This column provides examples of cases in which students have gained knowledge, insight, and experience in the practice of chemical engineering while in an industrial setting. Summer internships and co-op assignments typify such experiences; however, reports of more unusual cases are also welcome. Description of the analytical tools used and the skills developed during the project should be emphasized. These examples should stimulate innovative approaches to bring real-world tools and experiences back to campus for integration into the curriculum. Please submit manuscripts to Professor W.J. Koros, Chemical Engineering Department, Georgia Institute of Technology, Atlanta, GA, 30332-0100.

FROM LEARNING TO EARNING:

Making the Lesson Plan Cross the Divide

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Forty years with the DuPont company, 30 years helping out around the chemical engineering department at Queen's University, and 20 years reading *Chemical Engineering Education* magazine have resulted in a few thoughts about the formation and training of chemical engineers. Any engineering curriculum deals with a remarkable challenge: to take a high-school student, usually after one year of general engineering, and, in three years, turn that individual into a functioning professional. Given that professional licensure usually requires a few years of practice, the typically narrow scope of such experience means that systematic education has had to have been done back in engineering school. Few if any other professions attempt to do so much in so short a time.

In chemical, as in all the engineerings, the challenge is met by a carefully designed curriculum, which is different from school to school but which generally adheres to a standard pattern of courses, content, and sequence. This curriculum is widely accepted by the major stake-holders: the students, their employers, the educators, and society at large. Examples of chemical engineering undergraduate curricula at four universities have been presented in the last few years.[1-4]

Change is proposed from time to time by the various groups but it is often in divergent directions. The educators, who are the people who would have to make the changes, point to the already crowded curriculum and to the fact that they themselves have only limited time to make improvements to something that they consider to be already working quite well or at least well enough.

With that background in mind, here are three suggestions for the chemical engineering curriculum, followed by some ideas for implementation. The suggestions are aimed at preparation for the chemical and related process industries: while students may have management as a goal they realize that success in the technical work for which they were hired is the likeliest route to wider responsibilities.

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INTRODUCTION TO COMPLEXITY

In 1960, when Bird, Stewart, and Lightfoot published their book *Transport Phenomena,*[5] they crystallized the centrality of these phenomena as the underlying basis of all chemical engineering. The three balance equations—for momentum, for heat, and for mass (incorporating reaction as a source term)—are, to chemical engineering, the equivalent of Maxwell's equations to electrical engineering and Newton's three laws of motion to mechanical engineering. When we train our graduates to "think like chemical engineers," we mean that they are to view the processes of industry and nature in terms of these three phenomena. We believe that this fundamental approach is the path to understanding, improvement, and invention in chemical operations.

The problem arises when the graduate is confronted with the actual operations of industry, where there is complex interaction and where the complexity is hidden behind a mass of steel and insulation. The clean individuated concepts of academia seem impossible to apply and this impression is abetted by old hands telling the young engineer that this is the "real world" and that "we don't use much theory around here."

One way to prepare the graduate for this upcoming shock is to introduce analyses of complexity into the instruction, either as participatory classroom exercises or as assignments. Cast them into the form of what happens when two or more transport phenomena act at the same time, either in the form of a design study or as a trouble-shooting inquiry. Make the examples progressive: if the first course is Fluids, then present a situation where flow and statics are both at work; if the next course is Heat Transfer, present a situation where both heat and momentum are flowing; and so on. If the students were to see, say, four such analyses over the course of study it would strengthen their resolve to carry the fundamental approach over into the bear-pit of industrial practice.

Examples are not hard to come by. They may be imaginatively constructed or they may come from the experience of academic and industrial colleagues. Several books on process analysis and trouble-shooting have case studies—see for example the texts by Saletan,[6] Woods,[7] and Lieberman.[8] Course time may be harder to come by, but it can be argued that it is better to sacrifice some points of detail in favor of raising the likelihood of the graduate actually using what has been taught.

There is a related but separate benefit. Custodians of curricula are always conscious of the high desirability of incorporating a Design or Synthesis component, in which students have the opportunity to use their received knowledge. But this exercise in Process Synthesis is time-consuming and is often confined to a final-year "capstone" course. By contrast, exercises in Process Analysis, as described above, can provide many of the same benefits, at less cost in time and at more points in the course of study. There could be an optimal combination of the two approaches.

One of the hurdles with actual industrial processes is that, with the best will in the world, the engineer lacks the data to create a quantitative fundamental description of what is going on. Consequently, the acquisition of data by both standard and specialized methods is an accompanying skill of great value, to be taught probably in a course on process monitoring and control.

Finally, on the subject of analyzing complex processes, recourse is often had to the use of statistical correlations, *e.g.*, of process outputs with process inputs. These methods can provide a lot of insight into the overall operation and they can guide optimization and process changes. They can also be a sign-post to the internal workings of the operation. They are not, however, a substitute for the fundamental understanding, in terms of transport phenomena, which alone can produce major improvements and inventions in processes.

FRONT-LINE & SUPPORTING KNOWLEDGE: A NEW COURSE – "INDUSTRIAL PRACTICE"

When employers of chemical engineers put "communication and teamwork" at the top of the list of desirable skills and put technical knowledge further down the list, then we know that there is a disconnect between the employer and the university. It sometimes appears that graduates are valued more for having passed their courses than for what they have learned from the courses. We may conclude that one or both of two conditions apply

1) *the employer does not understand (perhaps has never understood) the value that the graduate's fundamental know-how can bring to the enterprise, and*
2) *the university has overlooked or under-taught some skills and knowledge that would help the new graduate be more effective in the employer's service.*

The only remedy for condition (1) lies with the graduate, who needs to make a case for applying fundamentals, with successful results that open the eyes of the employer. Hopefully the above described training in analyzing complexity will be of some help in making this happen.

Condition (2) lies within the purview of the university. People entrusted with the formation of chemical engineers recognize that there is more to the finished product than an understanding of momentum, heat, and mass transfer. Ability to communicate and to work as part of a team are important skills and generally are addressed in the curriculum. There are several others, as are listed below. Sometimes they get taught as part of a process design course, but this unfortunately takes time away from the actual design experience. There are others that are not taught at all because they are part of some other discipline. If a group of students, industrialists, and academics were asked to suggest useful skills and know-how, they would come up with a formidable list. Some are already covered (*e.g.*, teamwork as part of group assignments); a lot of others could constitute a new course, perhaps called Industrial Practice. This is a course that would precede the project of the Process Design course, with the latter drawing on many of the elements of the new course. Here are some possible topics.

Communications: often taught as a course in its own right. Desired outcomes are ability to write a letter or other document that is clear and gets to the point, ability to speak up and deliver a message verbally, and ability to think on one's feet, answer questions, and defend one's position. Graphical abilities, for presentations and for transmittal of specifications, are a considerable asset.

Teamwork: best taught by practice. A lecture would be helpful on group dynamics and on the planning and scheduling of a group effort. A good outcome is the ability to be a productive member of a team and also an idea of how to lead a team.

Economics: outcomes are ability to make first estimates of capital cost and operating cost, understanding of the expenditure approval procedure, and knowledge of how to calculate indicators such as net present value, return on investment, and cash flow.

Documentation: knowing the purpose of and knowing how to prepare the standard engineering transmittal documents are the desired outcomes. These documents consist of process specifications, process flow diagrams, functional specifications for monitoring and control systems, initial piping and instrumentation diagrams, equipment data sheets, and first draft of applications for environmental permits. Instruction might start with learning to read existing such documents.

Sources of information: the student will profit from guidance on accessing the vast amount of literature on technical, economic, and relevant social topics. The outcome is ability to go efficiently to sources of needed information—also a general appreciation of the books and journals that support lifelong learning and personal professional development.

Common process equipment: some things are ubiquitous across almost all processes and are encountered early in a chemical engineer's career. These items include pumps, blowers, piping, valves and fittings (filters, steam traps, etc.), vessels and mixers, process measuring devices, simple process controllers, and simple heat exchangers. An outcome would be to develop a level of familiarity with these devices beyond what may be learned in regular courses in fluids, heat transfer, and process control.

Process simulators: the student may have the opportunity to use a commercial general-purpose process simulator in the Process Design course and, later, may have (or press to have) the use of a simulator with an employer. The outcome is to learn the capabilities and limitations of the current programs on the market.

Safety and health: outcomes are knowledge of the major hazards (fire, explosion, toxic release), ability to conduct hazards analysis, and understanding of the financial and legal consequences of mishaps.

Environmental considerations: one outcome is knowing the applications of chemical engineering to remediation. Another is knowing how various types of waste are dealt with regardless of method, and knowing the legal consequences of non-sanctioned releases to earth, water, or atmosphere.

Plant services: as an outcome, understanding something about the provision of such auxiliaries as air, water, steam, electricity, etc.

Other engineerings: outcomes are introductory know-how in such areas as

Electrical – *motors, sub-stations, in-plant power distribution, control cabinets, data transmission*

Mechanical – *drive trains, vessels, steam plants, piping stress*

Civil – *hydraulics of environmental and other systems*

Metallurgical – *materials of construction, corrosion*

Operation of plants: the outcome is an understanding of how plants and their people work. The engineer acquires a picture of who does what. He or she learns that there are typically people engaged in supervision, operation, maintenance, technical support, accounting, etc., and learns what to expect from them and how to interface with them.

None of these topics are specific to any particular industry or plant. There are undoubtedly many more items that an employer or a new employee would like to see. Most of these topics can be covered in a lecture or two because the intended outcome is familiarity not expertise. A 30- to 40-hour course filled with such knowledge equips the student to plunge into a final-year Process Design project, makes the newly hired graduate more useful and impressive to the employer, and serves as an ongoing source of information during a whole technical career. An extensive set of online supplementary notes helps to ensure the long-term benefits.

Who will teach such an eclectic mixture of topics? Although the ideal would be one person, help from other departments or from outside the university may be necessary. But the overall content needs to be controlled and, most importantly, everything has to be potential material for the examination.

One notable omission from the topic list is the subject of Ethics and Integrity, an issue that stands above any of the ones listed. Because of its over-riding status it needs to be treated not only separately but also continuously over the course of the engineering program. A good and immediately applicable starting point is consideration of academic honesty on the part of students and teachers.

TASK-DRIVEN TECHNOLOGIES

Schools teach technologies but companies have tasks. The company is interested in a technology only insofar as it performs a task. Thus, the school teaches distillation but the company has a liquid mixture to separate and it cares for distillation only if it turns out to be the best way to carry out that specific separation task. In a professional development course,[9] my colleague David Mody and I attempted to organize the technology-vs.-task matrix by tabulating the needs that arise in chemical processes and then surveying the technologies available to meet them. With the help of several other persons we arrived at Table 1: a list of 10 general needs or tasks and specific ways in which they occur.

TABLE 1
Tasks in Chemical Process Design

General Tasks	Specific Situations
1. Shipping and Storage	Gas storage – low/high pressure, low/high volume Liquid storage – low/moderate volatility, above-atmospheric vapor pressure Solids storage – robust/hygroscopic/sticky Shipping – gas/liquid/solid, short/long distance, benign/dangerous
2. In-Plant Transport of Liquids and Solids	Liquid – low/high viscosity, low/high discharge pressure, low/high rate, closed/open channel Liquid-solids mixture (slurries) Gas-liquid mixture Solids—robust/friable/dusty
3. Transport and Compression of Vapors and Gases	Movement of gas – low/medium/high discharge pressure Compression – low/high rate, moderate/high pressure Gas with solid Gas with liquid Gas with aerosols
4. Solids Processing	Size reduction Size enlargement Solids formation Coating
5. Heating, Cooling, and Phase Change	Gas – heating/cooling Liquid – heating/cooling, low/high viscosity Solids – heating/cooling Condensation (single/miscible/immiscible component) Vaporization/boiling
6. Mixing and Agitation	Miscible liquids Solids in liquid Immiscible liquids Solid particles with each other Gas and liquid Solid particles and gas
7. Mechanical Separation	Liquid and liquid Gas and solid Solid and liquid Liquid and solid Gas and liquid
8. Molecular Separation	Permanent gases Solid-in-liquid solution Vapor and permanent gas Fluid-in-solid solution Vapor mixture Solid solution Liquid mixture
9. Chemical Reaction	Gas phase Fluid-solid (non-catalytic) Liquid phase Solid-catalyzed (in gas, liquid, or gas-liquid medium) Gas-liquid Biochemical Immiscible liquids Solid phase
10. Integrated Reaction and Separation	

Then we identified, as well as we could, the technologies available for these tasks and situations. By way of example, for the general task of Mechanical Separation and its five specific situations, Table 2 shows the several potentially suitable technologies. For the general task of Molecular Separation, Table 3 shows available technologies or methods.

What is immediately obvious is that, while some of these methods (*e.g.*, distillation, absorption) are generally taught in some detail, others are completely ignored, even to the point that teacher and student may not know what they are. Subjects like Solids Processing, Mixing and Agitation, and Mechanical Separation are often not taught at all. And yet the graduate goes into a job where the first problems that come his or her way may well be in these areas.

What is also obvious is that there is not enough time or space in the curriculum to thoroughly explore all of these technologies. A more realistic objective is simply to introduce them to the student, explaining

1) *what they are and how they work*
2) *under what conditions they are appropriate*
3) *what the key questions or calculations are.*

For many of the items a 15-minute tutorial supplemented by a set of online notes is sufficient. The major technologies that are traditionally taught can be given more attention.

The new graduate is in the position of a general practitioner in medicine, the "front line" person who needs to know enough of the whole range of conditions and treatments to be able to deal directly or to hand off to the correct specialist.

TABLE 2
Task: Mechanical Separation

Specific Task	Technologies
Liquid and Liquid	Decantation or Settling Coalescence Centrifugation
Solid and Solid	Screening Elutriation (air-classification) Magnetic attraction Electrostatic precipitation
Gas and Liquid	Gravity settling Cyclone flow Inertial precipitation (de-misting, scrubbing)
Gas and Solid	Gravity settling Cyclone flow Scrubbing Filtration Electrostatic precipitation
Liquid and Solid	Sedimentation centrifugation Filtration Settling Flotation Hydrocyclone flow Expression Wicking

Some instructors will be unhappy that there is time for only qualitative presentation of some of these technologies but could note that in many other disciplines in the university this is always the case and it still gets dealt with at examination time.

IMPLEMENTATION: TOWARDS A (SOMEWHAT) REARRANGED CURRICULUM

One or another of the above proposals may catch the eye of a curriculum-minded individual or perhaps a university department in the midst of curriculum review. Here are a few suggestions on implementation, which may actually lead to action.

Proposal #1, providing students with experience in analysis of complexity, is weakened if the treatments of the individual transport phenomena and of reaction are fully compartmentalized. The idea is to examine systems where two or more of these actions are occurring and interacting. The instructors in the individual subjects need to cooperate. For instance, if mass transfer is taught after momentum and heat transfer, then, to achieve the result, the mass transfer instructor has to be willing to devote some course time to a joint example/exercise involving the other two transfers.

The concept of proposal #2, for a new course, Industrial Practice, comprising industry-oriented supporting topics, is probably noncontroversial. It just needs to find room in the curriculum and to find knowledgeable instructors. No small tasks!

TABLE 3
Task: Molecular Separation

Specific Task	Technologies
Permanent Gases	Cryogenic distillation Adsorption Membrane permeation
Gas-vapor Mixture	Condensation Absorption Adsorption
Vapor Mixture	Distillation Absorption Adsorption Membrane permeation
Liquid Mixture	Distillation Stripping Extraction Adsorption Membrane permeation Melt crystallization
Liquid Solution (containing a dissolved solid)	Vaporization Solution crystallization Ion exchange Reverse osmosis Dialysis
Solid Solution (all solid or containing a dissolved fluid)	Drying Leaching Melt crystallization

This is a course that will be popular with students, who can see the immediate benefits. It will be popular with industrial sponsors and they may be willing to assist. Professors, themselves, may take pleasure in developing new expertise to teach some of the material: good references are Lieberman and Lieberman[10] and Ludwig.[11] Timing of the course is ideally in the term immediately preceding the Process Design course.

Proposal #3, the survey of Task-Driven Technologies, calls for a great widening of the subject material being taught, raising the controversial issue of depth vs. breadth. The issue was examined, for instance, in a 2001 article by Wankat[12] specifically for methods of mechanical and molecular separation: Wankat presented a list of such methods similar to the lists in Tables 2 and 3 above. In the present article the proposition is made that it is more important to understand the capability and behavior of a technology than to be able to design a unit to carry out the technology. If that premise is accepted, then the learning experience can be greatly widened and accelerated by student experimentation with dedicated mathematical models, of which there must be many suitable candidates in the great treasury of simple simulators developed by academics over the years. Another aid is a good suite of online supporting notes. Laboratory experiments can also help. The material could be taught during years one and two (of the three-year program), probably fitted into existing courses in fluids, heat transfer, and mass transfer, giving these courses a flavor more of Unit Operations than of Transport Phenomena. Prior to dealing with individual technologies certain underlying concepts would have to be taught, such as Bernoulli's equation, heat transfer coefficients, equilibrium and operating lines, and equilibrium-vs.-rate. But some of the current more mathematical aspects would be deferred. The deferment would be to a final-year course (or courses) presenting the theoretical and mathematical underpinnings, *i.e.*, the finer points of chemical engineering science. Put very simply, the proposal reverses the traditional sequence of fundamentals first and applications second.

Table 4 summarizes the way in which these curriculum elements might fit into the three-year program.

CONCLUSIONS

The following conclusions sum up what is being suggested.

1. *The chemical engineering undergraduate curriculum should be viewed as a work in progress, capable of and meriting continuous improvement.*
2. *Process analysis, as a complement to process synthesis, should be considered as a teaching tool.*
3. *Composite, multi-topic courses, such as the proposed Industrial Practice course, have a place: not every topic requires a full or half course of its own.*
4. *The teaching of applications before fundamentals may be a better sequence, particularly as a preparation for the process design course.*
5. *The balance between breadth and depth needs serious thought.*
6. *Persons outside the university can supplement the efforts of faculty.*
7. *The curriculum team needs to involve itself in course content, not just in the sequencing of courses and the assignment of instructors.*

TABLE 4
New and Re-arranged Material for the Curriculum

Year	Fall Term	Winter Term
One	Task-driven technologies	
Two	Task-driven technologies	Task-driven technologies, INDUSTRIAL PRACTICE course
Three	PROCESS DESIGN course, Chemical engineering science: Transport phenomena and other fundamentals	Chemical engineering science

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