparing my students for the jobs that they would face, but rather for jobs my father...had faced.”

While those events were occurring, an ancient notion about education began to resurface after centuries of dormancy. In his CP lecture, John Prausnitz (1986) suggested that the goal of higher education in technical disciplines should go beyond mere job training to encompass preparing students for satisfying lives “as professional engineers or scientists, as citizens, and as

mature and intelligent human beings with the will and capacity to achieve personal happiness.” In particular, chemical engineering education should help students develop the problem-solving, critical thinking, and self-directed learning skills they would need to succeed in their profession, achieve personal fulfillment, and make valuable contributions to society.

Several CP lecturers reflected on the failure of chemical engineering education to meet those goals. The missing pieces they identified fall into several categories:

- *Professional skills.* Some lecturers noted that professional skills could be more important to graduates’ professional success than their ability to solve differential equations and size pumps. These skills include communications (Canjar, 1972; Wei, 1979), creative and critical thinking (Canjar, 1972; Fogler, 1997), ethical reasoning (Canjar, 1972; Martin, 1974), and teamwork and leadership (Wei, 1979; Dorland, 2008).
- *Multidisciplinary problem solving skills.* To contribute to the solution of urgent technology-related problems facing society, graduates will need broader training than the traditional curriculum provides. CP lecturers proposed that the training should encompass technical areas such as environmental science and technology, sustainable development and conservation of nonrenewable natural resources, health, and safety (Corcoran, 1971; Lohmann, 1976, Tiller, 1977; Rousseau, 2002; Varma, 2003), and other areas such as economics, sociology, psychology, political science, and law (Canjar, 1972). In addition, problems routinely faced by engineers in industry or at universities rarely fall into neat disciplinary categories. Prausnitz (1986) suggested that to help prepare students to deal with multidisciplinary problems, core courses should include applications of chemical engineering methods to a broad range of technical and social problems and applications of methods from other disciplines to solve chemical engineering problems. He gave a number of excellent examples of applications in both categories.
- *Self-directed learning and critical thinking skills.* Scott Fogler (1997) noted several factors that are changing the work environment for engineers. They include the rapid obsolescence of technical knowledge, the ease of locating information and generating quantitative results and the difficulty of validating both; the fading of the concept of job security and the consequent frequency with which engineers now change jobs; and the growing migration of engineering jobs to developing countries with lower labor costs. The net result of those developments is a growing need for engineers to learn new material and methods independently and quickly—a call echoed by O’Connell (2002)—and to critically evaluate the utility and limitations of what they have learned.
- *Ability to educate the public and the government about the role of engineering in society.* Industrial technology has led to major developments with broad scales of constructive and destructive impacts on living things. A large segment of the public is justifiably critical of engineering for creating problems, but there is widespread ignorance about the irreplaceable role of engineering in solving the problems it helped create. A related issue concerns politicians who share the public’s lack of understanding of technology and pass laws requiring remedial measures that are either scientifically impossible or economically infeasible or both. Engineers must take responsibility for educating the public and the politicians about technology, and engineering educators should make sure that their students receive preparation for this task (Marshall, 1973; Peters, 1980; O’Connell, 2007).

STRUCTURE OF THE CURRICULUM

Most of the measures called for by CP lecturers involved making many additions to the curriculum and a few deletions from it. One lecturer suggested adding humanities and social science courses and going to a five-year curriculum (Lohmann, 1976). Most recognized, however, that adding a year to the curriculum would be unacceptable to universities and would make engineering schools that did it uncompetitive in student recruitment, and some suggested alternatives:

- Establish three different degree programs: (1) B.S. in chemical engineering (30–55% in traditional ChE courses), (2) B.S. in engineering (30–35% in ChE, 20–25% in a secondary engineering program); (3) B.A. in engineering (30–35% in ChE, 20–25% in an auxiliary science program) (Beckman, 1968).
- A 3-year B.S. program and an additional year for an M.S. (Corcoran, 1971). This approach has essentially been adopted throughout most of Europe, but has not caught on in the United States.
- Integrate important content related to pollution control, sustainable development, product design, process safety, and professional skills into core chemical engineering courses (Rousseau, 2001; Varma, 2003). The material and energy balance course is particularly suitable for demonstrating the breadth of chemical engineering applications and integrating basic scientific principles and engineering practice (Rousseau, 2001).
- Provide specialized tracks in the curriculum rather than one-size-fits-all (Sandler, 1993; Rousseau, 2001; Davis, 2004). Davis described such a program at Cal Tech comprising a three-year core of fundamentals, with heavy emphasis on the molecular basis of transport theory and thermodynamics, followed by one year focused on either materials, environmental, biomolecular, or process systems engineering.

EFFECTIVE TEACHING

Lecturing is a remarkably ineffective way to promote learning. Decades of cognitive science have demonstrated conclusively that people acquire knowledge and develop skills through active practice and feedback, not through passive reception of information. Thousands of research studies have shown that relative to lecturing, properly implemented learner-centered methods such as active, cooperative, and problem-based learning consistently lead to superior student attainment of almost all learning outcomes except low-level memorization of facts and formulas. Ronald Miller (2012) examined the validity of educational research studies, and while some studies never lead to definitive conclusions, he pointed to the research on active learning as an unequivocal success story.

Despite the overwhelming evidence of their ineffectiveness relative to newer methods, the old teacher-centered methods have dominated engineering education from its inception to the present time. Several CP lecturers have discussed this situation and reasons for it, notably that college teachers are not routinely taught about effective pedagogy and that the faculty incentive and reward system provides little motivation for instructors to change how they teach.

Effective teaching and evaluation of teaching

Donald Woods (2011) summarized research-validated characteristics of effective pedagogy. He observed that good teachers convey enthusiasm about what they are teaching, a

sense that they care deeply about the students' learning, and a belief that the students will succeed; make their expectations clear to the students; communicate clearly; base their design and evaluation of instruction on the knowledge, skills, and values students acquire and not just on what the lectures cover; periodically assess what students understand and where they are confused and take measures to clear up the confusion; and use active learning (engage students in brief course-related activities during class).

Faculty resistance to change

In his inaugural CP lecture, Hougen reviewed changes in chemical engineering curricula that had occurred during his decades on the faculty, and observed: "These changes required the constant struggle of instructors against vested interests of older faculty members; they meant the sacrifice of descriptive courses of great personal pride and familiarity" (Hougen, 1967). Frank Tiller (1977) also discussed faculty members' characteristic distress at the prospect of eliminating or restructuring their favorite courses. The following message should resonate with every veteran of faculty lounge discussions of the nontechnical learning outcomes specified in ABET Criterion 3:

Confronted with the charge of over-emphasis on technical content of the curriculum, chemical engineering professors agree and then retreat to a discussion of the horrors related to too-few credit hours in the stoichiometry-thermodynamics-transport sequence. An inquiry about the student's exposure to the economic structure of the chemical industry or the historical development of chemical engineering is met with a simple answer, there isn't time, or who would teach it? Efforts given over to investigation of social phenomena related to engineering are treated as "second-class activities" in fact if not in theory by deans and department chairmen. In anticipation of a torrent of complaints, I am prepared to acknowledge that each complainant to these statements is indeed an exception.

A common faculty argument against changing courses and curricula is that teaching can't be evaluated rigorously the way research can, and without hard evidence of the effectiveness of teaching there's no good reason to make changes. (The same argument is used to justify not counting teaching significantly in tenure and promotion decisions.) In fact, teaching can be evaluated with greater reliability and validity than research generally is. The keys are formulating observable, unambiguous goals and consistent, measurable criteria for assessing their attainment, and gathering and analyzing assessment data consistent with the goals and criteria. Student ratings are valid measures of teaching quality, but inadequate by themselves. Other measures include peer ratings of classroom instruction, syllabi, course handouts, assignments, projects, and exams; samples of student work; and retrospective interviews of graduating seniors and alumni. (Woods, 2011)

Improving teaching

Several CP lecturers discussed the surprising (at least to non-academicians) fact that college teachers are not routinely taught anything about how to teach, either before or after they join faculties. Neal Amundson (1985) observed that "The subject of teacher education is held in such low regard by the academic community (except in professional colleges of education) that almost no effort is made to emphasize at the university level the training of future pedagogues. This is probably indigenous and follows from the conceit of the great professor who feels that his student, seated at the feet of the master, will learn everything to stand him in good stead for his

future career.” Phillip Wankat (1998) suggested that training can and should be provided to both new and future faculty members, and described the design and impact of his pioneering graduate course on teaching.

Michael Prince (2013) noted that learner-centered teaching methods (which dominate all books and articles on effective teaching) fall on a continuum of ease of implementation. At one extreme is active learning, which can be done in classes of any size and provokes relatively minor student resistance provided certain precautions are observed. At the other extreme is problem-based learning, which places the primary responsibility for learning on the students and changes the instructor’s role from being the source of all knowledge (“the sage on the stage”) to being a consultant who only presents information when the students have established a need to know it (“the guide on the side”). Student resistance to instruction of the latter type can be intense, and instructors are advised to start at the easier extreme and gradually move toward the other one, never venturing too far out of their comfort zone.

Methods by which administrators can improve teaching quality in their schools and departments were proposed by two lecturers. Wankat (1998) suggested that deans and department heads make interest and ability in teaching a criterion for hiring; require interviewees for faculty positions to teach a class session; expect all new hires to get appropriate training in teaching as graduate students or in their first year on the faculty; make funds for instructional development part of new faculty start-up packages; and give each new faculty member teaching and research mentors. Woods (2011) stated that workshops can play an important role in improving teaching, but their effectiveness is limited if teaching isn’t recognized and rewarded in tenure and promotion decisions. He proposed that deans and department heads establish multiple-measure assessments of teaching, making it clear that the outcomes count in faculty performance evaluation. The administrators also should provide incentives to faculty members to improve their teaching, including participating in instructional development programs, and publicly acknowledge and reward teaching excellence.

Teaching and research: Allies or antagonists?

The heavily debated question of whether academic research augments or detracts from teaching quality appeared in several CP lectures. The common argument by those who justify imposing heavy expectations of research productivity on all engineering faculty members is that research and teaching are synergistic, and the most productive researchers are also the best teachers. All of the lecturers weighing in on this issue took exception to this assertion.

Felder (1992) observed that expecting every tenured faculty member to be both an outstanding researcher and an outstanding teacher is unrealistic. Some (the “superhuman professors”) can pull it off, but not enough to populate engineering faculties. Either research quality or teaching quality generally must be sacrificed, and things being what they are in research universities nowadays, teaching invariably takes the fall. Felder, Wankat (1998), and Woods (2011) cited research showing that the purported synergy between teaching and research is mostly fiction—the two activities have different goals and require different skills, each takes a lot of time, and faculty time is limited.

Felder proposed a system whereby most faculty members in an engineering department would put their primary emphasis on disciplinary research, and the rest would focus their attention mainly on teaching and educational scholarship. The research faculty must be excellent

disciplinary researchers and research mentors and good teachers, and the teaching faculty must be either excellent teachers, teaching scholars, and authors of textbooks and education-related papers, or excellent teachers and professional role models with industrial experience. Faculty members in both research and teaching tracks should be evaluated based on the quality of their performance of their designated tasks and should have equal opportunities for tenure and promotion (Felder, 1992).

Van Ness (1988) reflected on the reason for the growing dominance of research in the faculty incentive and reward system and the consequences of that dominance:

The struggle for research recognition strongly influences all activities of the typical chemical engineering department. The goal is not excellence in teaching, scholarship, and research, but the elevation of its rank among research-oriented departments. The ultimate goal of being included in the top ten of some artificial ranking based on research repute is administratively driven, and is motivated by the hope that a high ranking will lead to a high level of research funding. To reach such a goal, one strives not for excellence but for visibility. Quantity and not quality is what counts; the score is kept by numbers. The department must crank out the doctorates, the papers, and the presentations. Not only is the whole business academically misguided, but for most departments the chances of reaching the goal are negligible. Dozens of departments are vying for just the ten top slots already competently filled by departments that got there by paying attention over several decades to academic excellence. Visibility came as a consequence. So long as the leading departments hold to this course, few significant changes will occur at the top of the list.

Technology-assisted instruction

Stanley Sandler (1993) offered the following observation: “*Chemical engineering is a high technology field. As researchers, we demand the latest equipment and use the most advanced technologies in our laboratories. Ironically, as teachers we use methods in chemical engineering education that have not changed much in the thirty years since I was an undergraduate. A comment made recently in The Chronicle of Higher Education suggests that the only major innovation in most classrooms in the last several decades has been the overhead projector.*” Edgar (1999) similarly observed, “*So far, improvements in technology haven’t had that much impact on chemical engineering education. Thermo and transport are still being taught as they were 30 years ago.*”

Bruce Finlayson (1996) pointed out some of the things that instructional technology enabled (or would some day enable) teachers to do: (1) teach at a distance; (2) have a main lecturer at one campus and other lecturers doing recitation sections at satellite campuses; (3) have a “lecture on demand” system, similar to movie rentals, with a main lecturer and satellite instructors doing recitations; (4) provide individualized instruction; (5) engage students actively. He cited recent studies showing that computer-assisted instruction led to equal or better results than traditional instruction and that the absence of a professor in the classroom did not hurt students’ learning.

Scott Fogler (1997) reviewed other ways that instructional technology could facilitate learning. He mentioned visualizing molecular phenomena, conducting experiments in virtual laboratories and plants, and actively engaging students online using interactive teaching modules. Such modules could be used to provide individualized instruction to students with different rates of learning, interests, and learning style preferences.

STAN SANDLER'S CRYSTAL BALL

A remarkably accurate description of the current state of chemical engineering education was presented as a series of predictions by Sandler (1993):

- Since chemical engineering graduates enter a growing number of different fields, the curriculum will move away from its current one-size-fits-all model to offer a range of alternative tracks.
- As industry becomes more multinational, student foreign exchange programs will increase.
- Blackboards in classrooms will be replaced with screens and computer equipment. The use of multimedia simulators and virtual laboratories that combine computers, videodiscs, and lab instruments will increase.
- Individualized instruction based on students' needs and abilities will be combined with mastery education, with grades being based on time taken to complete all course material. "I would feel more comfortable knowing that chemical plants are being designed and operated by people who mastered all the material in our curriculum, rather than someone who only understood 70 or 80% of the material we consider to be important." The resulting tools will enable tailoring instruction to a broadly diverse population.
- "Another interesting question is what will the textbook of the future look like? Will it be of paper, a disk, or only electrical impulses traveling along computer networks. This is a question book publishers and authors such as myself are wrestling with." (They are still wrestling with it 22 years later.)
- Interactive video and computer networks and satellite communications will make the remote delivery of education possible. Such networks will result in linkages between colleges and universities permitting students to take courses available at other schools without leaving their home campus and perhaps without even leaving their homes. Professors may change roles from primarily lecturer to tutor and "knowledge navigator."
- As a consequence of the preceding development, the traditional university structure based on concentrating educators, students, and materials in central locations may become obsolete. "The availability of large electronic databases will allow everyone immediate access to stores of knowledge which far exceed that presently in the Library of Congress." That accessibility will make central campus universities less essential, and online universities will rise to compete and perhaps eventually replace them. Fields like engineering, which needs high-tech industrial equipment, and performing arts and other fields that require intense personal education, and areas that involve extensive clinical practice may still need campuses, but humanities and social sciences may have cause for serious concern.
- Prediction: "(K-12) education will be a major public agenda item and will continue to be viewed as the key to economic growth. However, without a national philosophy, U.S. elementary and public schools will remain inferior to those of other Western cultures."

As crystal ball gazing goes, it doesn't get much better than that.

MISCELLANEOUS TOPICS

Some of the CP lecturers explored issues that do not fit comfortably into any of the preceding themes.

- We're producing inadequate numbers of chemical engineering graduates to meet industry's needs—we need to increase our enrollments (Hougen, 1967). We're producing too many chemical engineering graduates for the number of openings for engineers in the job market—we need to cut down on our enrollments (Corcoran, 1971; Varma, 2003).
- We need instructional programs in chemical engineering technology (Hougen, 1967; Burnet, 1970).
- Advances in technology by the end of the 20th century will lead to a golden age in the United States, with self-driving cars, average life expectancies around 100, cures and preventatives for cancer, heart disease, and allergies, and crude brain transplants (McKetta, 1969). (McKetta also gets a high score in the forecasting department—he was just a bit too optimistic on the timing of his predicted achievements.)
- You should *really* want to write an undergraduate textbook before attempting to do it (Bird, 1982). The problems are that writing an undergraduate text is hugely time consuming, not valued by administrators, and unlikely to be financially rewarding (Davis, 2004).
- Thoughts about graduate education: History, degree completion statistics, and discussions of aspects of the graduate school experience (Reid, 1984).
- Thoughts about chemical engineering for foreign students, including their impact on U.S. graduates' employment, university enrollment and finances, faculty research productivity, and the chemical engineering curriculum (Smith, 1987).
- History of education in Western cultures, going back to Plato, and interactions between chemical engineering and liberal arts (Aris, 1991).
- Teaching students teamwork skills in the context of industry-generated projects carried out by multidisciplinary teams (Dorland, 2008).
- Concepts of sustainable development and how they can be integrated into engineering curricula, particularly freshman engineering and senior design courses (Allen, 2010).

WHAT'S NEXT?

Having gone through the enlightening and enjoyable task of summarizing the 1967–2013 ConocoPhillips lectures, I'll take advantage of my position as the 2015 lecturer to offer my two cents worth on chemical engineering education. I don't have the nerve to make predictions about it as my colleague, fellow plant design team member (City College of New York, Spring 1962), and friend Stan Sandler did so spectacularly in his CP lecture. Instead, I'll just say a few things about what I hope will happen.

Thanks to decades of cognitive science, educational research, and analyses of global trends in industry, technology, and education, we have good answers to two critically important questions:

1. *What facilitates learning? What hinders it?* The answer is that development of skills and expertise in any field involves people doing things, getting external feedback on their efforts or learning from their own mistakes, and then doing the things again. Teaching that provides active practice and feedback in targeted skills facilitates learning; teaching that makes students passive recipients of information (such as watching nonstop lecturing, either in a classroom or online) doesn't facilitate learning and can hinder it.

2. *What skills that have not been stressed in chemical engineering education in the past will be required of future chemical engineers in the U.S. and other developed countries?* The answers include critical and creative thinking, multidisciplinary teamwork, leadership and entrepreneurship, communication across cultures, and above all, the capacity for self-directed learning needed to keep up with the increasing pace of changes in jobs, job markets, and technology.

What we don't need to do next is form more NAE and ASEE panels of experts and conduct more multimillion-dollar studies to find more answers to those questions. We can re-engineer chemical engineering education starting next Monday, based entirely on answers available right now, and make tremendous strides toward moving our curricula, instruction, evaluation, and faculty development to where they need to be in the next decade. In the course of doing it, we will come up with answers to other questions now facing us:

3. *What will motivate faculty members to make substantial changes in curriculum content and teaching methods? How should the faculty members be prepared to make the changes? What will motivate administrators to provide the necessary support?*
4. *What is the appropriate distribution of expertise and focus on department faculties? How many faculty members should focus primarily on disciplinary research and graduate student mentoring, and how many on teaching, educational scholarship, instructional development, and mentoring in teaching? How many should be knowledgeable about engineering practice from first-hand experience?*
5. *How can the racial and gender diversity of U.S. engineering students, engineering faculty members, and engineering school and department administrators be raised to a level that reflects the diversity of the nation's population.*
6. *What role should technology play in chemical engineering education?*

Since Sandler, Edgar, Finlayson, and Fogler gave their lectures and made their predictions. Engineering instructors now have ready access to dynamic presentation software and tablet computers linked to projectors, mathematical software programs such as MATLAB[®] and Simulink[®], Mathcad[®], and Mathematica[®], chemical process simulation programs such as Aspen[®], sophisticated dynamic simulators and virtual laboratories, online screencasts and interactive tutorials, and course management systems. The faculty has not embraced the use of these tools in all core courses, but that day will inevitably come. In addition, online degree programs and massive open online courses (MOOCs) are becoming increasingly accessible and effective. Their eventual impact on traditional brick-and-mortar campuses is a major unresolved question in 2015, and several sub-questions are likely to be the subject of future CP lectures.

- 6a. *What is the optimal balance of technology-assisted instruction (including e-books, online screencasts and interactive tutorials, simulations and virtual laboratories, individualized lessons and mastery learning, and flipped classrooms) and face-to-face instruction in engineering courses?*
- 6b. *What percentage of the chemical engineering curriculum may be completed online to qualify for an accredited bachelors degree? What about masters and doctoral degrees?*
- 6c. *If accredited undergraduate chemical engineering degrees may be earned entirely online for much less than what they cost in traditional brick-and-mortar schools, how many of the*

latter will survive? What will become of the faculty members at the non-surviving institutions?

There won't be a single set of answers to these questions (especially 3 and 4) because different universities have widely varying missions. A few prestigious universities appropriately have as their top priority carrying out frontier disciplinary research and preparing students for academic careers. Many more institutions should have as their top priority providing high-quality and affordable education to their students. I hope to see Questions 3–6 explored in the coming years and alternative answers tested and validated for both types of institutions. I also look forward to seeing the results described in future ConocoPhillips lectures, ideally by lecturers who reflect the diversity sought in Question 5.

FINAL WORDS

As the splendid set of essays in the ConocoPhillips lecture series makes clear, chemical engineering educators are in an exciting, challenging, and often stressful profession. The demands of the profession on new faculty members are especially intense. Expectations of research productivity grow exponentially as research funding becomes harder to get, and at the same time calls for changes in how and what we teach keep getting more drastic and urgent. It is easy to become slaves to our calendars and to-do lists under these circumstances, jeopardizing our health, well-being, and in the long run, our productivity and professional success.

In his CP lecture, the wise Hank Van Ness (1988) reflected on this matter and offered some advice I'd like to leave you with. It's not easy advice to take when you're caught up in the scramble for success, and even at age 76, as I approach (slowly, I hope) the end of my professional career, I find it hard advice to live by. When I've managed to take it, however, even for brief periods of time, I've never regretted it. I suggest that you won't either.

Even as an undergraduate in an accelerated wartime program, I didn't devote all my time to the study of chemical engineering. As a boy I had fallen in love with music, and at the University of Rochester, with its Eastman School, I was able to hear and see the finest musicians of the day. I mention this because music has been an intrinsic part of my existence, providing counterpoint to the incessant struggle of a professional career, and modulating the pace of life. Music is, of course, only an example, but I would suggest to anyone embarking on a professional career that some serious but relaxing diversion is essential to it. No matter what, provision of time should be made for the enjoyment of this diversion. Time and health are the indispensable gifts of nature, not to be recklessly squandered in the quest for fame and fortune.

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- ⁱ Dr. Olaf Andreas Hougen, *Progress and Future in Chemical Engineering Education*
Dr. Bruce Hornbook Sage, *Research in an Academic Atmosphere*
Dr. Robert B Beckmann, *Profession for the Future or Derelict of the Past?*
Dr. John J. McKetta, *The Contribution of Chemical Engineering to the Fabulous Future of Man*
Dr. Geore Burnet, *Chemical Engineering Technology – An Educational Challenge*
Dr. William H. Corcoran, *Who Tends to Store? – Chemical Change, 1980*
Dr. Lawrence N. Canjar, *The Professional Engineering School*
Dr. W. Robert Marshall, *The Need for Public Understanding of Technology*
Dr. Joseph J. Martin, *No Engineer Can Serve Two Masters – Or Can He?*
Dr. James R. Fair, *Industry-University Interactions*
Dr. M.R. Lohmann, *Looking Forward – Looking Back An Old and New Problem of the Profession*
Dr. Frank M. Tiller, *Complexity and Confusion in World Affairs. Challenge to Engineers and Educators*
Dr. D.L. Katz, *Practice What You Teach*
Dr. James Wei, *Rejuvenation of Chemical Engineering*
Dr. Max S. Peters, *Politicians and Higher Education in a Technical Society*
Dr. Robert L. Pigford, *Merging Theory and Practice in Chemical Engineering Education*
Dr. R. Byron Bird, *Book-Writing and Chemical Engineering Education: Rites, Rewards and Responsibilities*
Dr. Robert C. Reid, *The Graduate Experience*
Dr. Neal R. Amundson, *Reminiscences, Random Comments, and Landmarks*
Dr. John M. Prausnitz, *Versatility and the Integration of Experience*
Dr. Joe M. Smith, *Chemical Engineering Education for Foreign Students –Blessing or Burden*
Dr. Hendrick C. Van Ness, *Chemical Engineering Education –Will We Ever Get It Right?*
Dr. Robert N. Maddox, *Chemical Engineering Design: Plant, Project, Process, Phreshman*
Dr. Stuart W. Churchill, *Perspectives and Counterparts in Chemical Engineering Education*
Dr. Rutherford Aris, *Chemical Engineering and the Liberal Arts Today*
Dr. Richard M. Felder, *The Myth of the Superhuman Professor*
Dr. Stanley I. Sandler, *Technological and Societal Change and Chemical Engineering Education*
Dr. Klaus D. Timmerhaus, *Education and Science—Do We Really Care Enough?*
Dr. Geoffrey F. Hewitt, *People Processing - The Chemical Engineering Way*
Dr. Bruce A. Finlayson, *Can Professors Use Technology To Teach Faster, Better, Cheaper?*
Dr. H. Scott Fogler, *Teaching Critical Thinking, Creative Thinking, and Problem Solving in the Digital Age*
Dr. Phillip C. Wankat, *Educating Engineering Professors in Education*
Dr. Thomas F. Edgar, *Process Engineering in the 21st Century: The Impact of Information Technology*
Dr. G. V. “Rex” Reklaitis, *Preparation of Chemical Engineers for Manufacturing Leadership in the 21st Century*
Dr. Ronald W. Rousseau, *Striking a balance in Teaching Today’s Students to Solve Tomorrow’s Problems*
Dr. E. L. Cussler, *What Happens to Chemical Engineering Education*
Dr. Arvind Varma, *Future Directions in Chemical Engineering: A New Path to Glory*
Dr. Mark E. Davis, *Adapting Chemical Engineering Education to Increasing Job Diversity*
Dr. Timothy J. Anderson, *Investing in Faculty: Rationale and Approach to Faculty Career Development*
Dr. Robert C. Armstrong, *Frontiers in Chemical Engineering Education*
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Dr. Dianne Dorland, *Learning Strategies that Promote Teamwork*
Dr. David T. Allen, *Green Engineering: Incorporating Sustainability Concepts into Engineering Education*
Dr. Donald R. Woods, *Ideas to Measure and Reward Efforts to Improve Student Learning*
Dr. Ronald L. Miller, *“Education Research – Does it Really Have Anything To Offer Classroom Instructors?”*
Dr. Michael J. Prince, *“Introduction to Active Learning for Busy Skeptics”*