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American Institute of Chemical Engineers

Chemical Engineering at . . .

Colorado State University

AUTHOR GUIDELINES

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Colorado State University

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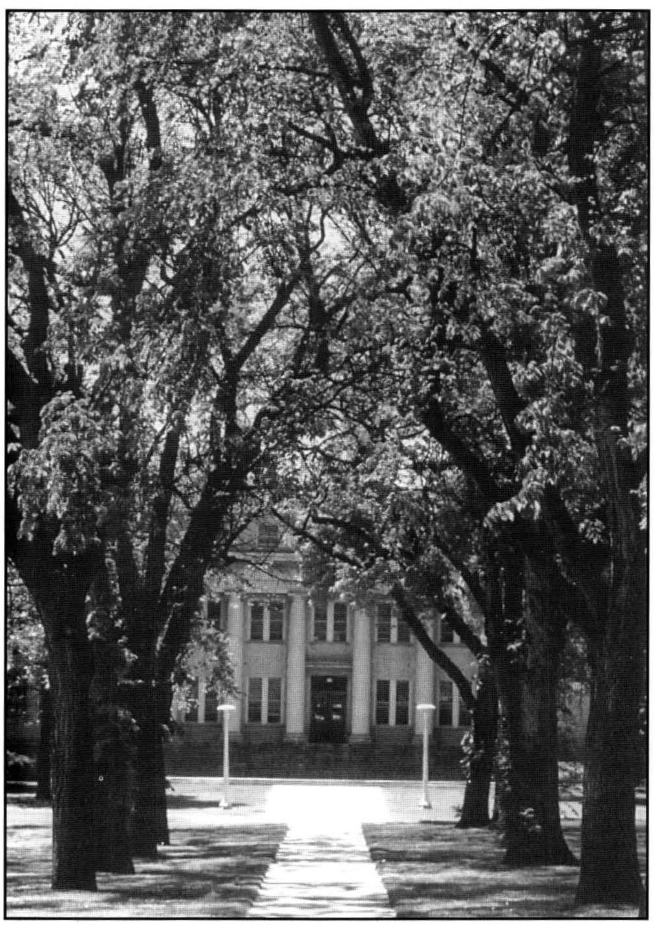

The historic Colorado State University Oval with its twin rows of American elms leading to the Administration Building lies just to the east of the College of Engineering complex.

Paradigm: . . . a set of rules and regulations (written and unwritten) that does two things: (1) it establishes or defines boundaries; and (2) it tells you how to behave inside the boundaries in order to be successful.

Joel A. Barker

Paradigms may shift, rattle, and roll, but Judson Harper possesses no doubts that new boundaries were established with the advent of chemical engineering at Colorado State University. Now the University's Vice President for Research and Information Technology, Harper speaks of "fresh cloth" and a "new model" when outlining what he calls the genesis of the chemical engineering program in 1976.

Part of the Department of Chemical and BioResource Engineering, chemical engineering at Colorado State started with the coupling of food and chemical engineering undergirded by Harper's own work in food extrusion. In fact, the program was the first one nationally to emphasize the interface between chemical engineering and the biological sciences. Two decades later, Colorado State is still one of the few American universities developing its chemical engineering program in such a unique manner.

If the program is unique, it is because of its origins and evolution; as Harper implies, its genesis is its hallmark—namely, an integration of interdisciplinary collaboration, emerging technology, and applied research.

INTERDISCIPLINARY COLLABORATION

Prior to Harper's arrival at Colorado State, a movement was underway to expand the then Department of Agricultural Engineering. Rather than go down a traditional road such as machinery, however, the powers-that-be decided to expand into food engineering. Harper was hired out of industry to become the department head, and the evolution of chemical engineering at Colorado State began.

The 1970s, with its fuel shortage crises, pushed the evolutionary process along—emphases merged, changed, and moved on. Research on the conversion of biomass to alternative fuels led to broader involvement in biochemical engineering, with strong programs developing in design and control of bioreactors and, more recently, in environmental biotechnology. By the early 1980s, a new front was opened with the addition of the emerging area of advanced materials and its focus on understanding fundamental chemical principles of high-tech thin film and polymer processing.

These areas—biochemical engineering, environmental engineering, and advanced materials—together with the traditional or fundamental chemical engineering areas of thermodynamics, heat and mass transfer, and process control form the core research of the eight-member faculty today. Throughout all of their undertakings, however, the cross- or inter-disciplinary hallmark can be found. According to former department head, Vincent Murphy, "We only hired people who had an interdisciplinary bent. Since we were a small group, if we wanted to accomplish much, we had to form partnerships."

An excellent example can be found in the work of Kenneth Reardon and the area of bioremediation—that is, the use of biological agents such as microorganisms and plants to solve hazardous waste pollution problems. Reardon wants to incorporate bioremediation concepts into both undergraduate and graduate engineering courses. He and five other Colorado State colleagues, through a $350,000 grant from the National Science Foundation's Engineering Education and Centers Division, are developing seven teaching modules that contain laboratory, video, minilecture, and case study components. Two modules are presently being tested at Colorado State and five other universities; one module is in a multimedia (CD-ROM) format and the other is in a video/paper format.

EMERGING TECHNOLOGY

David Dandy builds diamonds one atom at a time. Although Dandy is involved in fundamental research, its future applications are mind-boggling—supercomputers the size of a deck of cards and surgi-

Setting the Scene

Founded in 1870, six years before Colorado gained statehood, Colorado State University has an enrollment of 22,000 on-campus students. The College of Engineering has 1600 undergraduates and 500 graduate students.

Fort Collins, a former territorial army fort, has a population of 100,000 and is nestled in the foothills of the Rockies, 65 miles north of Denver, at an elevation of 5,000 feet. With 300 days of sunshine, residents freely enjoy all the natural beauty for which Colorado is known. Camping, skiing, climbing, boating, fishing—name your pleasure and you'll probably find it within easy distance of Fort Collins.

The University itself consists of an 833-acre main campus that houses most of the administration offices and classrooms. The chemical engineering program is located in the 41,200 square-foot Engineering South Building, which was completely renovated in 1984.

The main campus also houses the Lory Student Center, the hub of student life, which was ranked one of the top ten student unions by the *New York Times* columnist Richard Mall in 1986. Pauline Yoshihashi, writing in the *Wall Street Journal* in March of 1992, cites the Center for its student-oriented services: "Scholars can drop by . . . to buy a computer, and also [to] rent skis or hiking boots for a weekend of work and play." An extensive renovation of the facility was completed recently.

In addition to the main campus, a 1,700-acre Foothills Campus is devoted primarily to research. The Engineering Research Center (ERC) is located on this campus—chemical engineering research programs in semiconductor processing and groundwater/contaminant transport use these facilities.

The eight-member chemical engineering faculty focuses on three applied areas of research: biochemical engineering, environmental engineering, and advanced materials. This work is complemented by more basic research in the traditional chemical engineering fields of thermodynamics, heat and mass transfer, and process control.

Virtually all the chemical engineering research groups interact actively with other departments at Colorado State. These contacts range from information exchange to joint projects with investigators in departments such as microbiology, electrical engineering, biochemistry, civil engineering, and chemistry. The interdepartmental environmental engineering program is an exciting new area of interaction for both teaching and research, bringing together faculty and students from five engineering fields.

For more information about the program, contact

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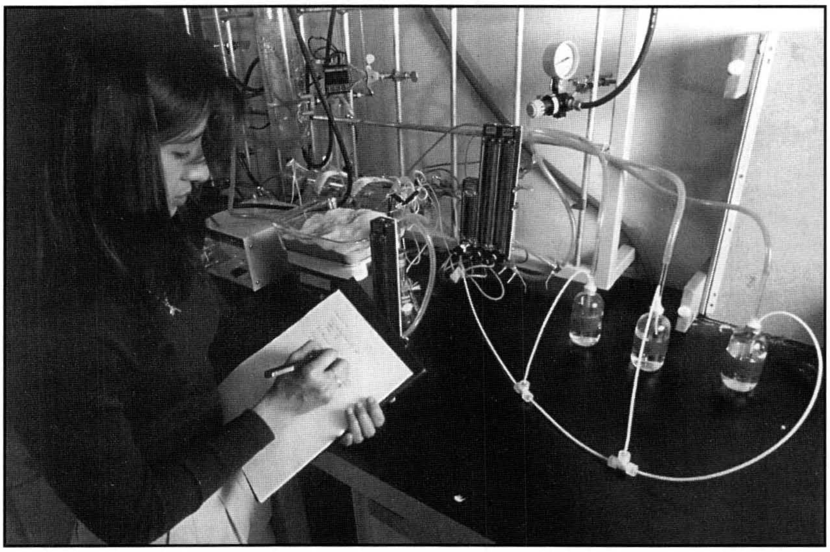
cal blades that never dull, to name a few. Considered a world expert in diamond fabrication, Dandy conducted research at Sandia National Laboratories in Livermore, California, to develop hair-like diamond slivers for a major commercial application—AT&T's transatlantic fiber optic telephone cable. According to Dandy, growing diamonds (using a process called chemical vapor deposition) is easy; the real challenge is understanding how they grow, how they interact with other materials, and how to make them behave in an orderly manner. The complexity of issues that are involved in the process makes any major scientific breakthrough a future event, but Dandy anticipates being part of that ultimate breakthrough.

. . . [Colorado State's] youth is the very factor that has allowed it to do what more established programs often cannot—change the boundaries, alter the rules, shift the paradigm.



Adeyma Arroyo (grad student) records data from an apparatus used to study biofiltration of off-gases from coating operations.

Because his investigations on polymers also fall outside the realm of basic research, Larry Belfiore considers them high risk. His overall objective is to understand how a material's components interact in a mixture and then to use that information to make chemically compatible systems. Since his work is not directly market-driven, Belfiore concentrates on developing methods that will enhance the thermal and mechanical properties of materials. On another project, Belfiore and Allen Rakow are combining stress-strain testing, infrared spectroscopy, and electron microscopy to explore the use of agar, an edible marine polysaccharide, for packaging and potential biomimicry applications.

During the fourteen years she has been on the chemical engineering faculty, Carol McConica has been a key figure in the department's advanced materials thrust. The bulk of her more than $2 million in contracts and grants for integrated circuit process research has been spent on graduate education and a special master's program, which she developed. The program, through twelve months of course work and some eighteen months of experimental, hands-on experience, offers students a broad understanding of microelectronics while identifying the fundamental principles behind manufacturing problems that are supplied from industry. Given a grounding in those principles, the students then develop new processes.

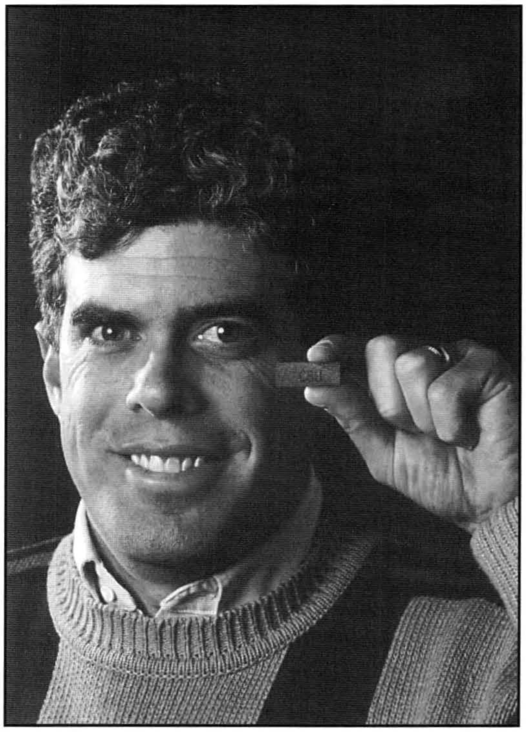
Before joining the faculty, McConica helped Hewlett-Packard design the chemical processes necessary to build more powerful computer chips. The major emphasis of a current grant from the National Science Foundation is to develop more environmentally benign processes for that manufacturing. To McConica, this university-industry cooperation not only fits the land-grant mission of Colorado State ("We are an educational institution."), but it also prepares chemical engineering graduates to fit into an ever-changing technological landscape.

APPLIED RESEARCH

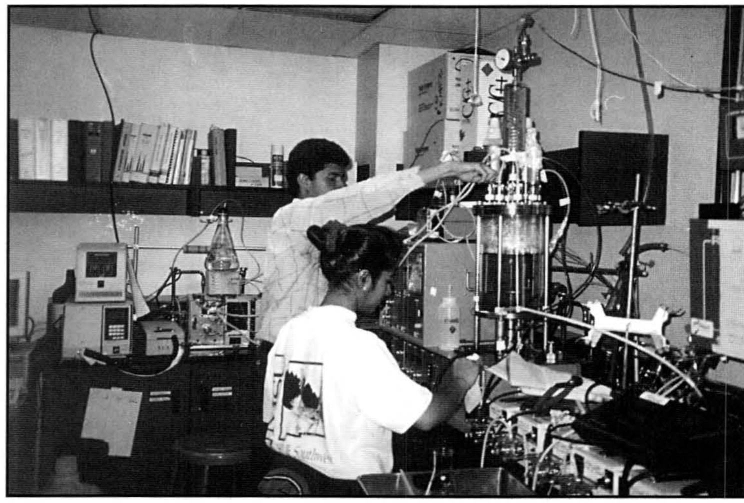
Much of chemical engineering research at Colorado State is applied. In fact, that was part of the program's original mission. This focus spotlights the final characteristic of the program; that is, its emphasis on real-life systems and cooperation with the private sector. Whether developing computer chips, using biotechnology to extract gold in hard-to-mine ores, or developing innovative medical cures, the push is out into the real world.

This push is clearly exemplified by the work of James Linden, who holds a joint appointment with the Department of Microbiology. Linden conducts research into the use of plant cell cultures for production of valuable medicinal compounds such as artimisinin, a possible natural treatment for malaria. On another project, he is studying another plant cell culture process that produces taxol, an anti-cancer drug. Linden works with private chemical research companies on both of these projects, indicative of the growing private/public cooperation.

This cooperative approach is further seen in the work being conducted under the leadership of Brian Batt at the Colorado Bioprocessing Center, a state-supported entity that



"Diamond" Dave Dandy admires the fruits of his latest (thin film) research.



Victor Saucedo (grad student) and Sohana Karim (undergrad) prepare a computer-controlled bioreactor for a fermentation experiment.

is administered through the Department of Chemical and BioResource engineering. The Center houses a full spectrum of pilot-scale equipment for cell culture and product recovery. Its mission is to assist new biotechnology companies in proof-of-concept and process development studies. Researchers at the Center conduct basic and applied research to develop high-value products from genetically engineered microorganisms.

The Center is an integral part of the Research Experiences for Undergraduates Program in Bioprocess Engineering, a project sponsored by the National Science Foundation in which outstanding undergraduates from across the country are given an opportunity to participate in a ten-week research program during the summer months. It also works closely with the Colorado Institute for Research in Biotechnology (CIRB), a university-industry-federal laboratory network that offers seed grants to university researchers to initiate university/industry projects. In addition, CIRB provides support for graduate students and for students who intern in Colorado biotechnology companies.

Professor Karim, who has been at Colorado State University since the Spring of 1981, is regarded as one of the world leaders in the research area of process control application to biotechnology. He is one of the first researchers who has applied neural network technology to model and optimize bioprocesses. He is also involved in multivariate statistical analysis (Principal Component Analysis) for on-line process fault detection and diagnosis of chemical and biological systems. Dr. Karim has researched various microbial species: bacteria, yeast, fungi, mammalian, and plant cell cultures. He has been either an advisor or co-advisor to approximately one-third of the department's PhD graduates. In recognition of his contributions to research and graduate support, the College of Engineering awarded him the Abell Research Award in May of 1997.

EDUCATIONAL MODEL

"Interdisciplinary," "emerging," and "applied" are simply adjectival buzzwords if they do not represent a testable reality within the academic setting. The quality of research must impact the quality of education at both the undergraduate and graduate levels. At Colorado State, that impact exists—with a unique twist that only a smaller program can offer. The faculty like to think that chemical engineering at Colorado State delivers the best of what expensive private schools offer, small classes and high-quality students, plus the best of a research university—all within the context of a nurturing environment.

Numbers can be impressive: 8 faculty members advise 135 undergraduates and 35 graduate students. Because the faculty are aggressive in their research efforts, individually averaging \$200,000 a year in contracts and grants, students have numerous opportunities, starting at the undergraduate level, to work on research projects. During the last eight years, 60 BS graduates (25% of the total number) have been involved in research.

FACULTY PROFILES

Judson M. Harper, Professor
Vice President for Research and Information Technology
Ph.D., Iowa State University
Interests: Extrusion processing of foods; manufacturing of low-cost nutritious foods; structural and chemical changes of polymers during processing.

M. Nazmul Karim, Professor
Associate Department Chair
Ph.D., University of Manchester
Interests: On-line adaptive control of solid-state fermentations, use of neural networks, principal component analysis and genetic algorithms in bioprocess control and optimization; lignin biodegradation and recombinant E. coli *fermentation for ethanol production from xylose.*

Terry G. Lenz, Professor
Ph.D., Iowa State University
Interests: Computational and experimental studies in chemical and biochemical thermodynamics as well as in more applied areas such as solar cooling systems.

Carol M. McConica, Professor
Ph.D., Stanford
Interests: The use of ultrahigh vacuum as well as in situ Raman spectroscopy techniques to elucidate reaction mechanisms relevant to integrated chip processing; selective metal deposition processes for three-dimensional integration of integrated circuits.

Vincent G. Murphy, Professor
Ph.D., University of Massachusetts
Interests: Fundamental and applied studies in biochemical and food process engineering; bioremediation of contaminated soils.

Laurance A. Belfiore, Associate Professor
Ph.D., University of Wisconsin
Interests: Phase behavior of polymer blends; polymeric transition-metal complexes that exhibit synergistic macroscopic physical properties; applications of solid-state NMR spectroscopy.

David S. Dandy, Associate Professor
Ph.D., California Institute of Technology
Interests: Vapor deposition of diamond, silicon nitride, and cubic boron nitride; three-dimensional laminar flows; parallel numerical algorithm development; application of physical models to process control design.

James C. Linden, Associate Professor, Joint Appointment
Ph.D., Iowa State University
Interests: Biomass refining to provide starting material for ethanol fermentation; cultivation of fungi and bacteria for enzyme production; plant cell cultures for the production of useful secondary metabolites.

Allen L. Rakow, Associate Professor, Research Appointment
Sc.D., Washington University, St. Louis
Interests: Bioseparations, biorheology, and food engineering

Kenneth F. Reardon, Associate Professor
Ph.D., California Institute of Technology
Interests: Microbial degradation of hazardous organic compounds; the effects of cultivation conditions on genetically modified bacteria.

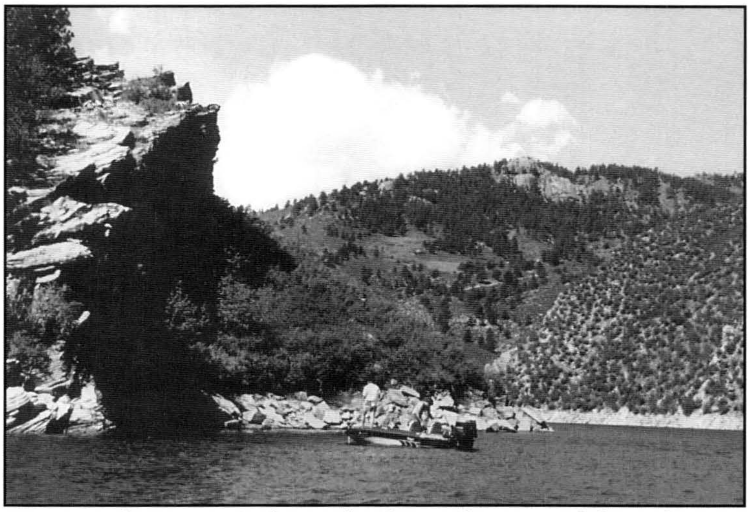
Ranil Wickramasinghe, Assistant Professor
Ph.D., University of Minnesota
Interests: Application of the principles of mass transfer and rheology to the development of new separation processes for biochemical/biomedical systems.

Brian C. Batt, Research Scientist
Director of the Colorado Bioprocessing Center
Ph.D., University of Colorado
Interests: Development of bioprocessing systems involving the use of recombinant microorganisms and mammalian cell cultures.

UNDERGRADUATE PROGRAM

Such hands-on experience is possible because of the quality of the students. At the undergraduate level, for example, students have received two AIChE Outstanding Senior awards and six National Science Foundation fellowships. Over 30% of the undergraduates are high school valedictorians, and the average GPA for the 1996 incoming class was 3.8. Alumni have gone on to graduate programs at MIT, UC Berkeley, Stanford, Purdue, Wisconsin, and Cornell. The program's AIChE Student Chapter has received an Outstanding Chapter Award from the national organization in 12 of the past 14 years.

The faculty have worked hard to develop a cohesive curriculum that begins in the freshman year and includes at least one core chemical engineering course each semester. The design experience is fully integrated, beginning with a project-oriented course in the freshman year. Such attention to the curriculum simply underlines an overall commitment to students as persons and professionals. It permeates the whole program at both the undergraduate and graduate levels.



Horsetooth Reservoir, located a few miles west of the Colorado State campus, provides a wealth of recreational opportunities.

GRADUATE PROGRAM

The graduate students, who represent a number of nations but are primarily American, appear to agree with the undergraduate consensus of an overall departmental commitment. At a recent round-table discussion attended by PhD-track students, the shared stories emphasized the same program characteristics noted by the undergraduates—small numbers, personal contact, teaching ability of faculty, research opportunities, interdisciplinary approach, and real-life challenges.

One student specializing in bioremediation and molecular biology commented, "The faculty seems determined to make you step from graduate school into real life—and do it successfully." Other students concurred, pointing out the numerous ways in which they are not only encouraged, but are also forced, to stand on their own (research) feet. This includes proposal writing, attending conferences, and presenting papers, as well as weekly seminars in which they give research updates to the faculty and regular interdisciplinary reviews of projects. As one student spontaneously shared, "It keeps you alert about what you are doing!"

Asked to support their contention of an interdisciplinary approach, seven students listed the following areas that they themselves were incorporating into their chemical engineering programs: microbiology, biochemistry, physics, chemistry, plant science, and toxicology.

Colorado State alumni are now filling faculty and postdoctoral research positions in chemical engineering throughout the U.S. and abroad, including such institutions as Stevens Institute of Technology, the University of Wyoming, Michigan State University, and Cal Tech. Graduates also are easily found in companies such as Intel, Hewlett-Packard, Sandoz, International Paper, Genentech, Hoffman-LaRoche, J.D. Searle, and Exxon.

PARADIGM OF REALITY

No one denies how young the chemical engineering program at Colorado State is. In fact, its youth is the very factor that has allowed it to do what more established programs often cannot—change the boundaries, alter the rules, shift the paradigm.

As Harper notes, "We created a program out of dust into something substantial that is recognized today both nationally and internationally. We crossed disciplines to create a new model, one more reflective of reality . . . maybe you could call it a paradigm of reality."

McConica expands, "Not only were we created out of dust, but also outside the boundaries. With the advent of emerging technologies and the collaboration of industry and academia, we were already out there, waiting. You could say that the paradigm engulfed us."

Joel A. Barker, quoted at the opening of this article, contends in his book *Paradigms: The Business of Discovering the Future* (Harper, 1992) that with any paradigm shift, a new game begins with a new set of rules. The way to measure your ability to be successful, he maintains, is by your ability to solve problems.

By any measure, chemical engineering at Colorado State is not only in the game, but it also continues to make new rules. ❐

TOWARD TECHNICAL UNDERSTANDING*

Part 1. Brain Structure and Function

J.M. HAILE
Clemson University • Clemson, SC 29634-0909

One must acquire many different ways to understand.

Minsky[1]

"You know, Prof, my grades on the quizzes don't really reflect my understanding of the material." . . . "When you talk to Clarence about the material, it's evident he understands a lot about it, so why can't he do the homework?" . . . "I know the class understands this concept, we've been through it many times, so why can't they apply it when they need it? Why can't students access what they know?"

These kinds of comments, from students and colleagues, are familiar to any of us who have spent time in education. They signal frustration in various guises, and often a voiced frustration is but a symptom of deeper dissatisfaction and perplexity. In pondering such comments, I've concluded that many of them spring from a common basis: confusion and misconception about what we mean by an understanding of technical material. Such confusion should not be dismissed lightly, for it can hamper our attempts to help others learn; and so it seems worthwhile to try to clarify what it means to understand. But to unravel such confusion is no small task. The word *understanding* is itself obscured by a vagueness that approaches the enigmatic. For once, Webster fails us, merely offering as synonyms "perception," "comprehension," "appreciation," and "mental grasp." These move us no closer to the root of the matter.

The ambiguity arises because there is not one understanding, or even just a few. There are, in fact, many—many kinds of understanding and many ways to reach them. It is one thing to recognize you have a problem, another thing to articulate the problem, yet another to identify what is needed to solve it, still another to carry out the solution, and even another to appreciate what the solution means. Given those many goals and the many paths to each, it is no wonder we have difficulty articulating general rules—or even rules of thumb—that will consistently lead us to an understanding. But what is difficult in general may be manageable in particular. Perhaps by restricting our attention to particular realms of knowledge, such as those embodied by engineering and the physical sciences, we can clarify what it means to understand—at least for those restricted realms. That is the thesis for the papers in this series.

Having recognized that there are many ways to understand technical material, we then ask how those ways can be organized. One appealing organization is a hierarchy because hierarchies identify levels, and this usage coincides with commonly used, but ill-defined, ideas concerning levels of understanding. In addition, a hierarchy provides a systematic progression that can serve as the basis for helping people learn. For example, a hierarchy of understanding can

J.M. Haile, *a professor of chemical engineering at Clemson University, is the author of* Molecular Simulation, *Published by John Wiley & Sons in 1992.*

* *EDITOR'S NOTE: This is the first of three installments. The second installment, "Elementary Levels," will appear in our Fall 1997 issue, and the third installment, "Advanced Levels," will be published in our Winter 1998 issue.*

help us identify the current stage in a student's study of a topic, it can help us show the student what must be done to reach the next stage, and it can help us determine when a transition between stages has been successful. This series of papers is primarily concerned with presenting and discussing a hierarchy for understanding technical material.

But the job of fostering understanding can also be clarified if we know something about how people learn—that is, how the human mind assimilates new information and integrates it with old information. Over the past ten years we have seen significant progress in neuroscience, especially in neurobiology, psychology, and artificial intelligence. As educators, we should take advantage of that progress, recognizing that the next ten years will bring still more progress. By clarifying how the brain functions, we can obtain clues as to how to improve learning. We therefore will use the rest of this paper to review, in an elementary way, relevant aspects of brain structure and function. These discussions will support the hierarchy of understanding presented in the second and third papers in this series.

Since learning creates new structures in the brain by modifying existing structures, learning can only begin from things the student already knows. This has implications as to whether a topic should be taught top-down (deductively) or bottom-up (inductively).

BRAIN STRUCTURE AND FUNCTION

The human brain is not a single entity, but rather a composite of several brains. The top of the spinal cord forms the *medulla,* which supervises basic motor functions, including heart beat, respiration, and digestion. Behind the medulla lies the *cerebellum,* which coordinates body position, movement, and balance. Above the cerebellum we find the *limbic system,* which includes the pituitary gland, the hypothalamus, the hippocampus, and other structures. The pituitary makes hormones that control the function of most other glands in the body; its action is controlled by the hypothalamus. More generally, the hypothalamus regulates all life-support functions, including heart rate, body temperature, chemical balances in the body, hunger, thirst, and emotional responses to threats for survival. The hippocampus apparently participates in the formation of long-term memories; this will be discussed in the third of this series of papers. Atop the limbic systems sits the *cerebrum,* which is devoted to all higher mental activities, including language, conscious awareness, and abstract thought.

Of all these structures, the cerebrum is by far the largest, yet most high-level mental activities are confined to its surface—the *cerebral cortex*—a layer only 2mm thick and convoluted into folds to increase its surface area within a confined volume. The cortex contains a significant portion of the brain's gray matter—the little gray cells so favored by Hercule Poirot. The volume enclosed by the cerebral cortex is filled largely with white matter: the strands and filaments that connect brain cells. That is, much of the human brain is mere wiring.

The following sections of this paper present an elementary overview of the functioning of the neuron and of the huge number of neurons that form the cerebral cortex. These functions allow us to draw certain conclusions about the nature of learning. For a more detailed introduction to brain structure and function, see references 2-6; the illustrations by Macaulay[6] are particularly instructive.

THE NEURON

The basic unit of mental activity is a single nerve cell—the *neuron.* Functionally, a neuron in the cortex collects signals from other neurons, integrates them into a single signal, and then either suppresses the signal or forwards it to other neurons. Structurally, a neuron is composed of three principal parts: a *cell body,* which contains the nucleus and performs the life-support functions common to any biological cell; a tree-like array of branches called *dendrites* that carry signals from other neurons to the cell body; and an *axon,* a single strand that carries the signal from the cell body to other neurons.

More generally, neurons are the primary functional elements of the nervous system; for example, a nerve is a bundle of axons. Axons vary in length from millimeters in the cortex to about a meter in the case of the axons that connect the toes to the spinal cord. Variations in geometry provide a means for classifying neurons by structure;[5] those in the cerebral cortex are called *pyramidal neurons* because of the distinctive shape of the cell body.

The function of an individual neuron is illustrated schematically in Figure 1 (next page). From contacts with other neurons, a dendrite carries a signal, as a voltage difference, to the cell body. At the cell body, signals from all dendrites are combined into a single voltage that propagates to the head of the axon. If this output voltage exceeds a certain threshold, the neuron is said to fire, and a pulse voltage propagates down the axon. The end of the axon divides into branches, providing hundreds of terminals to other neurons.

Each axonal terminal is separated from another neuron by a microscopic gap called a *synapse.* When a voltage pulse reaches an axonal terminal, it causes *vesicles* in the terminal region to fuse onto the wall (the presynaptic membrane) of the neural cell. This, in turn, causes the vesicles to open, releasing a few thousand molecules of a *neurotransmitter* into the synapse. These molecules diffuse across the synapse to a dendrite or cell body of another neuron. If the neurotransmitter can find an appropriate *receptor*—a protein—embedded in the postsynaptic membrane, then the signal is successfully passed from one neuron to the other.

The voltage difference propagating from dendrite through cell body and down an axon is not carried electrically, but chemically; that is, it is not carried by free electrons but by sodium ions. Therefore, the speed of signal propagation is of the order of milliseconds, which is slow relative to the speed of electrical conduction in metal wires.

Further, an axon does not conduct the signal by a current propagating axially, as in a wire. Instead, a local voltage difference in one part of an axon relative to a neighboring part induces opening and closing of molecular gates on channels within the cell membrane; these channels allow flow of ions between the interior and exterior of the neuron, changing the voltage in one region of the neuron relative to an adjacent region. Thus, sequential radial flow of ions through cell walls produces the effect of a voltage propagating axially.

The activity induced by the voltage reaching a synapse amounts to a key-lock-gate scenario. If a neurotransmitter (the key) can find its receptor (the lock), then a molecular gate opens, allowing ions to enter the dendrite, creating a local voltage difference.

A few dozen neurotransmitters have been identified, and more probably remain to be discovered.[5] The common ones include glutamate, dopamine, acetylcholine, and γ-aminobutyric acid (GABA). Certain drugs, including the opiates, nicotine, and the antipsychotics, are known to either mimic or block the actions of certain neurotransmitters.[5,6] This is possible because neurotransmitters activate receptors by matching physical structures, so any molecular fragment that matches the receptor structure might activate that receptor; not only will a key open a lock, but so too will a skeleton key.

Synaptic connections are of two general types. *Excitatory* synapses tend to promote firing of the neuron by activating receptors that allow sodium ions to enter the neuron through the postsynaptic membrane. These connections typically occur on dendritic branches, with the common excitatory neurotransmitter being glutamate. In contrast, *inhibitory* synapses tend to suppress firing by activating receptors that allow chlorine ions to enter through the postsynaptic membrane. These typically occur directly on the cell body, with the common inhibitory neurotransmitter being GABA.

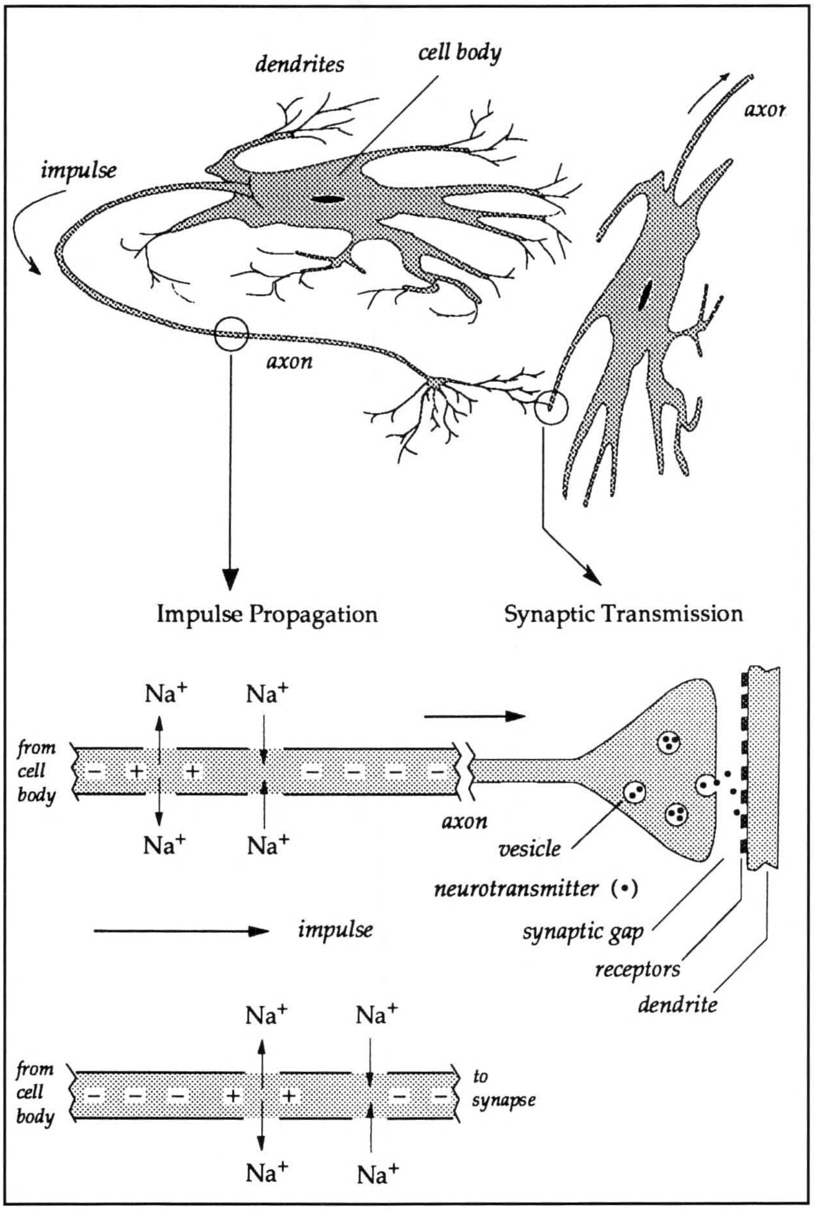


Figure 1. *(top) Principal parts of a single neuron, including synaptic connection to the dendrite of another neuron. (lower left) Exploded view of an axonal segment; radial flow of sodium ions between axon and extracellular fluid propagates a nerve impulse from the cell body to the synapse. (lower right) Exploded view of an axonal terminal and synapse. At the terminal, a nerve impulse stimulates vesicles to fuse with the presynaptic membrane, releasing neurotransmitters into the synaptic gap. The bottom views are adaptations of drawings by Macaulay.*[6]

THE NEURAL NETWORK

Although the functioning of a single neuron is a fascinating electrochemical process, the really astonishing functions occur not at the molecular or cellular levels, but in the collective behavior of large numbers of connected neurons. The number of neurons in the human brain is estimated at between 20 and 100 billion. Further, the average pyramidal neuron makes roughly 1000 connections to other neurons; so the total number of connections may well be about 10^{14}.[3,6] Most connections are among neighboring neurons, but many axons connect neurons that lie in very different regions of the cortex. In principle, any neuron can influence the firing of any other neuron.

By itself, the firing of a single neuron is essentially meaningless. Meaning only arises when a pattern is established by the simultaneous or sequential firings of many neurons. We do not know how firing patterns encode meanings (that is part of the puzzle), but the following metaphor may capture the essence. Imagine an array of lights forming a scoreboard. The array itself has no meaning; if none of the lights are activated, we have no meaning, and if all of the lights are activated, we still have no meaning. Informative meaning occurs only when some lights are activated while others are not. Moreover, the meaning is in the pattern, not in any particular lights; that is, meaning is encoded in the spatial and temporal relations among the lights that are activated and those that are not. For example, meaning is preserved even when the pattern scrolls across the array. Now reread the previous four sentences, everywhere replacing "light" with "neuron" and "array" with "neural net." This metaphor suggests one reason for having both excitatory and inhibitory synapses for in this way, not only can any one neuron participate in any pattern, but in addition, when the same pattern is replayed at different times, a neuron can participate by sometimes being activated and other times being quiescent.

Neural activity in the cerebral cortex distinguishes brain from mind; that is, brain is the structure and mind is the function. As Minsky has written,[1] "Minds are what brains do." But what is it that minds do? In particular, what does the cerebral cortex do?

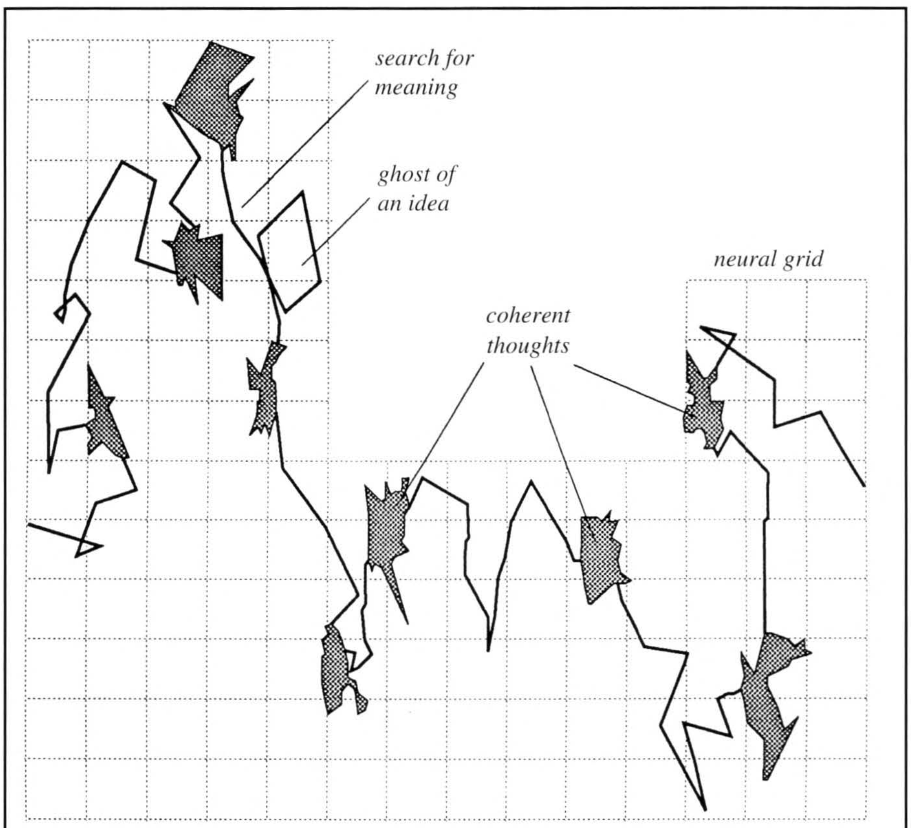


Figure 2. *Schematic representation of sequences of neural firings in the cerebral cortex. Grid represents an array of neurons; path represents the firing sequence. Shaded areas represent repeated firings of patterns of neurons that have meaning, such as recognition of a sight or formation of a coherent thought. Path segments between shaded areas represent the search for meaning. In studies of dynamic systems, such as in process control and statistical mechanics, the grid is interpreted as a phase space and the path is a trajectory of the system. Then the shaded regions are local attractors that order the trajectory into patterns. Based on a figure in Calvin[7] and a phase-space plot in Freeman[8] from EEG data taken from a rat's olfactory bulb.*

There is always at least a baseline of neural activity in the cortex. It can be seen crudely on an electroencephalogram (EEG). But that minimal activity can be driven to more active modes by stimulation, either from the external world through the senses or from the internal world through other parts of the brain. The response appears to be a search for meaning—an attempt to find a pattern that interprets or makes sense of the stimulus. In other words, the baseline firing of a huge number of interconnected neurons amounts to a chaotic dynamics—not random, but apparently random with some underlying order.[7-9] Such dynamics are, by definition, sensitive to small disturbances, so even a small stimulation of the cortex can produce a qualitative change in the character of the firing pattern. Some changes in the dynamics take the form of convergence to a local *attractor*—a firing pattern that is recreated and sustained whenever the firing trajectory passes sufficiently "close" to neurons that activate the pattern. Such attractors constitute meaning to the organism. This is illustrated in Figure 2.

We may become conscious of attractors—that is, conscious of thought patterns—when we encounter ambiguity. An ambiguous stimulus causes neural firing patterns to bifurcate into conflicts or competition between two or more attractors; the result is mental confusion. In such situations, the mind contrives more than one pattern that is consistent with the data, and the conflict can only be resolved with more data.

For example, consider the object shown in Figure 3, which presents a conflict between foreground and background. If you focus to bring the shading to the foreground of the figure, you see the letter E. But if you shift your focus slightly, the shading can be pushed to the background, and you see the characters L and 3.

Your recognition of the E is an attractor produced by one assembly of neurons, while recognition of the L and the 3 is a second attractor produced by another assembly of neurons. Both attractors are consistent with the data and additional visual cues would be needed for one attractor to dominate.

The interpretation of thought as a dynamic process driven to local attractors, as shown schematically in Figure 2, is appealing, but it is likely an oversimplification for at least a couple of reasons. First, the coding of meaningful patterns is probably not just in the relative positions of firing neurons; it may also involve firing rates and sequences. That is, meaning may involve both positional codes and temporal codes.[10] Second, the action of the cortex appears to involve distributed processes, in which multiple subprocesses are performed simultaneously.[1,10] For example, visual recognition of an object involves perception of contours, depth, and color—three activities that are performed simultaneously but in separate regions of the cortex.

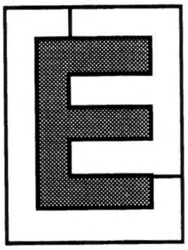


Figure 3. Mental confusion can arise when the brain devises two conflicting patterns from the same information. This figure can be ambiguous because it does not provide enough cues to allow one to distinguish foreground from background. Focusing to bring the shaded area into the foreground reveals one character, but focusing to push the shaded area into the background reveals two different characters.

More complex functions appear to progress through hierarchies of distributed processes, which may explain why we like to use hierarchies for organizing societies, institutions, and problem-solving tasks.[1] Distributed processes make efficient use of neural networks because the same assemblies of neurons can be used for the same kinds of tasks in different situations.

Although we do not yet know the details for *how* meanings are assigned to patterns, we at least know *what* is being done: minds are what brains do, and the search for meaning is what the cortex does.

MODIFICATION OF BRAIN STRUCTURE: LEARNING

The association of meanings with particular stimuli constitutes one aspect of learning. For example, if the stimulus is a right triangle, then part of the associated meaning would be the Pythagorean theorem. But meaning is connected to a stimulus through neural firing patterns created in the cerebral cortex, so to learn new meanings, we must create new firing patterns. For these new patterns to be accessible over long times, the mind must bias connections among neurons so that the new pattern is recreated whenever an appropriate stimulus is encountered. That is, to make long-lasting changes in function (the mind), we must make changes in structure (the brain).

We do not yet know much about how learning modifies the brain, though many observations are suggestive and the more obvious possibilities are listed below. But we do know one mechanism that is *not* used—the brain does not modify itself by growing new neurons. The number of neurons is constant through adolescence, and then neurons begin to degenerate and die over the remaining lifetime. Estimates usually put the average total loss at 10% of the original number.[3] During youth, the brain grows in complexity by forming and pruning dendritic trees and axonal branches, that is, by increasing and refining connections among existing neurons.[3,6]

Here are some ways by which learning may change brain structure and function:[5]

- Changes in the size and shape of axon terminals coupled with changes in the number of presynaptic vesicles (which hold the neurotransmitter) to increase or decrease the amounts of neurotransmitter released
- Changes in the size and shape of postsynaptic receptors and channels to change the level of activation voltages created when a receptor opens
- Increases and decreases in the number of receptors at certain synapses
- Changes in the number and location of synapses
- Sprouting of new axonal terminals
- Remolding of terminal bulbs on dendrites.

IMPLICATIONS FOR EDUCATION

The brain, then, is a self-modifying neural network. The processes carried out by that network constitute the mind, and the function of a part of that mind—the cerebral cortex—is to ascribe meanings or interpretations to both external and internal stimuli. These observations lead to certain implications about the nature of education, including

- ► Learning is a natural activity of the human mind.
- ► Learning is not storage and retrieval of information; the brain does not store information.[8,11] It only develops a propensity to reproduce neural firing patterns that have been found beneficial; that is, what we call memory is actually a *re-creation* of information. To be able to use what they know, students must learn cues that re-create useful patterns.
- ► Since learning creates new structures in the brain by modifying existing structures, learning can only begin from things the student already knows. This has implications as to whether a topic should be taught top-down (deductively) or bottom-up (inductively).
- ► The brain apparently modifies neural connections as part of its response in those neurons that are activated to form a pattern. Thus, learning new things amounts to a perturbation of things already known; but if the perturbation is too large, then no related neural firing pattern can be created and no learning takes place. Thus, students must be led to new knowledge in small chunks of information that allow the brain to modify existing neural networks. Repetition is then needed to strengthen new neural connections. The importance of repetition is addressed in the third of this series of papers.
- ► Experts in a topic have highly interconnected constellations of neurons that can be activated by stimulating any of many different nodes.[1] These elaborate networks allow experts to quickly learn new things because their vast networks offer numerous nodes that can be easily modified to assimilate new information. In contrast, students generally have few networks related to technical material; the networks they do have tend to be meager and largely fragmented. The assimilation of new information into those networks is often a laborious task because a small addition to a small structure can require a large change in the structure.

  We often witness instances at which disjointed neural assemblies finally become fused into a coherent network. It happens to those students who struggle with a topic for several weeks, laboriously piecing together several disjoined networks. Then, about midterm or shortly thereafter, one more piece of new information perturbs the entire system sufficiently that those several disjointed networks become united—revelation! The student understands.
- ► Recognition is easier than recall.[1,7] *Recognition* forms a meaningful pattern in response to an external stimulus, while *recall* forms a meaningful pattern in response to an internal stimulus. To test recognition, we might pose a question such as "What quantity is defined by $Re = u\rho d/\mu$?" But to test recall, we would ask, "What equation defines the Reynolds number?" Recall is more difficult because we must not only create the pattern, but we must also generate the stimulus that produces the pattern. Because of this difference in difficulty, students generally prefer certain kinds of quizzes over others.
- ► Learning is easier than unlearning. Unlearning refers to correcting misunderstandings from earlier learning. During learning, we modify a neural network to create a new net; but during unlearning, we not only create a new network, but we must also suppress formation of the old erroneous pattern.
- ► To learn, students must actively participate in their own education. Only the individual can modify its own synapses, dendritic trees, and axonal terminals. No instructor can do this for the student.
- ► Quickness of mind (a commonly used indicator of intelligence) decouples from the ability to think.[12] A quick mind is one that moves immediately and decisively to a local attractor. But the Latin root for *intelligent* is *inter + legere,* which means *to select.* And to select implies a consideration of alternatives; that is, intelligent thinking involves the identification of alternative attractors and choosing from among them. This cannot necessarily be done quickly.

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A NEW APPROACH TO TEACHING DIMENSIONAL ANALYSIS

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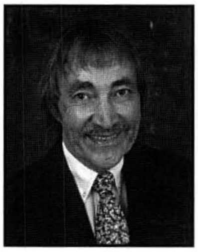
Rayleigh,[1] in the opening lines of a short note on the subject of this article, wrote "I have long been impressed by the scanty attention paid by the original workers in physics to the great principle of similitude. It happens not infrequently that results in the form of 'laws' are put forward as novelties on the basis of elaborate experiments, which might have been predicated *a priori* after a few minutes consideration." The full power of dimensional analysis (which Rayleigh referred to as "similitude") has, in the intervening eighty years continued to be underestimated and underutilized by engineers as well as by physicists.

Dimensional analysis is most powerful when it is applied to a complete mathematical model in algebraic (differential and/or integral) form, but it is remarkably productive even when a complete model is unknown or unwieldy and the analysis must be applied to a simple list of the relevant variables. The utility of dimensional analysis when applied to either a model or a list of variables may often be greatly enhanced by the collateral use of speculative and asymptotic analyses. It is this combined use that first suggested to the author the new educational approach described in this paper in which dimensional analysis itself is interpreted as a speculative process.

Undergraduate students in chemical engineering are usually first exposed to dimensional analysis in a course in fluid mechanics, transport phenomena, or unit operations. In that first exposure, the application of dimensional analysis is ordinarily and appropriately limited to a list of variables. Expression of relationships and correlations in terms of dimensionless groups is invariably implied in subsequent courses. The application of dimensional analysis to a mathematical model is usually illustrated in a higher-level undergraduate course, but too superficially to impart a working knowledge. The subject of dimensional analysis may or may not be reintroduced and reinforced in the graduate program. In this article, attention will be confined to the application of dimensional analysis to a list of variables. A companion



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article using the speculative approach in connection with mathematical models is in preparation.

Dimensional analysis of a list of variables that define a physical, chemical, or biological process is invaluable in guiding the correlation of experimental data or numerically computed values, but its contribution to understanding may be even more important for students. The development of skill and confidence in applying this methodology and in interpreting the results should be recognized as an essential element of undergraduate education in chemical engineering. Unfortunately, the exposure of most undergraduates to dimensional analysis in the previously mentioned context is brief, incomplete, and unsatisfying. The students ordinarily learn the mechanics of the algebraic method of dimensional analysis and are usually convinced that they should always express experimental results, either graphically or algebraically, in terms of dimensionless groups. They are, however, invariably put off by the mysterious and seemingly arbitrary choice of the appropriate dimensional variables. Furthermore, they generally gain only a hazy idea of the significance, scope, and possible non-uniqueness of the results. Since these uncertainties and misunderstandings are not excised in subsequent courses, they graduate with insufficient confidence in dimensional analysis, and in particular in the choice of variables, to apply it to some entirely new problem that they encounter in practice. As a consequence, they will probably not use dimensional analysis in their entire career, at least on their own initiative.

The commonly used textbooks on heat transfer and mass transfer, as well as on the subjects mentioned above, are almost all adequate in terms of describing the mechanics of dimensional analysis, but as a rule are deficient in their discussion of alternative groupings, limiting cases, the significance of the groupings, and most of all, the topic of greatest concern to the students—the selection of the proper set of variables. On the other hand, the monographs and books on dimensional analysis, similitude, and related topics are too lengthy and cover too wide a range of subject matter to be wedged into an undergraduate course such as fluid mechanics. In any event, these specialized books generally sidestep, by starting with a mathematical model, the problem of selection of an appropriate set of variables. If such a model is known, dimensional analysis is more effectively applied thereon instead of using the model merely to compile a list of variables. The inclusion or omission of terms from a model is analogous to the inclusion or omission of variables in a list. The material presented in this paper is intended as a compromise in the form of a brief supplement to the coverage in the current elementary textbooks on fluid mechanics, etc.

The utility of dimensional analysis when applied to either a model or a list of variables may often be greatly enhanced by the collateral use of speculative and asymptotic analyses. It is this combined use that first suggested to the author the new educational approach described in this paper in which dimensional analysis itself is interpreted as a speculative process.

The description herein of the process of dimensional analysis as applied to a list of variables differs only marginally from the standard treatment, but that slight difference has been found to have a great, positive impact on the comprehension and understanding of this process by students. The novelty of the exposition is in the presentation and interpretation of dimensional analysis as a speculative process. This concept has three distinct but closely related aspects. First, the mere designation of the process as speculative greatly relieves student's frustration at the lack of guidance by their teacher and their textbook in the selection of variables. They suspect, quite justifiably, that this omission is not accidental, but rather that it reflects a lack of knowledge in this respect by both the teacher and the author(s) of the textbook. The term speculation implies that the choice is tentative and must be tested with experimental data. This is an acceptable state of affairs for the student. The choice by their teacher or the author(s) is now recognized as being based on experience with the result of the analysis, not omniscience. They now have, at least in principle, a criterion for evaluation of any particular choice of variables.

The second aspect of speculation as applied to dimensional analysis consists of the methodical reduction of the original, presumably complete, set of variables one at a time, then two at a time, etc., in the hope of determining useful asymptotic or limiting relationships. Of course, the range of validity, if any, of these reduced representations must also be tested experimentally or by comparison with the theoretical solutions that may be possible for the simplified cases. Most of the reduced expressions will not be found to have any physical validity, but some may prove to be useful and enlightening. As a generic example, elimination of the density of the fluid may result in a valid expression for the limiting case of purely viscous flow, while elimination of the viscosity may result in a valid expression for the other extreme of purely inertial flow. For flow through a circular sharp-edged orifice, both of these limiting expressions have physical validity as confirmed by experiments and theory, whereas for flow through a smooth round pipe the result for purely viscous flow has validity but not that for purely inertial flow, as evidenced by the ever-decreasing value of the friction factor for a smooth pipe as the Reynolds number increases.

A third aspect of speculation as applied to dimensional analysis is associated with the inverse process, namely the determination of the variable or variables that must be eliminated from a listing in order to obtain a known experimental or theoretical result. This procedure, which has seldom been employed, often provides unexpected insights. As an example, consider the identification of those variables that lead by dimensional analysis to the Reynolds analogy.

The above introductory and expository section is intended primarily for teachers, while the details that follow are intended primarily for students. For that reason, some limited repetition has been considered necessary.

SPECULATIVE DIMENSIONAL ANALYSIS

The following description and examples of dimensional analysis differ from previous ones in the literature by virtue of the treatment of this process as a speculative one. In particular, the choice of variables is considered to be tentative and subject to experimental confirmation or refutation.

General Principles

Dimensional analysis is based on the simple principle that all additive or equated terms of a complete relationship, whether known or unknown, between the variables must have the same net dimensions. As described herein, dimensional analysis starts with the preparation of a list of the individual dimensional variables (dependent, independent, and parametric) that are presumed to define the behavior of interest. As will be shown, the performance of dimensional analysis in this context is reasonably simple and straightforward; the principal difficulties and uncertainties arise from identification of the variables to be included in or excluded from the listing. If one or more important variables are inadvertently omitted, the reduced description achieved by dimensional analysis will be incomplete and inadequate as a guide for the correlation of a full range of experimental data or computed values. The familiar band of plotted values in many graphical correlations is more often a consequence of the omission of one or more variables than of inaccurate measurements. If, on the other hand, one or more irrelevant or unimportant variables are included in the listing, the consequently reduced description achieved by dimensional analysis will result in one or more unessential dimensionless groups. Such excessive dimensionless groups are generally less troublesome than missing ones because the redundancy will ordinarily be revealed by the process of correlation. Excessive groups may, however, suggest unnecessary experimental work or computations, or result in misleading correlations. For example, real experimental scatter may inadvertently and incorrectly be correlated in all or in part with the variance of the excessive grouping.

The selection of a necessary and sufficient set of dimensional variables may require knowledge gained from experience, and hence is particularly difficult and uncertain when dealing with a new or unfamiliar aspect of behavior. A complete and certain mathematical model is an ideal source for identification of the variables, but in that event the analysis might more profitably be applied to the model itself rather than to a listing, even though the latter is exact. Of course, if significant terms are inadvertently omitted from the model or if unnecessary terms are included, a list of variables based on the model may also be incomplete or redundant.

In consideration of the inherent uncertainty in selecting the appropriate variables for dimensional analysis, it is recommended that this process always be interpreted as *speculative,* that is, as tentative and subject to correction on the basis of experimental data or other information. Speculation may also be used as a formal technique to identify the effect of eliminating a variable or of combining two or more. The latter aspect of speculation, which may be applied either to the original listing of dimensional variables or to the resulting set of dimensionless groups, is often of great utility in identifying possible limiting behavior or dimensionless groups of marginal significance.

Speculation in this context is to be distinguished from *conjecture,* in which a decision (here the inclusion or omission of a variable) is based on some mechanistic rationale. The failure of a speculation carries no burden of explanation or guilt while that of conjecture may.

The systematic speculative elimination of all but the most certain variables, one at a time, two at a time, etc., followed by regrouping, is recommended as a general practice. The additional effort as compared with the original dimensional analysis is minimal, but the possible return is very high. A general discussion of this process is presented by Churchill[2] and further illustrations are provided by Churchill[3,4] as well as by the examples of dimensional analysis that follow herein.

Determination of the Minimum Number of Required Independent Dimensionless Groups

The minimum number of independent dimensionless groups, i, that are required to describe the fundamental and parametric behavior was stated by Buckingham[5] to be

$$i = n - m \tag{1}$$

where n is the number of variables and m is the number of fundamental dimensions such as mass M, length L, time θ, and temperature T that are introduced by the variables. The inclusion of redundant dimensions such as force F and energy E that may be expressed in terms of mass, length, time, and temperature is at the expense of added complexity and is to be avoided. (Of course, mass could be replaced by force or temperature by energy as alternative fundamental dimensions.)

Van Driest[6] has since shown that in some rare cases, i is actually greater than n-m and that a more exact expression is

$$i = n - k \tag{2}$$

where k is the maximum number of the chosen variables that cannot be combined to form a dimensionless group.

On the other hand, Kline[7] has shown that an excessive number of dimensionless groups may be predicted by Eqs. (2) and (3) if necessary relationships between some of the variables are not recognized. As an example, an excessive number of dimensionless groups is predicted for the description of the performance of a double-pipe heat exchanger if the two mass rates of flow, w_1 and w_2, and the corresponding specific heat capacities, c_1 and c_2, are all four considered to be independent variables. The recognition that these variables enter the description of the process only in the form of the products w_1c_1 and w_2c_2 leads to the correct prediction.

Equations (1) and (2) are analogous to the Gibbs Phase Rule in one respect—they appear to be very simple, but actually are quite difficult to apply because of the uncertainty in determining the components of the equation, in this instance the number of variables n.

Determination of the minimum number of dimensionless groups is helpful if the groups are to be chosen by inspection, but is unessential if the algebraic procedure described below is used to determine the groups, since the number is then obvious from the final result.

Form of the Results of Dimensional Analysis

The particular minimal set of dimensionless groups is arbitrary in the sense that two or more of the groups may be multiplied together to any positive, negative, or fractional power as long as the number of independent groups is unchanged. For example, if the result of a dimensional analysis is

$$\phi\{X, Y, Z\} = 0 \tag{3}$$

where X, Y, and Z are independent dimensionless groups, an equally valid expression is

$$\phi\left\{XY^{\frac{1}{2}}, Z/Y^2, Z\right\} = 0 \tag{4}$$

Dimensional analysis itself does not provide any insight as to the best choice of equivalent dimensionless groupings, such as between those of Eqs. (3) and (4). But isolation of each of the variables that are presumed to be the most important in a separate group may be convenient in terms of interpretation and correlation. Another possible criterion in choosing between alternative groupings may be the relative invariance of a particular one as demonstrated by experimental data.

The functional relationship provided by Eq. (3) may equally well be expressed as

$$X = \phi\{Y, Z\} \tag{5}$$

where X is now implied to be the dependent grouping and Y and Z to be independent or parametric groupings.

Methods of Dimensional Analysis

Three primary methods of determining a minimal set of dimensionless variables will be described: 1) by inspection; 2) by combination of the residual variables, one at a time, with a set of chosen variables that cannot be combined to obtain a dimensionless group; and 3) by an algebraic procedure. It is more expeditious to illustrate these three methods for a number of specific examples than to describe them in general terms.

ILLUSTRATIVE EXAMPLES

Example 1

Fully Developed Flow of Water through a Smooth Round Pipe.

Choice of variables • The shear stress τ_w on the wall of the pipe may be postulated to be a function of the density ρ and the dynamic viscosity μ of the water, the inside diameter D of the pipe, and the space-mean u_m of the time-mean velocity. The limitation to fully developed flow is equivalent to a postulate of independence from distance x in the direction of flow, and the specification of a smooth pipe is equivalent to the postulate of independence from the roughness e of the wall. The choice of τ_w rather than the pressure drop per unit length $-dP/dx$ avoids the need to include the acceleration due to gravity g and the elevation z as variables. The choice of u_m rather than the volumetric rate of flow V, the mass rate of flow w, or the mass rate of flow per unit area G, is arbitrary, but has some important consequences as noted below. This speculatively postulated dependence may be expressed functionally as

$$\phi\{\tau_w, \rho, \mu, D, u_m\} = 0 \tag{6}$$

or

$$\tau_w = \phi\{\rho, \mu, D, u_m\} \tag{7}$$

Tabulation • It is convenient as a first step in all instances and with all procedures to prepare a tabular listing of the variables and their dimensions. In this example, that tabulation takes the following form:

	τ_w	ρ	μ	D	u_m
M	1	1	1	0	0
L	-1	-3	-1	1	1
θ	-2	0	-1	0	-1
T	0	0	0	0	0

Minimal Number of Groups • The number of postulated variables is 5. Since the temperature does not occur as a dimension for any of the variables, the number of fundamental dimensions is 3. From Eq. (1), the minimal number of dimensionless groups is 5 - 3 = 2. From inspection of the above tabulation, a dimensionless group cannot be formed from as many as three variables such as D, μ, and ρ. Hence, Eq. (2) also indicates that i = 5 - 3 = 2.

Method of Inspection • By inspection of the tabulation or by trial and error it is evident that only two independent dimensionless groups may be formed. One such set is

$$\phi\left\{\frac{\tau_w}{\rho u_m^2}, \frac{Du_m\rho}{\mu}\right\} = 0 \tag{8}$$

Method of Combination • The residual variables τ_w and μ may be combined in turn with the noncombining variables ρ, D, and u_m to obtain two groups such as those of Eq. (8).

Algebraic Method • The algebraic method makes formal use of the postulate that the functional relationship between the variables may in general be represented by a power series. In this example, such a power series may be expressed as

$$\tau_w = \sum_{i=1}^{N} A_i \rho^{a_i} \mu^{b_i} D^{c_i} u_m^{d_i} \tag{9}$$

where the coefficients A_i are dimensionless. Each additive term on the right-hand side of Eq. (9) must have the same net dimensions as τ_w. Hence, for the purposes of dimensional analysis, only the first term need be considered and the indices may be dropped. The resulting highly restricted expression is

$$\tau_w = A\rho^a \mu^b D^c u_m^d \tag{10}$$

Substituting the dimensions for the variables in Eq. (10) gives

$$\frac{M}{L\theta^2} = A\left(\frac{M}{L^3}\right)^a \left(\frac{M}{L\theta}\right)^b L^c \left(\frac{L}{\theta}\right)^d \tag{11}$$

Equating the sum of the exponents of M, L, and θ on the right-hand side of Eq. (11) with those of the left-hand side produces the following three simultaneous linear algebraic equations:

$$1 = a + b \tag{12}$$

$$-1 = -3a - b + c + d \tag{13}$$

$$-2 = -b - d \tag{14}$$

These three equations may be solved for a, c, and d in terms of b to obtain

$$a = 1 - b \tag{15}$$

$$c = -b \tag{16}$$

$$d = 2 - b \tag{17}$$

Substituting in Eq. (10) from Eqs. (15) through (17) gives

$$\tau_w = A\rho^{1-b}\mu^b D^{-b} u_m^{2-b} \tag{18}$$

Equation (18) may be regrouped as

$$\frac{\tau_w}{\rho u_m^2} = A\left(\frac{\mu}{Du_m\rho}\right)^b \tag{19}$$

Since the simplification of Eq. (9) to Eq. (10) was for the purpose of dimensional analysis only, Eq. (19) should *not* be interpreted as implying that $\tau_w/\rho u_m^2$ is necessarily proportional to some power of $\mu/Du_m\rho$. Rather, Eq. (19) should be inferred to be equivalent to Eq. (8) in every respect. The misinterpretation of Eq. (19) and its analogs for other processes as implying a power-dependence between the dimensionless groups is the most common and serious error in applying dimensional analysis.

Speculative Reductions • Eliminating ρ as a variable in Eqs. (6) and (7) on speculative grounds leads by each of the above three methods of dimensional analysis to

$$\phi\left\{\frac{\tau_w D}{\mu u_m}\right\} = 0 \tag{20}$$

or its equivalent

$$\frac{\tau_w D}{\mu u_m} = A \tag{21}$$

where A is a dimensionless number. Equation (21) with A=8 is actually the exact solution for the laminar regime $Du_m\rho/\mu < 1800$. A relationship that does not include ρ may alternatively be derived directly from Eq. (8) as follows: first, ρ is eliminated from one group, say $\tau_w/\rho u_m^2$, by multiplying it with $Du_m\rho/\mu$ to obtain

$$\phi\left\{\frac{\tau_w D}{\mu u_m}, \frac{Du_m\rho}{\mu}\right\} = 0 \tag{22}$$

The remaining group containing ρ is then simply dropped, resulting in Eq. (20). Had Eq. (8) been composed of three independent groups, each containing ρ, that variable would have to be eliminated from two of them before dropping the third one.

The relationships that are obtained by the speculative elimination of μ, D, and u_m, one at a time, do not appear, on the basis of experimental data, to have any range of physical validity. Furthermore, if w or G had been chosen as the independent variable rather than u_m, the limiting relationship for the laminar regime would not have been obtained by the elimination of ρ.

The postulated attainment of a state of fully developed flow as the length of the pipe increases indefinitely might be considered to be speculative. The inclusion of the distance x from the inlet as a variable would result in the appearance of another dimensionless group such as x/D in Eq. (8). The dependence, if any, on this group and hence on x would then need to be tested experimentally.

Alternative Forms • Equation (8) may also be expressed in an infinity of other forms such as Eq. (22) and

$$\phi\left\{\frac{\tau_w D^2\rho}{\mu^2}, \frac{Du_m\rho}{\mu}\right\} = 0 \tag{23}$$

If τ_w is considered to be the principal dependent variable, and u_m the principal independent variable, Eq. (23) is preferable to Eqs. (8) and (22) in that these two quantities do not then appear in the same grouping. On the other hand, if D is considered to be the principal independent variable, Eq. (8) is preferable to Eqs. (22) and (23). The variance of $\tau_w/\rho u_m^2$ is known on the basis of experimental data to be less than that of $\tau_w D/\mu u_m$ and $\tau_w D^2\rho/\mu^2$ in the turbulent regime, while that of $\tau_w D/\mu u_m$ is known from a theoretical solution to be zero in the laminar regime. Such considerations may be important in devising convenient graphical correlations.[8]

Alternative Notations • Equations (8), (22), and (23) are more commonly expressed as

$$\phi\left\{\frac{f}{2}, Re\right\} = 0 \tag{24}$$

$$\phi\left\{\frac{f\,Re}{2}, Re\right\} = 0 \tag{25}$$

$$\phi\left\{\frac{f\,Re^2}{2}, Re\right\} = 0 \tag{26}$$

where $f = 2\tau_w/\rho u_m^2$ is the *Fanning friction factor* and $Re = Du_m\rho/\mu$ is the *Reynolds number.* The more detailed form of Eqs. (8), (22), and (23) is, however, to be preferred for purposes of interpretation or correlation because of the explicit appearance of the individual, physically measurable variables.

Addition of a Variable • The above results may readily be extended to incorporate the roughness e of the pipe as a variable. If two variables have the same dimensions, they will always appear as a dimensionless group in the form of a ratio. In this case, e appears most simply as e/D. Thus, for a rough pipe, Eq. (8) becomes

$$\phi\left\{\frac{\tau_w}{\rho u_m^2}, \frac{Du_m\rho}{\mu}, \frac{e}{D}\right\}=0 \tag{27}$$

Surprisingly, as contrasted with Eq. (22), the speculative elimination of μ and hence of the group $Du_m\rho/\mu$ from Eq. (27) is found on experimental grounds to result in a valid asymptote for $(Du_m\rho/\mu)\to\infty$ and all finite values of e/D, namely

$$\phi\left\{\frac{\tau_w}{\rho u_m^2}, \frac{e}{D}\right\}=0 \tag{28}$$

Although it is not apparent from dimensional analysis, Eq. (21) is found experimentally to remain valid for the laminar regime for e/D<<1.

Example 2

Velocity Distribution in Fully Developed Flow of Water in a Smooth Round Tube

This example is closely related to the prior one, but their interrelationship is instructive. The description of the process of solution is abbreviated from that above as appropriate.

The time-mean local velocity u might be postulated to be a function of y, the radial distance from the wall, as well as of τ_w, ρ, μ, D, and u_m. In Example 1, however, τ_w was postulated to be a function of ρ, μ, D, and u_m. Hence, one of these variables is redundant. The most reasonable candidate for elimination on this basis is u_m since it may be determined by integrating u over the cross-section of the pipe. Hence, the following relationship will be used as an improved speculative starting point:

$$u=\phi\{\tau_w,\rho,\mu,D,y\} \tag{29}$$

The corresponding tabulation is

	u	τ_w	ρ	μ	D	y
M	0	1	1	1	0	0
L	1	-1	-3	-1	1	1
θ	-1	-2	0	-1	0	0

The number of variables is six, the number of fundamental dimensions is three, and the maximum number of variables, such as μ, ρ, and D, that cannot be combined to obtain a dimensionless group is three. Hence from both Eqs. (1) and (2), the minimal number of independent dimensionless groups is three.

Since y and D have the same dimensions, the ratio y/D will constitute one dimensionless group and y may be excluded from the continuing process of analysis. By inspection or by reference to Eq. (8), the remaining variables may be grouped and then combined with y/D to obtain

$$\phi\left\{u\left(\frac{\rho}{\tau_w}\right)^{\frac{1}{2}}, \frac{Du\rho}{\mu}, \frac{y}{D}\right\}=0 \tag{30}$$

On the other hand, the residual variables u and τ_w may be combined, one at a time, with ρ,μ, and D to obtain the first two groups of

$$\phi\left\{\frac{uD\rho}{\mu}, \frac{\tau_w D^2\rho}{\mu^2}, \frac{y}{D}\right\}=0 \tag{31}$$

Obviously, the first two groups in Eq. (31) may be combined with one another to obtain Eq. (30) or vice versa.

With y withheld from the algebraic process, the analog of Eq. (10) is

$$u = A\rho^a \mu^b D^c \tau_w^d \tag{32}$$

Substituting the dimensions in Eq. (32), equating the exponents of M, L, and θ and then solving the resulting set of simultaneous equations for a, b, and c in terms of d leads to

$$\frac{uD\rho}{\mu} = A\left(\frac{\tau_w D^2\rho}{\mu^2}\right)^d \tag{33}$$

which, with the inclusion of y/D is the equivalent of Eq. (31).

The following three rearrangements of Eqs. (30) and (31) prove to be convenient in considering speculative limiting cases:

$$u\left(\frac{\rho}{\tau_w}\right)^{\frac{1}{2}} = \phi\left\{\frac{y(\tau_w\rho)^{\frac{1}{2}}}{\mu}, \frac{D(\tau_w\rho)^{\frac{1}{2}}}{\mu}\right\} \tag{34}$$

$$u\left(\frac{\rho}{\tau_w}\right)^{\frac{1}{2}} = \phi\left\{\frac{y(\tau_w\rho)^{\frac{1}{2}}}{\mu}, \frac{y}{D}\right\} \tag{35}$$

$$\frac{u\mu}{\tau_w D} = \phi\left\{\frac{y(\tau_w\rho)^{\frac{1}{2}}}{\mu}, \frac{y}{D}\right\} \tag{36}$$

Speculative Reductions • The principal supplemental value of Example 2 with respect to Example 1 is in the demonstration of the great usefulness of speculative reductions. For example, eliminating D reduces Eq. (34) to

$$u\left(\frac{\rho}{\tau_w}\right)^{\frac{1}{2}} = \phi\left\{\frac{y(\tau_w\rho)^{\frac{1}{2}}}{\mu}\right\} \tag{37}$$

which is found experimentally to provide such a good approximation near the wall (y<0.2D) that it is called the "law of the wall." On the other hand, eliminating μ as a variable reduces Eq. (35) to

$$u\left(\frac{\rho}{\tau_w}\right)^{\frac{1}{2}} = \phi\left\{\frac{y}{D}\right\} \quad (38)$$

which is found experimentally to be a very good approximation for the balance of the cross-section ($0.2<y\leq1$). Eliminating ρ as a variable reduces Eq. (36) to

$$\frac{u\mu}{\tau_w D} = \phi\left\{\frac{y}{D}\right\} \quad (39)$$

which is known on theoretical grounds to be an exact result for the laminar regime. Eliminating ρ from Eq. (37) or D from Eq. (39), or both ρ and D from Eq. (34) results in

$$\frac{u\mu}{y\tau_w} = A \quad (40)$$

which with A=1 is found experimentally and computationally to be a valid asymptote for both the laminar and turbulent regimes very near the wall, such that

$$\frac{y(\tau_w\rho)^{\frac{1}{2}}}{\mu} << 5$$

Including e/D in Eq. (34) and then eliminating both D and μ leads to

$$u\left(\frac{\rho}{\tau_w}\right)^{\frac{1}{2}} = \phi\left\{\frac{y}{e}\right\} \quad (41)$$

which proves experimentally to be a valid expression for $e<<y<0.2D$. Since laminar flow is affected minimally by moderate roughness, Eq. (37) remains valid for that regime.

Example 3

Flow Through a Horizontal Circular, Sharp-Edged Orifice

It may be postulated speculatively that

$$\Delta P = \Phi\{u_o, \rho, \mu, D_o, D_p\} \quad (42)$$

where here ΔP is the pressure drop across the orifice, u_o is the mean, linear velocity of the fluid, D_o is the diameter of the orifice, and D_p is the diameter of the pipe in which the orifice is installed. The value of the pressure drop depends on the exact location of the pressure tap, but those locations need not be identified for the purposes of this example. The density and viscosity are implied to be constant. The corresponding tabulation is

	ΔP	u_o	ρ	μ	D_o	D_p
M	1	0	1	1	0	0
L	-1	1	-3	-1	1	1
θ	-2	-1	0	-1	0	0

The number of variables is six and the number of independent dimensions is three, as is the number of variables such as D_o, u_o, and ρ that cannot be combined to form a dimensionless group. Hence, the minimal number of dimensionless groups is 6-3=3.

The following acceptable set of dimensionless groups may be derived by any of the procedures illustrated in Example 1:

$$\frac{\Delta P}{\rho u_o^2} = \phi\left\{\frac{D_o u_o \rho}{\mu}, \frac{D_p}{D_o}\right\} \quad (43)$$

Elimination of D_p reduces Eq. (43) to

$$\frac{\Delta P}{\rho u_o^2} = \phi\left\{\frac{D_o u_o \rho}{\mu}\right\} \quad (44)$$

The further elimination of ρ leads to

$$\frac{(\Delta P)D_o}{u_o\mu} = A \quad (45)$$

whereas the elimination of μ leads to

$$\frac{\Delta P}{\rho u_o^2} = B \quad (46)$$

Equation (44) is found experimentally to be valid for $D_o<<D_p$, and Eqs. (45) and (46) to be valid on both experimental and theoretical grounds for $D_o<<D_p$ and $u_o \to 0$, and $u_o \to \infty$, respectively.

Example 4

Free Convection from a Vertical Isothermal Plate

The behavior may be postulated to be represented by

$$h = \phi\{g, \beta, T_w - T_\infty, x, \mu, \rho, C_p, k\} \quad (47)$$

where g is the acceleration due to gravity, β is the volumetric coefficient of expansion with temperature, T_∞ is the unperturbed temperature of the fluid, and x is the vertical distance along the plate. The corresponding tabulation is

	h	g	β	$T_w - T_\infty$	x	μ	ρ	C_p	k
M	1	0	0	0	0	1	1	0	1
L	0	1	0	0	1	-1	-3	2	1
θ	-3	-2	0	0	0	-1	0	-2	-3
T	-1	0	-1	1	0	0	0	-1	1

The minimal number of dimensionless groups given by both Eqs. (1) and (2) is 9-4=5. A satisfactory set of dimensionless groups, as found by any of the methods described in Example 1, is

$$\frac{hx}{k} = \phi\left\{\frac{\rho^2 g x^3}{\mu^2}, \frac{C_p\mu}{k}, \beta(T_w - T_\infty), C_p(T_w - T_\infty)\left(\frac{\rho x}{\mu}\right)^2\right\} \quad (48)$$

It may be reasoned that the buoyant force that generates the convective motion must be proportional to $\rho g\beta(T_w - T_\infty)$, hence g in the first term on the right-hand side of Eq. (48) must be multiplied by $\beta(T_w - T_\infty)$. Thereby, Eq. (48) becomes

$$\frac{hx}{k} = \phi\left\{\frac{\rho^2 g\beta(T_w - T_\infty)x^3}{\mu^2}, \frac{C_p\mu}{k}, \beta(T_w - T_\infty), C_p(T_w - T_\infty)\left(\frac{\rho x}{\mu}\right)^2\right\} \tag{49}$$

The effect of expansion other than on the buoyancy is now represented by $\beta(T_w - T_\infty)$ and the effect of viscous dissipation by $C_p(T_w - T_\infty)(\rho x/\mu)^2$. Both effects are negligible for all practical circumstances. Hence, Eq. (49) may be reduced to

$$\frac{hx}{k} = \phi\left\{\frac{\rho^2 g\beta(T_w - T_\infty)x^3}{\mu^2}, \frac{C_p\mu}{k}\right\} \tag{50}$$

or

$$Nu_x = \phi\{Gr_x, Pr\} \tag{51}$$

where $Nu_x = hx/k$ and $Gr_x = (\rho^2 g\beta(T_w - T_\infty)x^3)/\mu^2$ is the *Grashof number.*

Elimination of x speculatively reduces Eq. (60) to

$$\frac{hx}{k} = \left(\frac{\rho^2 g\beta(T_w - T_\infty)x^3}{\mu^2}\right)^{\frac{1}{3}} \phi\{Pr\} \tag{52}$$

or

$$Nu_x = Gr_x^{\frac{1}{3}} \phi\{Pr\} \tag{53}$$

Equation (53) appears to be a valid asymptote for $Gr_x \to \infty$ and a good approximation for the entire turbulent regime.

Eliminating μ speculatively from Eq. (50) results in

$$\frac{hx}{k} = \phi\left\{\frac{\rho^2 C_p^{\,2} g\beta(T_w - T_\infty)x^3}{k^2}\right\} \tag{54}$$

or

$$Nu_x = \phi\{Gr_x\, Pr^2\} \tag{55}$$

Equation (55) appears to be a valid asymptote for $Pr \to 0$ for all Gr_x, that is for both the laminar and the turbulent regimes.

The development of a valid asymptote for large values of Pr requires more subtle reasoning. First, $C_p\mu/k$ is rewritten as $\mu/\rho\alpha$ where $\alpha = k/\rho C_p$. Then ρ is eliminated speculatively except as it occurs in $\rho g\beta(T_w - T_\infty)$ and $k/\rho C_p$. The result is

$$\frac{hx}{k} = \phi\left\{\frac{C_p\rho^2 g\beta(T_w - T_\infty)x^3}{\mu k}\right\} \tag{56}$$

or

$$Nu_x = \phi\{Ra_x\} \tag{57}$$

where $Ra_x = (C_p\rho^2 g\beta(T_w - T_\infty)x^3)/\mu k = Gr_x\, Pr$ is the *Rayleigh number.* Equation (57) appears to be a valid asymptote for $Pr \to \infty$ and a reasonable approximation for even moderate values of Pr for all Gr_x, that is, for both the laminar and turbulent regimes.

Eliminating x for Eqs. (54) and (56) speculatively results in, respectively

$$Nu_x = A(Gr_x\, Pr^2)^{\frac{1}{3}} = A(Ra_x\, Pr)^{\frac{1}{3}} \tag{58}$$

and

$$Nu_x = B(Gr_x\, Pr)^{\frac{1}{3}} = B(Ra_x)^{\frac{1}{3}} \tag{59}$$

Equation (58) appears to be a valid asymptote for $Pr \to 0$ and $Gr_x \to \infty$ and a reasonable approximation for very small values of Pr in the turbulent regime, while Eq. (59) is well confirmed as a valid asymptote for $Pr \to \infty$ and $Gr_x \to \infty$ and as a good approximation for moderate and large values of Pr over the entire turbulent regime. The expressions in terms of Gr_x are somewhat more complicated than those in terms of Ra_x, but are to be preferred since Gr_x is known to characterize the transition from laminar to turbulent motion in natural convection just as Re_D does in forced flow in a channel.

The power of speculation combined with dimensional analysis is well demonstrated by this example in which valid asymptotes are thereby attained for almost every regime.

SUMMARY

The mechanics of dimensional analysis are relatively simple, but the choice of the appropriate variables provides an uncertain and intimidating task for students. The concept of speculation provides a rational approach to both the initial choice of variables and their elimination to attain asymptotic forms. The necessity of testing the results with experimental or computed values introduces no difficulty, at least in concept.

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ENGINEERING EDUCATION FOR THE 21ST CENTURY

Listen to Industry!

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As chemical engineering education approaches the complete implementation of ABET's Engineering Criteria 2000 in the next few years, much of the focus in our colleges and universities has turned to the meaning and measurement of outcomes assessment. Successful employment in the chemical industries of the 21st century will require that graduates of our chemical engineering programs meet their needs with real-world work experience.

Graduating engineers need to quickly develop an understanding of how their work contributes to the business results of a company. The way our graduates speak and present ideas and the way they write to communicate results are becoming assessable knowledge bases that industry looks for. Besides deriving or finding the proper chemical engineering equation and cranking out a computer solution to provide the numerical answer to a problem, industry also wants chemical engineers to consider the impact of their work on the environment—both on people and on business.

Communication skills, both oral and written, are not emphasized enough in today's typical chemical engineering curriculum. Chemical engineers need to prepare for the fact that they will spend much more of their time communicating with others than they will spend determining an answer to some engineering problem. It's one thing to get the correct answer to an exam problem, but it's another to design something useful that others are going to be involved with and that people are going to use.

What evidence has been provided to substantiate this call for change in the education of our chemical engineering graduates? The Council for Chemical Research's (CCR) Education Committee has developed the following "Challenge" statement:

> *The general view is that the scientific research and technical development expertise of U.S. graduates is excellent in both science and engineering. However, there exists in today's rapidly changing global economy a need for a shift of focus for the "knowledge workers" to an emphasis on traits and skills and not just content.*
>
> *With this in mind, the Education Committee recommends that CCR adopt the following positions*
>
> - *New chemists and chemical engineers must have the opportunity for a broader exposure to other areas of science and engineering to foster interdisciplinary and collaborative research. Examples include biological science, polymer science, catalysis, physics, environmental science, etc. The desired benefit would be that, in future employment, the successful graduate has a greater appreciation for issues broader than the pursuit of pure research goals.*
> - *So called "soft" skills must be more strongly incorporated into the graduate curriculum to allow for the success of the graduate. It has been repeatedly emphasized that failure in industrial positions is more often related to these areas than to technical expertise. This is true in academic positions as well. These areas include a basic understanding of ethics, the environment, team working, economics, patents, and corporate/university culture.*
> - *Communication skills of all types—oral, written, computer, and group dynamics—must be more heavily stressed. Foreign language skills have gained renewed importance in this respect.*
> - *Breadth of training must be reemphasized to produce a graduate capable of handling the diverse and rapidly changing global world of industry.*
> - *Awareness of the goals, products, competitors, and areas of emphasis in industry should be increased in all graduates to better facilitate university/industry interactions as well as to better prepare those students interested in industrial positions.*

Although this statement was prepared for the Council for Chemical Research and thus it contains references to gradu-

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ate research and education, it also has significant application directly to undergraduate chemical engineering education. In addition to the recent reports from ABET, ASEE, NAE, NAS, and NSF that provided much information for this CCR Education Committee statement, a survey of two large employers of chemical engineers and chemists was conducted several years ago.

Dr. Norman N. Hochgraf of Exxon Chemical Company (now retired) conducted a survey of technical employees with less than five years experience at Exxon and Dow Chemical. The survey basis included 138 people identified as campus technical hires in R&D at Exxon and 427 individuals as technical hires in central R&D at Dow. In addition, 102 supervisors at Exxon were surveyed. The results of the survey were presented in a session at the 17th Annual Meeting of CCR (Pittsburgh) in October of 1995. The survey response was 68% for Exxon Chemical and 82% for the Dow employees and included chemistry, chemical engineering, and other engineering related personnel at all degree levels. Although the Exxon group included 52% BS, 25% MS, and 23% PhD degrees and the Dow group had 38% BS, 15% MS, and 47% PhD degrees, no significant differences were found between the companies, degree levels, disciplines, new hires and supervisors, or researchers and plant technical people.

The 26 survey questions were the same for all and were grouped into the six skill categories: Technical Knowledge (6), Application of Knowledge (5), Work (5), Communication (3), Team/Interaction (4), and Independence (3). The survey respondents were asked to evaluate both the importance of a particular skill to their job and the degree of their preparation upon entering the workplace.The response measures were values (1-5) from "none" to "utmost" for Importance, and from "very little" to "very great" for Preparation; 22 of the 26 skills rated importance greater than preparation (denoted by > in Table 1). Table 1 summarizes the survey results.

TABLE 1
Survey Results

	Importance		Preparation
Technical Knowledge			
science/engineering concepts	very	=	great
plant operations and control	very	>	little
computing/computers	very	>	some
statistical experimental design	moderate	>	little
use of technical/patent literature	moderate	=	some
environmental/safety requirements	moderate	>	little
Application of Knowledge			
gathering necessary information	very	>	some
defining the problem	very	>	some
applying concepts to obtain solutions	very	>	great
applying concepts to business value	moderate	>	little
reaching workable results	very	>	some
Work Skills			
judging proper time	very	>	some
acquire and retain information	moderate	=	some
setting priorities/developing plans	very	>	some
judging "perfection" needed	very	>	some
meeting schedule dates	very	>	some
Communication Skills			
explaining ideas and concepts	very	>	some
preparing and delivering presentations	very	>	some
writing effective reports	very	>	some
Team/Interaction Skills			
effectiveness in a team	very	>	some
learning through consulting	very	>	some
getting cooperation	very	>	some
supervising others	moderate	>	little
Independence			
originating own projects	very	>	some
working independently	very	=	great
continuing to learn/develop	very	>	some

Several open-ended questions were also included in the survey. Responses to the question "What experiences or activities in academia were most helpful?" were mostly in accordance with the responses for the importance/preparation responses. Team interactions to solve complex problems, working together, technical communications course, technical writing, speaking to an audience, presenting papers, and literature searching were most frequently cited as helpful. In another open-ended question 99% of the supervisors responded that prior work experience is desirable. The new hires valued prior work experience as valuable in relating theories and concepts to real-life problems, in solving problems with incomplete data, and teaching the "art" of human interactions. One new hire, a co-op student, offered that co-op experience was more valuable than the degree program. Very few responders offered excellence, breadth, or depth of technical course work as being helpful.

Dr. Hochgraf concluded that the results of the survey suggest that colleges and universities should

- Change the ways in which learning takes place.
- Provide more emphasis and opportunity for solving incompletely specified problems, deciding the data needed, working in and leading problem-solving teams, and presenting and defending results.
- Build in more "real-world" experience by seeking and creating opportunities for industrial input, expecting faculty to obtain industrial experience, and supporting the value of co-op and intern experiences.
- Sacrifice some science/engineering knowledge to achieve a greater overall effectiveness.

Dr. Hochgraf also concluded that the survey results suggest that industry should

- Provide more early training in environmental and safety requirements and problems, in reaching and making decisions, in industrial structure relating to competition and economics, and in working in teams.
- Increase supervisor training to provide mentoring responsibilities that recognize the long-term impact of early job experiences, and to recognize and solve problems before they develop.
- Increase industrial experience opportunities for faculty experiences in industry and for student co-op and intern experiences.
- Improve overall effectiveness by sacrificing short-term costs to improve long-term effectiveness.

As we in chemical engineering education move toward full implementation of ABET Engineering Criteria 2000, the changes that are sought appear to be in line with and substantiated by the industrial views presented here. Let us not lose sight of the results we seek to achieve as we focus on the process of providing relevant chemical engineering education for the 21st century. ❒

TEACHING STATISTICS TO ChE STUDENTS

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There is a general consensus that statistics is needed in chemical engineering curricula,[1] and recently ABET added the requirement, "Students must demonstrate knowledge of the applications of probability and statistics to engineering problems." We must prepare our customers—future engineers and researchers—to effectively use statistical methods in product development and improvement as well as in scientific research.

With the dramatic shift in management attitudes toward using quality measures for competitive advantage and survival in the challenging world market, statistics has been recognized as a useful tool for decision making and quality improvement. We as educators must respond to the needs of industry and provide both technical support and well-equipped personnel in a timely fashion.

Realizing the importance of statistics in engineering education, the Chemical Engineering Department at the University of Minnesota Duluth has, since 1986, included in its required curriculum a three-credit course, "Experimental Design for Chemical Engineering." Our main objective has been to help the students comprehend the omnipresence of variability in the real world and to equip them with necessary statistical tools to deal with it.

COURSE CONTENT

The course content was determined by the needs of our students and the demands of industry. Over the past ten years, most of our graduates have taken entry-level jobs in diverse industries, while others pursued advanced studies. A number of the junior and senior students have also participated in co-op or intern programs with various industries.

In a concerted effort to collaborate with industry, our faculty consults and has offered different short courses (including applied statistics) for local industries. The feedback from students, the input from industry, and our own experiences have not only confirmed our belief in the necessity of the course, but also offered us better insights into what should be taught. We keep track of the most frequent questions and the subjects of most interest to industries, and we have been making continuous efforts to tailor the course to address them.

The course is designed to show the kind of problems that call for the use of statistics, when and where they may arise, and how they can be solved. By carefully explaining these questions, we are able to help the students understand the rationale and usefulness of statistics and to develop "statistical thinking."

One of the challenges we face in teaching such a course is to strike a proper balance between statistical foundation and its application. Because of the already fully packed chemical engineering curricula, it does not seem feasible to require a prerequisite course in probability and statistics. Therefore

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***We must prepare our customers—
future engineers and researchers—to effectively
use statistical methods in product development and improvement
as well as in scientific research . . . . We as educators must respond to the
needs of industry and provide both technical support and
well-equipped personnel in a timely fashion . . .***

only the first-year calculus is designated as a prerequisite.

Given the main objective of this course and the background of the majority of students taking it, we have been "application oriented" and have allotted very little class time for proofs and mathematical derivation of probability and statistical theory. Rather, we emphasize understanding the essence of statistical inference from the engineer's point of view.

The course is based on the following objective: To efficiently teach the statistical methods in experimental design, data analysis, and statistical process control that are most useful in chemical engineering. The key components of the course are closely related, proceeding from the easy concepts to the more difficult ones and from the simple case studies to the more complicated applications.

The course is taught in a lecture format with 25% of the classes in a computer laboratory. The course outline is shown in Table 1, and a brief description of each of the components follows.

TABLE 1
Course Outline

1. **Basic Theory**
   - Probability and statistics
   - Distributions
2. **Comparing Two Averages**
   - Procedure
   - Randomization and blocking
   - Hypothesis testing
3. **Comparing Multiple Averages**
   - ANOVA
   - Between and within treatment variations
4. **Factorial Design at Two Levels**
   - Analysis
   - Applications
   - Software
5. **Statistical Process Control**
   - Basic tools
   - Noisy data
   - Control charts
   - Multivariate SPC
6. **Regression Analysis**
   - Linear models from data
   - Software analysis
7. **Applications**

Basic Theory

This component provides students with some fundamental knowledge of probability and statistics. The use of several introductory real-world examples enables the students to differentiate between *populations* and *samples* and helps them understand that extracting information from data, an everyday task in research or in industry, often requires using sample statistics or estimates of *population parameters.* The emphasis on the omnipresence of variability highlights the necessity of using statistics.

After the introduction of certain basics in probability, we discuss random variables and the most frequently used probability distributions, including the normal, t, χ^2, and F distributions. Without spending too much time on mathematical details, we strive for an understanding of the meaning of distribution and probability and the use of various tables.

The central limit theorem is elaborated following the discussion of the common knowledge that averages are usually better estimates than individual observations. That, in turn, leads to the use of the sample mean as an estimate of the population mean, the assessment of the quality of the estimate by the confidence interval approach, and the determination of sample size to give a good estimate with desired accuracy with a certain confidence level—one of the most frequently encountered questions in reality.

Estimating population variances with sample variances, evaluating the closeness of the estimate to the 'true' parameter, and determining the required sample size are also addressed, in that order. Our experience has shown that students have little trouble following the logic of these methods or applying them to case studies.

Comparing Two Averages

This topic addresses the comparison of two things—two methods, two materials, two operating conditions, etc. A class discussion can be a good review of the general procedure needed: determining the sample size, planning an experiment, conducting the experiment to collect data, and finally, analyzing the data for a conclusion. We then use several examples to convince the students that "conclusions are easily drawn from a well-designed experiment, even when rather elementary methods of analysis are employed," and conversely, "even the most sophisticated statistical analysis cannot salvage a badly designed experiment."[2]

The two important strategies in experimental design, randomization and blocking, are then discussed in detail, followed by the rationale of hypothesis testing, the procedure of t tests for simple comparison, and the method of handling paired data. Our approach is to use in-depth discussion of real-world examples to show the students the philosophy of experimentation and data analysis and the role that statistics plays in it.

The course is based on the following objective: To efficiently teach the statistical methods in experimental design, data analysis, and statistical process control that are most useful in chemical engineering. The key components of the course are closely related, proceeding from the easy concepts to the more difficult ones and from the simple case studies to the more complicated applications.

Comparing Multiple Averages

A discussion of the comparison of more than two averages naturally follows the previous topic. The analysis of variance (ANOVA) methodology is introduced and used. It is very important to make sure that the students comprehend the essence of ANOVA—the estimation and evaluation of variations caused by various sources.

We normally use several relatively simple examples to show the calculation of different sums of squares and mean squares for the *between* and *within* treatment variations. More complicated and practical cases are then solved using computers. There are many statistical software packages available, and data entry and use of the packages are usually straightforward and easy to follow. Therefore we spend most of the time interpreting and elaborating on the results.

Our experience has been that further discussion of certain questions will greatly enhance the students' understanding. Some of the questions we have used include: Why do we need to use a t (or F) test? When can we use it? What is the meaning of t (or F)? What does a big t (or F) mean? What is the effect of the sample size on the result? How do you select α? Why should you be concerned about β?

Factorial Design at Two Levels

The concepts of factorial design are introduced next. We choose a relatively simple example to demonstrate how to plan a two-level factorial design as well as how to calculate and evaluate the effects. Graphic descriptions are used whenever possible so that the class can "visualize" the design and the idea behind the calculation. More complicated case studies are again solved by using computers.

The homework assignments in this component require solutions obtained by both using and not using computer software packages, enabling the students not only to understand and carry out design and analysis correctly, but also to do it effectively.

Statistical Process Control

To improve process productivity and product quality, statistical process control (SPC) has been widely used in industry, although at different levels of sophistication. In this component, we aim to expose the students to SPC in industry and to equip them with such basic tools as control charts. For these purposes, a brief review is given of the current situation in industry, the roles of control engineers and statisticians, and the importance of a chemical engineer's ability not only to handle process dynamics using first principles and process knowledge, but also to use statistical tools to deal with noisy data.

The most commonly used control charts, such as $\bar{x}$ charts and R charts, and their rationales and use are discussed in detail with several industrial examples. A brief introduction to some more advanced techniques, such as multivariate SPC, is also given to broaden students' fields of vision.

Regression Analysis

Building linear models from data is the subject of this component. Probabilistic models, a new concept to many of the students, are introduced first, followed by the idea of the least-squares estimation and its role in regression analysis. There are many software packages available for this purpose whose uses are similar to each other and which are not difficult to learn.

Our practice has been to spend most of the lecture time on illustration and elaboration of the assumptions, things needed for model validation, as well as on introducing the most commonly used transformations. No attempts at theoretical derivation are made. Rather, examples and graphic descriptions are presented whenever possible to help explain important but fairly sophisticated concepts such as noise correlation and equal variances. One of the purposes here is to remind the students that it is not sufficient for them to be merely aware of available techniques or methods for their purposes, but that they must also be able to use them correctly under specific conditions.

We have used as our required textbooks *Statistics for Experimenters* by Box, Hunter, and Hunter, and *Engineering Statistics* by Hogg and Ledoter. Each has its own strengths. We also include current literature and examples from process industries for their practical relevance.

Applications

Experimental design techniques are heavily integrated into undergraduate research projects. A typical example involved the removal of mercury during incineration and wastewater treatment. Because a high percentage of the mercury was associated with particulates in the scrubbing water, their removal was key to mercury removal.

A two-level factorial experimental design examined mercury removal efficiency as a function of inorganic coagulants, polymers, combinations of coagulants and polymers, reaction conditions, and dosages. The experimental work economically provided information on trends and parameter interactions so that the optimum parameters could be selected for mercury removal. Plant-scale tests were performed and the industrial process was permanently changed to provide the mercury removal demonstrated by this project.[3]

STUDENT RESPONSE

The course evaluation system at the University of Minnesota Duluth is similar to that used in many other universities. Students rank various aspects of the course on a scale of one to seven at the end of the quarter. Among the 27 questions asked, 5 are related to course design and course content. The average ranking of these questions in the last three years was 5.0. Most students were satisfied with its orientation toward application, and some of them even took additional courses in statistics out of interest or perhaps a newly developed realization of its importance.

We should mention that a similar syllabus was adopted for an intensive workshop offered at a local industry. The main difference between the industrial workshop and the regular undergraduate course is that in the former, more applied examples from the plant were included and discussed. We also put particular emphasis on correct methodology for each example at the host's request. The inclusion of familiar examples never failed to generate lively discussions and it also was conducive to a better understanding of the concepts and methods.

Most of the workshop attendees had not taken any probability and statistics courses before. However, the majority of them had little trouble following the lectures and showed strong interest and appreciation for them. Among the largely favorable evaluations we received, many students indicated that the strongest point of the course was its practical nature. The inclusion of more class discussions was suggested, which, we believe, should be adopted in the future undergraduate teaching as well.

CONCLUSIONS

We have developed and taught a course in applied statistics to chemical engineering undergraduate students. Our intent has been to show the relevance and importance of statistics in engineering practice and to provide students with the necessary statistical tools, such as experimental design, statistical process control, and model building.

The main feature of the course is its practical emphasis. The students are frequently reminded of the role that statistics plays in the real world, and their motivation is thereby sustained throughout the entire course. We hope they leave this course with a clear sense of use and a firm grip on how to apply theory to practice, rather than possessing merely a collection of loose-knit, half-understood topics or theorems.

We believe this course is well suited to chemical engineering undergraduates. The universal use of the computer has made it possible to include practical problems that are more complicated and require more computation than traditional textbook examples. Our experience in teaching this course has been interesting, rewarding and enjoyable.

To foster the students' ability to use statistics correctly and effectively is not an easy task. To train and to bring up a "statistically minded generation"[4] requires much more than a single course. The integration of statistics into our curriculum is but the first step; it remains for us to make continuing efforts to improve it to meet the growing challenge in the real world.

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The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and which elucidate difficult concepts. Please submit them to Professor James O. Wilkes (e-mail: wilkes@engin.umich.edu) or Mark A. Burns (e-mail: maburns@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

AN INTRODUCTION TO PROCESS FLEXIBILITY

Part 1. Heat Exchange

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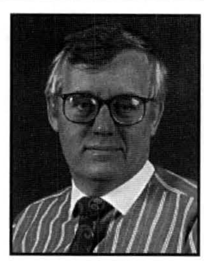
Process plants need to be flexible to cope with changes in production rates, product specifications, feedstock, catalyst deactivation, and heat exchanger fouling. Traditionally, once the process structure has been decided, various operating cases are evaluated and one is chosen as the basis for detailed design. However, selection of the design case is not straightforward. Effectively dealing with all the highly interrelated issues during design is a formidable problem. Hence, engineers often resort to the application of rule-of-thumb safety factors during equipment design (*e.g.*, adding 10% extra area to a heat exchanger) in an effort to ensure flexibility. Following this strategy, an experienced engineer would hope to develop a design that is operable across the anticipated process range, but there is no guarantee that the required flexibility will be achieved.[1-4] As the problem presented here clearly illustrates, different plant operating modes can easily lead to equipment design situations that are not covered by a simple safety factor.

The above comments explain why no substantial coverage of flexibility is found in any of the standard undergraduate design textbooks, apart from a few remarks on safety factors. Despite these difficulties, we feel the topic is very important, particularly because of the highly integrated plants being built today, and that the basic ideas should be introduced to all students.

Some students will encounter flexibility problems as part of their final-year design project. These projects are normally simplified from industrial reality, considering only one feedstock and, at worst, a catalyst deactivation or heat



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exchanger fouling cycle. Nevertheless, to design an operable plant, thought must be given at an early stage to conditions under which each item of equipment is expected to operate and to the process-control scheme to be used. Unless the project supervisor is alert, many students will simply size equipment for the conditions implied by the design mass and heat balances without considering flexibility.

This and a subsequent article will attempt to illustrate how selected aspects of flexibility can be introduced through interesting examples. In particular, the heat-exchange problem developed here may be used directly in a design course, while the reactor recycle loop featured in the second article could form the basis for project work, or for a discussion question in reactor design, or simply to indicate to supervisors an area worth discussing and developing in future design projects.

BACKGROUND

Most students, if asked, will suggest adjusting steam pressure or hot oil flow rate to a heat exchanger in order to maintain exit temperature in the face of process flow change. Slightly less obvious would be the suggestion to alter the condensate level in the heat-exchanger shell, thereby covering/exposing more heat transfer area for steam condensation. The important point is that steam and hot oil are utilities, and changing their consumption does not disturb the process.

Difficulty is immediately encountered when considering heat exchange between *two* process streams; changing the flow rate of one will certainly affect the exit temperature of the other. Unfortunately, interfering with a *process* stream flowrate immediately upsets the plant mass balance, which is undesirable. The difficulty is overcome by using a by-pass (see Figure 1) that does not affect the total flow rate but changes the proportion actually passing through the heat exchanger and hence the heat transferred. The problem presented here is concerned with heat exchanger by-pass arrangements to ensure satisfactory operation, in the face of aging catalyst, of a reactor at both beginning-of-run (BOR) and end-of-run (EOR).

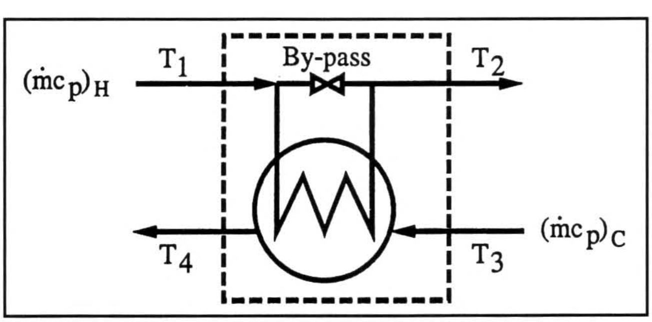

Figure 1. *Heat exchanger with by-pass.*

Students are familiar with using heat balances to calculate the heat load, Q,

$$Q = (\dot{m}c_p)_H (T_1 - T_2) = (\dot{m}c_p)_C (T_4 - T_3) \tag{1}$$

and the rate equation

$$Q = UA \frac{[(T_1 - T_4) - (T_2 - T_3)]}{\ell n\left(\dfrac{T_1 - T_4}{T_2 - T_3}\right)} \tag{2}$$

to determine heat transfer area A, knowing the overall heat transfer coefficient U. Here, $(\dot{m}c_p)_H$ and $(\dot{m}c_p)_C$ are the products of flow rate and specific heat capacity for the hot and cold streams. Temperatures T_1 to T_4 are identified in Figure 1, and for the moment we assume the by-pass is closed. But design to take into account flexibility implies not only calculating A, but also looking at the implications for other operating conditions, and this is where Eqs. (3) and (4) become useful.[5,6] They are derived for Eqs. (1) and (2) in order to permit the writing of explicit temperature equations:

$$(1 - RB)T_2 + R(B - 1)T_3 + (R - 1)T_1 = 0 \tag{3}$$

$$(1 - RB)T_4 + B(R - 1)T_3 + (B - 1)T_1 = 0 \tag{4}$$

where $R = (\dot{m}c_p)_C / (\dot{m}c_p)_H$ and $B = \exp\left[\left(UA / (\dot{m}c_p)_C\right)(R - 1)\right]$.

To illustrate, for a given heat exchanger (A specified) and known stream properties ($(\dot{m}c_p)_C$, $(\dot{m}c_p)_H$, and U specified), we can easily calculate the effect of an inlet temperature (T_1 and T_3) change on both exit temperatures (T_2 and T_4) using Eqs. (3) and (4). It is a very simple extension to apply sequentially the above pair of equations to a heat exchanger network, thereby evaluating the new temperatures throughout the network.[6]

Bearing in mind that various operating modes are to be accommodated, it is likely that the heat exchanger sized for the most severe case will be too large for the other modes. As hinted earlier, this difficulty is overcome by opening the by-pass. We assume the heat exchanger will operate with the same UA (see the Appendix), but the effective UA for the heat exchanger *plus* the partially open by-pass (as indicated by the dotted box in Figure 1) is reduced. Increasing by-pass flow progressively reduces the effective UA, whereas maximum heat transfer is achieved when the by-pass is closed. Good engineering practice would maintain a minimum flowrate of 5-10% through the by-pass.

Equations (1) through (4) are written for the case of sensible heating and sensible cooling of process streams. Special cases result for Eqs. (3) and (4) when one side of the heat exchanger operates isothermally. If the cold-side operates with isothermal vaporization at T_3, then Eq. (3)

reduced to

$$T_1 - BT_2 + (B-1)T_3 = 0 \tag{5}$$

where $B = \exp\left(UA/\left(\dot{m}c_p\right)_H\right)$.

If the hot-side operates with isothermal condensation at T_1, then Eq. (4) reduces to

$$(B-1)T_1 - BT_3 + T_4 = 0 \tag{6}$$

where $B = \exp\left(-UA/\left(\dot{m}c_p\right)_C\right)$.

For the special case of $\left(\dot{m}c_p\right)_H = \left(\dot{m}c_p\right)_C$ (*i.e.*, constant temperature driving force, ΔT, throughout the heat exchanger), it is easy to show that

$$\Delta T\left(\left(\frac{UA}{\dot{m}c_p}\right)+1\right) = T_1 - T_3 \tag{7}$$

In the following problem, Eqs. (5) and (7) are more immediately useful than the general Eqs. (3) and (4).

Finally, the hydraulic interaction between the heat exchanger and control valve in the by-pass line is important. Selection of control-valve type and size is crucial to ensure it remains operable over the range of by-pass flows expected. Difficulty occurs because transferring flow from the heat exchanger to the by-pass results in a reduced pressure drop across the heat exchanger. The control valve experiences the same pressure drop and so must accomodate the largest flowrate at the lowest pressure drop. (To achieve steady-state by-pass flowrates in excess of 30-35%, if the minimum is 5%, requires an unrealistically large control-valve size, and it is better to use two synchronized valves, the second being in series with the heat exchanger and compensating for the decreasing pressure drop.[7])

Luyben[8] summarizes the important properties of control valves. Volume flowrate, $\dot{q}\left(m^3/\text{sec}\right)$, through a control valve depends on the pressure drop, $\Delta P(\text{bar})$, control-valve size, C_v, fluid density, $\rho\left(\text{kg}/m^3\right)$, and valve opening, x. The relevant equation, if we assume ΔP is small compared to the operating pressure is

$$\dot{q} = C_v f(x)(\Delta P/\rho)^{0.5}$$

or, for mass flowrate

$$\dot{m} = C_v f(x)(\rho\Delta P)^{0.5} \tag{8}$$

where f(x) defines the control-valve characteristic in terms of valve opening. For this problem, two valve characteristics are important:

1) Linear $\quad f(x) = x$

2) Equal percentage $f(x) = \alpha^{x-1}$ (typically, α=50)

Note particularly that C_v must have dimensions consistent with the other variables in Eq. (8). The units used here are chosen for convenience in the rest of the problem rather than to agree with engineering practice; hence, the C_v values cannot be compared directly with, say, control valve manufacturer's data.

PROBLEM STATEMENT

Figure 2 shows the basic flowsheet for the heat exchangers surrounding a catalytic reactor operating at EOR conditions. The hot reactor effluent is cooled first by boiling water at 200°C and then by preheating the reactor feed. The process operates entirely in the gas phase, and you may assume a constant specific heat capacity of 2.5 kJ/kgK.

At BOR, the catalyst is much more active, requiring a reactor inlet temperature of only 185°C. The corresponding process flowrate and reactor effluent temperature are 22.5 kg/sec and 296.1°C.

a) Calculate the UA requirements for both heat exchangers implied by EOR operation. Investigate the feasibility of BOR operation using the UA values just determined if no flexibility is added to the flowsheet.

b) Determine UA requirements for BOR operation if the temperature to product recovery is to be maintained at

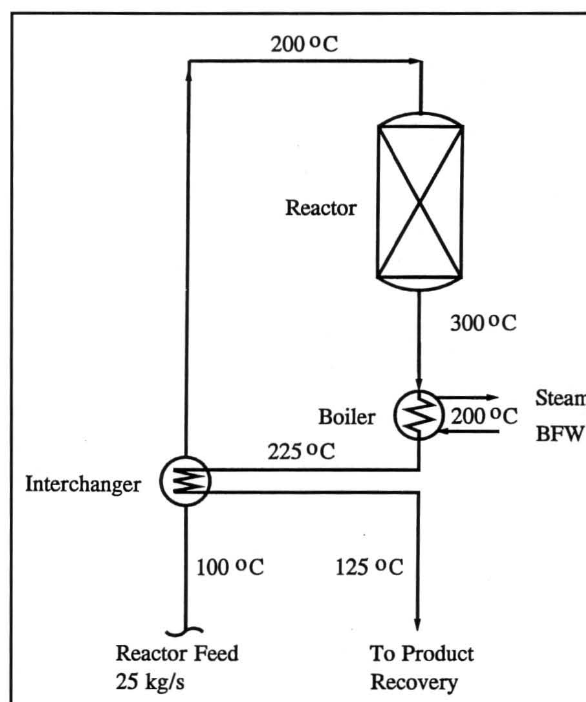

***Figure 2.** EOR flowsheet.*

125°C. Which operating mode sets the design for

1) the interchanger?

2) the boiler?

c) If the minimum flowrate through the by-pass is 5% of the main flowrate, determine the design UA requirements for both heat exchangers. What percentage of the main flowrate should pass through the by-pass to permit the alternative operating mode?

d) Add the by-passes to the flowsheet and indicate how you would configure the temperature control loops. How would the plant be operated with your control scheme?

e) The interchanger has a cold-side pressure drop of 0.6 bar calculated for EOR flowrate and no by-passing. Select a suitable control valve from the following range of valves with linear characteristics:

C_v = 1.0, 1.75, 2.5

In steady-state operation, a control valve should operate with an opening between 0.2 and 0.8. You may assume a constant gas density of 20 kg/m^3 and neglect piping friction losses.

f) The boiler has a hot-side pressure drop of 0.4 bar calculated for EOR flowrate with no by-passing. Why would an equal percentage valve with α=50 be more suitable for this service than a linear one?

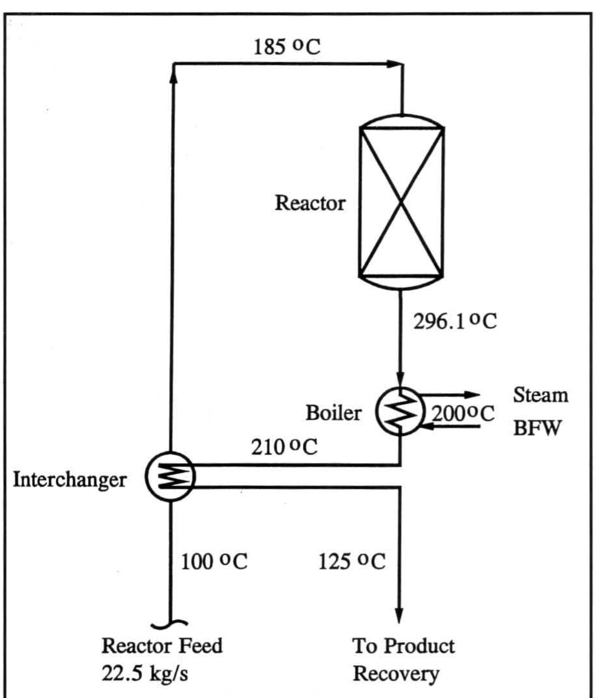

Figure 3. *BOR flowsheet.*

SOLUTION

a)

Interchanger duty	= 25 × 2.5 × 100 = 6250 kW
Temperature difference	= 25 K
Interchanger UA	= 6250/25 = 250 kW/K
Boiler duty	= 25 × 2.5 × 75 = 4687.5 kW
Log mean temp. difference	= 54.1 K
Boiler UA	= 4687.5/54.1 = 86.65 kW/K

To investigate the feasibility of BOR operation with the above UA values, it is probably best to start with the boiler. Using Eq. (5),

$$B=\exp(86.65/(22.5 \times 2.5)) = 4.667$$

and the process exit temperature

$$= \frac{296.1 + (4.667 - 1)200}{4.667} = 220.6°C$$

We can now calculate the two exit temperatures from the interchanger. Using Eq. (7),

$$UA/(\dot{m}c_p) = 250/(22.5 \times 2.5) = 4.444$$

and the temperature difference is

$$(220.6 - 100)/(4.444 + 1) = 22.15\,K$$

Hence the preheated reactor feed will be at

$$(220.6 - 22.15) = 198.45°C$$

and the stream to product recovery is slightly too cold at 122.15°C (but may be acceptable). The preheated reactor feed, however, is certainly far too hot at 198.45°C. *Conclusion:* heat exchangers sized for EOR operation will not function satisfactorily at BOR.

b) To determine the UA requirements for BOR, it is advisable to redraw the flowsheet to reflect BOR operation, as shown in Figure 3. The reactor feed must be heated from 100°C to 185°C, hence the cross-over temperature of the reactor effluent from the boiler to the interchanger is 210°C to maintain a temperature of 125°C to product recovery.

Interchanger duty	= 22.5 × 2.5 × 85 = 4781.3 kW
Temperature difference	= 25 K
Interchanger UA	= 4781.3/25 = 191.25 kW/K

which is 23.5% *less* than the UA required for EOR; hence, EOR operation will set the design of this item of equipment.

Boiler duty	= 22.5 × 2.5 × 86.1 = 4843.1 kW
Log mean temp. difference	= 38.05 K
Boiler UA	= 4843.1/38.05 = 127.28 kW/K

which is 46.9% *more* than the UA required for EOR; hence BOR operation will set the design of this item of equipment.

c) We consider the interchanger case in detail here. Figure 4A shows the actual interchanger exit temperature for the reactor feed at EOR to be T^*; after blending with the by-pass, the required preheated temperature of 200°C is achieved. Our first concern is to calculate T^*.

$$200 = (0.05 \times 100) + (0.95 \times T^*)$$

$$T^* = 205.26°\text{C}$$

and this implies a log-mean temperature difference of 22.27 K, giving a UA of 280.65 kW/K, *i.e.,* this UA should be installed to give an effective UA of 250 kW/K for the combination of heat exchanger plus 5% by-pass.

Figure 4B shows the fraction by-passed during BOR operation to be Z. The determination Z is a trial-and-error calculation, requiring

1) Guess Z
2) Calculate T^* to give mix temperature of 185°C
3) Calculate log-mean temperature difference
4) Calculate UA and compare with installed value of 280.65 kW/K. If agreement is not achieved, return to 1) and repeat calculations until convergence is obtained.

The converged solution is

Z = 0.1415, *i.e.,* well below maximum by-pass of 0.3

$T^* = 199.01$°C

Log-mean temperature difference = 17.05 K

UA = 280.5 kW/K, close enough to installed value of 280.65 kW/K

A similar procedure is used for the boiler, for which the following key values are calculated:

1) installed UA = 153.2 kW/K based on BOR and 5% by-pass
2) Z = 0.216 for EOR operation

d) Figure 5 shows the flowsheet with by-passes and temperature-control loops added. The setpoint for TC1 may be set at 125°C for all operating modes, but the operator will need to increase the setpoint of TC2 from time to time to compensate for the fall off in reactor catalyst activity.

e) If a control valve with $C_v = 1.75$ is selected, the following f(x) values are calculated using Eq. (8):

1) EOR $0.05 \times 25 = 1.75\, f(x)\, (0.542 \times 20)^{0.5}$

   $f(x) = 0.217$

   where 0.542 bar has been estimated by $0.95^2 \times 0.6$

2) BOR $0.1415 \times 22.5 = 1.75\, f(x)(0.358 \times 20)^{0.5}$

   $f(x) = 0.68$

   where 0.358 bar has been estimated by

$$\left(\frac{0.8585 \times 22.5}{25}\right)^2 \times 0.6$$

The valve is known to have linear characteristics; hence, f(x) translates to openings of 0.217 and 0.68. These are acceptable, lying within the specified range of 0.2 to 0.8.

Using either of the other valves gives unacceptable or impossible solutions. $C_v = 1.0$ means the valve is not large enough to handle BOR and $C_v = 2.5$ is too large,

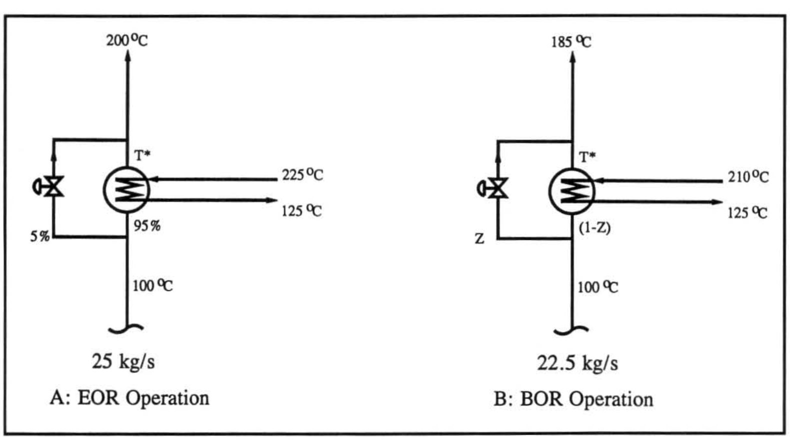

Figure 4. *Temperature and flowrate details for the interchanger.*

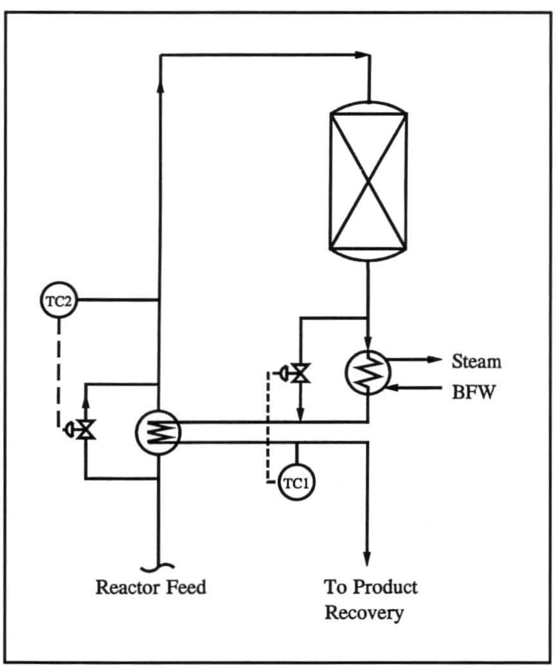

Figure 5. *Flowsheet showing by-passes and temperature control loops.*

such that the opening for EOR is below 0.2.

f) Trial-and-error calculations soon show that it is impossible to find a C_v for a linear valve that spans the BOR-EOR flow range, giving both openings between 0.2 and 0.8.

Equal percentage characteristics enable a wider range of by-pass flowrates to be accommodated; *i.e.,* calculation soon demonstrates that a C_v of 5.32 gives an opening of 0.8 for EOR and 0.404 for BOR.

APPENDIX

Strictly, the assumption of constant UA is inaccurate because opening the by-pass reduces flow through the heat exchanger, which affects the film coefficient and hence the overall coefficient. The lower real UA means slightly less would have to be by-passed, hence the by-pass flow calculated on the assumption of constant UA is an upper bound. For the problem presented, you would expect the by-pass to change from 14.15% to around 13% if account is taken for the reduced U. Thus for design, provided that the most severe case and associated flows have been identified, the small "errors" for the alternative modes are easily accommodated by the control loop.

ACKNOWLEDGMENTS

Thanks to Carl Pulford for drawing the figures and John Dos Santos for helpful discussions on heat recovery.

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ChE *letter to the editor*

Dear Editor

The universities with the eight top-ranked doctoral programs in chemical engineering in 1982, as rated by the National Academy of Sciences, were listed in *Changing Times.* In a 1991 letter to the editor of this journal (Vol. 25, page 181), I pointed out that an analysis of this ranking revealed that 63.4% of the faculty members in these eight "elite" programs had obtained their doctoral degrees from one of the same eight top-ranked schools. I suggested that these programs had maintained and enhanced their reputations by hiring their own and one another's graduates.

Doctoral programs in chemical engineering were ranked more than one decade later by the National Research Council (*Chronicle of Higher Education,* **42**(4), 1995). I studied this report to find 1) the extent to which the eight chemical engineering programs that ranked highest in 1982 retained their high rankings in 1995, and 2) the extent to which these programs persisted in hiring their own and one another's graduates.

The eight universities and their respective ranking in 1982 and 1995 are: Minnesota, 1, 1; Wisconsin, 2, 4; California, Berkeley, 3, 3; California Institute of Technology 3, 6; Stanford, 4, 7; Delaware, 5, 8; Massachusetts Institute of Technology, 6, 2; Illinois, 7, 5. Each of the eight programs that ranked highest in 1982 was again ranked among the top eight programs in 1995.

The names and alma maters of the full-time faculty members in these eight programs in 1982 and 1995 were obtained from the Internet. The median percentage of faculty members who had obtained their doctoral degrees from their own school or from one of the other seven top-ranked schools in 1995 was 70.8% (range, 50.0% to 91.7%). This is very similar to the 67.4% (range, 50.0% to 75.0%) figure in 1982.

Sincerely,

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OBJECTIVELY SPEAKING

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> **Student A:** *"Buffo's first test is next Monday. I haven't had him before—can you just plug into formulas on his exams or does he make you do derivations and stuff?"*
>
> **Student B:** *"There's no telling—last fall most of his questions were straight substitution, but a couple of times he threw in things I never saw in the lectures."*
>
> **Student C:** *"Yeah, and if you ask him what you're responsible for on the test he just gets mad and gives you a sermon on how bad your attitude is . . . we had a 600-page textbook and according to Buffo we were supposed to know everything in it."*
>
> **Student A:** *"Forget that—no time. I'll just go through the homework problems and hope it's enough."*

You can often hear conversations like that in the student lounge, and if you step across the hall to the faculty lounge you'll hear their counterparts.

> **Professor X:** *"All these students can do is memorize—give them a problem that makes them think a little and they're helpless."*
>
> **Professor Y:** *"I don't know how most of them got to be sophomores. After my last exam some of them went to the department head to complain that I was testing them on things I never taught, even though the chapter we just covered had everything they needed to know."*
>
> **Professor Z:** *"It's this whole spoiled generation—they want the grades but don't want to work for them!"*

Things are clearly not going quite the way either group would like. Many students believe that their primary task is to guess what their professors want them to know, and if they guess wrong they resent the professors for being unreasonably demanding, tricky, or obscure. Professors then conclude that the students are unmotivated, lazy, or just plain dumb.

There is another way things can go. Suppose you hand your students a preview of the kinds of problems they will be expected to solve, including some that require real understanding, and then include such problems on homework assignments and tests. Since they will know up front the things you want them to do and will have had practice in doing them, most of them will be able to do them on the tests—which means they will have learned what you wanted them to know. Some professors might regard this process as "spoon-feeding" or "coddling." As long as you maintain high expectations, it is neither. It is successful teaching.

INSTRUCTIONAL OBJECTIVES

An effective way to communicate your expectations is by giving your students *instructional objectives,* statements of specific observable actions they should be able to perform if they have mastered the course material. An instructional objective has one of the following stems:

- *At the end of this [course, chapter, week, lecture], you should be able to ****
- *To do well on the next exam, you should be able to ****

where *** is a phrase that begins with an action verb (*e.g.,* list, calculate, solve, estimate, describe, explain, predict,

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model, design, optimize,...). Here are some examples of phrases that might follow the stem of an instructional objective, grouped in six categories according to the levels of thinking they require.[1]

1. **Knowledge** (repeating verbatim): *list* [the first ten alkanes]; *state* [the steps in the procedure for calibrating a gas chromatograph].
2. **Comprehension** (demonstrating understanding of terms and concepts): *explain* [in your own words the concept of vapor pressure]; *interpret* [the output from an ASPEN simulation].
3. **Application** (applying learned information to solve a problem): *calculate* [the pump brake horsepower required for a specified process line and fluid throughput]; *solve* [the compressibility factor equation of state for P, T, or $\hat{V}$ from given values of the other two].
4. **Analysis** (breaking things down into their elements, formulating theoretical explanations or mathematical or logical models for observed phenomena): *derive* [Poiseuille's law for laminar Newtonian flow from a force balance]; *explain* [why we feel warm in 70°F air and cold in 70°F water].
5. **Synthesis** (creating something, combining elements in novel ways): *formulate* [a model-based alternative to the PID control scheme presented in Wednesday's lecture]; *make up* [a homework problem involving material we covered in class this week].
6. **Evaluation** (choosing from among alternatives and justifying the choice using specified criteria): *determine* [which of several specified heat exchanger configurations is better, and explain your reasoning]; *select* [from among available options for expanding production capacity, and justify your choice].

WHY BOTHER?

Well-formulated instructional objectives are more than just an advance warning system for your students. They can help you to prepare lecture and assignment schedules and to spot course material that the students can do little with but memorize and repeat. They also facilitate construction of in-class activities, out-of-class assignments, and tests; you simply ask the students to do what the objectives say they should be able to do. A set of objectives prepared by an experienced instructor can be invaluable to someone about to teach the course for the first time and can help instructors of subsequent courses know what their students should have learned previously. If objectives are assembled for every course in a curriculum, a departmental review committee can easily identify both unwanted duplication and gaps in topical coverage, and the collected set makes a very impressive display for accreditation visitors.

TIPS ON WRITING OBJECTIVES

- *Try to write instructional objectives for every topic in every course you teach.* Take a gradual approach, however—you don't have to write them all in a single course offering.
- *Include some objectives at the levels of analysis, synthesis, and evaluation.* They are not that hard to write, even in undergraduate courses,[2] but if you don't consciously set out to write them you probably won't.
- *Avoid four leading verbs in instructional objectives: know, learn, appreciate, and understand.* You certainly want your students to do those things but they are not valid instructional objectives, since you cannot directly see whether they have been done. Think of what you will ask the students to *do* to demonstrate their knowledge, learning, appreciation, or understanding, and make those activities the instructional objectives for that topic.

Formulating detailed instructional objectives for a course or even for a single course topic takes effort, but it pays off. When we have asked alumni of our teaching workshops to rate the usefulness of the instructional methods we discussed, instructional objectives ranked second only to cooperative learning. Many professors testified that once they wrote objectives for a course—sometimes one they had taught for years—the course became more interesting and more challenging to the students and more enjoyable for them to teach.[3] ❐

[1] *The six given categories are the levels of Bloom's Taxonomy of Educational Objectives [B.S. Bloom,* Taxonomy of Educational Objectives. 1. Cognitive Domain. *Longman, New York, NY 1984]. The last three categories—analysis, synthesis, and evaluation—are often referred to as the* higher level thinking skills.

[2] *Examples of higher-level questions are given by Felder ["On Creating Creative Engineers,"* Engr. Edu., ***77****, 222 (1987)] and Brent and Felder ["Writing Assignments—Pathways to Connections, Clarity, Creativity,"]* College Teaching, ***40****(2), 43 (1992)].*

[3] *For more information about objectives, see N.E. Gronlund,* How To Write and Use Instructional Objectives, *4th ed., Macmillan, New York (1991). For examples of their use in engineering education, see J.E. Stice, "A First Step Toward Improved Teaching,"* Eng. Ed., ***66****(5), 394 (1976).*

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USE OF COMPUTATIONAL TOOLS IN ENGINEERING EDUCATION

A Case Study on the Use of Mathcad®

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With the widespread use of personal computers, a variety of powerful computational tools are now available that permit engineers to routinely perform calculations and analyses that were once very difficult. The introduction of these tools into the undergraduate engineering curriculum can facilitate student computations, but can the use of these tools also foster student learning and understanding of engineering principles?

The purpose of this paper is to examine issues related to incorporating an equation-solving package into the undergraduate curriculum in chemical engineering. Although the content of the paper is based on our experience with Mathcad®, our observations and conclusions are equally applicable to other equation-solving packages. Of particular interest is the impact that using equation solvers has on student learning and ways in which such software might be used to enhance learning.

HISTORY OF MATHCAD AT BYU

Five years ago, most undergraduate student work in our department was done with calculators, with some of the more demanding problems requiring spreadsheets or FORTRAN programming. At that time we felt that equation-solving packages had been developed to the point where they represented a potentially useful tool for our students (see Table 1). After reviewing several different numerical- and symbolic-based equation solvers, the faculty voted to incorporate Mathcad into the undergraduate curriculum. It was our opinion that the department should adopt a single package and that Mathcad was the package best suited to our needs. In particular, Mathcad's graphical interface was appealing from an educational point of view since students could manipulate equations that looked like those found in their textbooks or presented in class.

Mathcad was initially implemented in our sophomore material balance course taught from the Felder and Rousseau text[1]. We required the students to use the software and instructed them on its use, providing instructions throughout the course when new material suggested the need for new computational techniques. We also prepared a short tutorial to help beginning students. As a general rule, students did not have easy access to Mathcad manuals since relatively few were available in the student computer labs. Therefore, students generally depended upon on-line help, the tutorial, in-class examples, the instructors, and the TA for assistance. In addition to the material balance course, Mathcad was heavily used in two upper division undergraduate courses and was incorporated to a lesser degree into several other undergraduate and graduate courses.

Four years have passed since the initial implementation of Mathcad. Since that time we have observed a significant change in the way in which our students approach and solve engineering problems, and some of the change is directly related to use of the math software. In addition, we have gained experience with the software and have learned ways

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in which it can be used to enrich learning. We have also been able to observe the impact of adapting such software on our overall undergraduate program in chemical engineering.

BENEFITS FROM USING THE PACKAGE

To illustrate the benefits listed in Table 1, we will examine the solution of an engineering problem with Mathcad. Note that the benefits listed in the table apply to equation-solving packages in general, although specific capabilities will vary from package to package.

An important part of engineering is the use of mathematical expressions to describe and model the behavior of physical systems. Solution of the resulting equations can be very difficult and time consuming. Therefore, solutions are often limited in scope, based on simplifying assumptions, and dependent on a restricted set of variables in order to be computationally tractable. With use of a tool such as Mathcad, students can perform calculations more rigorously and broadly, obtaining a deeper and more complete understanding of the problem. The following solution of an undergraduate-level thermodynamics problem illustrates the use of Mathcad to solve an engineering problem.

TABLE 1
Potential Benefits of an Equation-Solving Package in an Undergraduate Engineering Program

1. It enables more efficient solution of problems that had previously been tedious or difficult to solve.
2. It enables solution of more realistic engineering problems that had previously been impossible or impractical for undergraduate students.
3. Use of the new capabilities provided by the tool could enrich and enhance student learning.

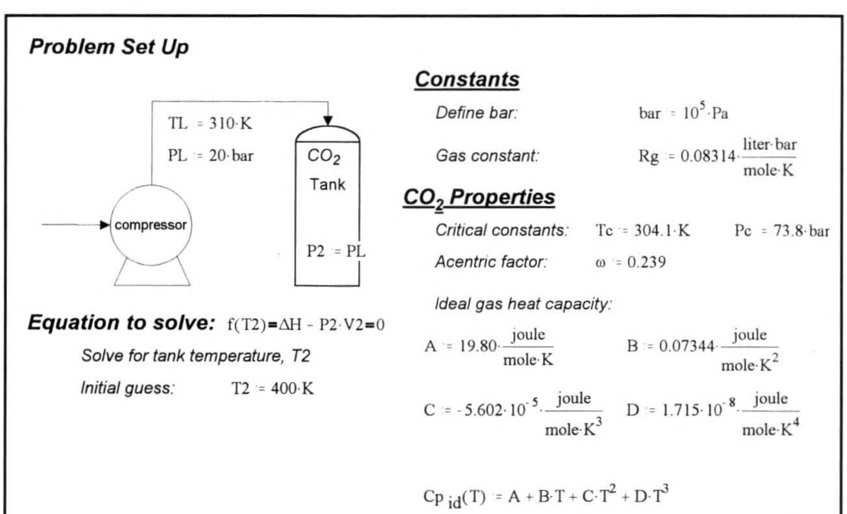

***Figure 1.** Input section of Mathcad sheet for example problem.*

Problem Statement • A cylinder is to be filled with CO_2 from a compressor that discharges the CO_2 at 20 bar and 310K. Initially, the cylinder (also at 310K) is evacuated (see Figure 1). Assuming no heat transfer to the cylinder, what is the final temperature of the CO_2 in the cylinder when the cylinder reaches the compressor line pressure?

Solution • One can show from the first law of thermodynamics for this situation that the final temperature is found by solving the following equation:

$$\Delta H - P_2 V_2 = 0 \tag{1}$$

where ΔH is the difference between the final gas enthalpy and the enthalpy of the gas in the filling line, P_2 is the final gas pressure in the cylinder, and V_2 is the final molar volume of gas in the cylinder. All terms in this equation can either be evaluated in terms of known values or be represented as a function of the unknown final gas temperature (T_2). The enthalpy of the gas in the filling line is a function of the filling line pressure (P_2) and temperature (T_L), both of which are known. The final gas enthalpy must be evaluated at the known final pressure P_2 and the unknown T_2. The volume (V_2) is related to P_2 and T_2 through an equation of state.

Figure 1 is the input section of a Mathcad sheet for the above problem. Mathcad allows text to be inserted alongside the computation lines so that the calculation is easily documented. In this example, text is shown in "Arial italics" whereas the active Mathcad equations are in "Times Roman." Note that units can be used with variables and Mathcad will take care of all unit conversions. Additional units, not internal to Mathcad, can be defined, as has been done here with bar. The newly defined unit can then be used throughout the worksheet. Known values are defined for T_L and P_2. The gas constant is also specified, along with physical data for CO_2. The heat capacity is specified as a function of temperature to be used by numerical routines.

Also included in the input section of the sheet is a specification of an initial guess for the final temperature. The equation to be solved is also noted for convenience as text; this is not an active Mathcad equation. The equation has been written explicitly in the form $f(T_2) = 0$ to emphasize that we seek a root that satisfies Eq. (1). Two separate solutions to the problem are illustrated in Figure 2 and discussed in the following sections. These sections are intended to illustrate the first two benefits listed in Table 1. Such benefits are commonly perceived and have been documented by others.[e.g., 2] However, we often fall short of achieving the full educational benefits that the software makes possible. Therefore, the last section of the example attempts to illustrate how the capabilities of Mathcad can be used to further enhance learning (Benefit #3).

Using Mathcad for Efficient Problem Solutions (Benefit #1)

The first solution, which assumes an ideal gas, is similar to the type of solution required of students in the past. The enthalpy difference is expressed as an integral over the heat capacity, which is substituted into the equation $f(T_2) = 0$. The Mathcad "root" function is then used to solve for the desired temperature T_2. The solution was completed in four lines with minimal algebra. In contrast, a calculator could have been used to obtain the same solution. To do so, one would first perform the integration, then substitute the resulting polynomial into Eq. (1), and finally, program the final function of T_2 into the calculator. In this case, Mathcad provides a more efficient solution to a problem that has traditionally been solved by other methods. Mathcad also makes it easier to correct a mistake made during the calculation. Independent of how the solution is obtained, however, the student arrives at the answer with little physical insight. For example, how accurate is the ideal gas assumption?

Using Mathcad to Solve More Realistic Problems (Benefit #2)

Figure 2 also presents a more realistic solution to the problem, which uses the Soave equation of state in place of the ideal gas assumption. (A full description of the equations used in the solution is beyond the scope of this paper—interested readers should refer to a text on thermodynamics for more information.) Mathcad provides an elegant solution to a complex mathematical problem that would be difficult and/or impractical for undergraduate students to solve using either a calculator or a spreadsheet. For example, P_2V_2 is required in the equation, but the Soave equation cannot be solved explicitly for V. In Mathcad, V is obtained as a function of temperature and pressure by solving the equation of state using a root function. This volume is then used in the calculation of the enthalpy departure function, which is in turn used as part of the expression that is solved iteratively for T_2.

A realistic solution of the problem can thus be achieved in a straightforward manner. Such a solution would not have been practical for undergraduates without the use of software such as Mathcad.

What have we gained from the more realistic solution of the problem? Because of the time saved in the simplified solution of the problem, it is feasible to ask students to solve the problem both ways and to compare the answers. The fact that the answers are different is significant, but the physical insight gained from the comparison is still quite limited since the student is only comparing two numbers. Note that students also gain experience in using realistic equations of state by performing the more complicated calculations. Using a tool such as Mathcad to expose students to models and methods actually used in industry better prepares graduates for realistic engineering calculations. In contrast, using inappropriately simple models for computational convenience may give students a false impression of the applicability of such models.

Using Mathcad as a Teaching Tool (Benefit #3)

There is considerably more that can be done in using the software to improve learning. For example, learning can be enhanced by extending the problem statement itself. In this

Solution for Ideal Gas with Cp as a function of temperature

$$\Delta H_{id}(T2) := \int_{TL}^{T2} Cp_{id}(T)\, dT$$

$f(T2) := \Delta H_{id}(T2) - Rg\cdot T2$ *Note: For ideal gas,* $P2\cdot V2 = Rg\cdot T2$

$T2_{id} := \mathrm{root}(f(T2), T2)$

$T2_{id} = 392.874\cdot K$ ***Answer for ideal gas***

Solution for Soave Equation of State

1) Define equation of state in terms of known parameters

$$a := \frac{0.42747\cdot Rg^2\cdot Tc^2}{Pc} \qquad b := \frac{0.08664\cdot Rg\cdot Tc}{Pc} \qquad m := 0.48508 + 1.55171\cdot\omega - 0.15613\cdot\omega^2$$

$$\alpha(T) := \left[1 + m\cdot\left(1 - \sqrt{\frac{T}{Tc}}\right)\right]^2 \qquad F(T,P,V) := P - \left[\frac{Rg\cdot T}{V - b} - \frac{a\cdot\alpha(T)}{V\cdot(V+b)}\right]$$ *Soave equation of state*

2) Set up expression to calculate V for a given T and P from the equation of state

Initial guess: $V := 0.5\cdot liter$ *Expression:* $V(T,P) := \mathrm{root}(F(T,P,V), V)$

3) Define enthalpy departure function (Hid - H) for Soave equation of state

$$K(T) := m\cdot a\cdot\alpha(T)\cdot\sqrt{\frac{T}{Tc\cdot\alpha(T)}} \qquad \Delta H(T,P) := Rg\cdot T\cdot\left(1 - \frac{P\cdot V(T,P)}{Rg\cdot T} + \frac{a\cdot\alpha(T) + K(T)}{b\cdot Rg\cdot T}\cdot\ln\left(1 + \frac{b}{V(T,P)}\right)\right)$$

4) Define and solve final expression for T2

$\Delta H_{real}(T2,P) := \Delta H(TL,P) - \Delta H(T2,P) + \Delta H_{id}(T2)$

$f(T2,P2) := \Delta H_{real}(T2,P2) - P2\cdot V(T2,P2)$

$T2_{real}(P2) := \mathrm{root}(f(T2,P2), T2)$

$T2_{real}(P2) = 380.36\cdot K$ ***Answer for real gas***

Figure 2. *Mathcad solution assuming ideal gas (top) and using the Soave equation of state (bottom).*

problem, students might be asked to calculate the final temperature in the cylinder for a range of compressor line pressures and to plot the results. This extension is easily achieved with Mathcad by adding a couple of assignment statements and creating a graph. The resulting Mathcad figure, Figure 3, provides physical insight not previously available. The student can see that the two solutions approach each other as the pressure is decreased and CO_2 behaves more ideally. It is also apparent that the two solutions diverge as the pressure is increased, and that the ideal gas solution does not change with pressure.

To be still more useful, the extended problem statement should include qualitative questions that ask the students to explain, justify, and generalize their observations. For example, why do the two curves diverge as the pressure is increased? Or, why is the ideal gas solution independent of pressure? It is also useful to have them evaluate the practical importance of the result by asking a question such as what significance would the error introduced by the ideal gas assumption for CO_2 have on the design of . . . ?

The extended problem helps students gain insight into the effect of pressure on the nonideal behavior of CO_2, but what about other gases? When would they need to worry about nonidealities? To teach this, one might have the students repeat the solution for a different gas. As the equations are identical, the solution is readily obtained by simply changing the parameters at the top of the sheet. You may want to ask the students to *predict* the results for the second gas *prior* to performing the calculation. For example, "Would you expect N_2 to behave more or less like an ideal gas than CO_2? " and "Why?" Because the selected temperature range is so far above the critical point of N_2, the students should expect more ideal behavior from N_2. Figure 4 shows the results for N_2 indicating that this is indeed the case. Students could be asked to compare the solutions and rationalize their observations. For example, "Why is one gas more ideal than another at these conditions?" Other questions related to the properties of the two gases might also be included, such as "Which gas has the higher heat capacity, and why?"

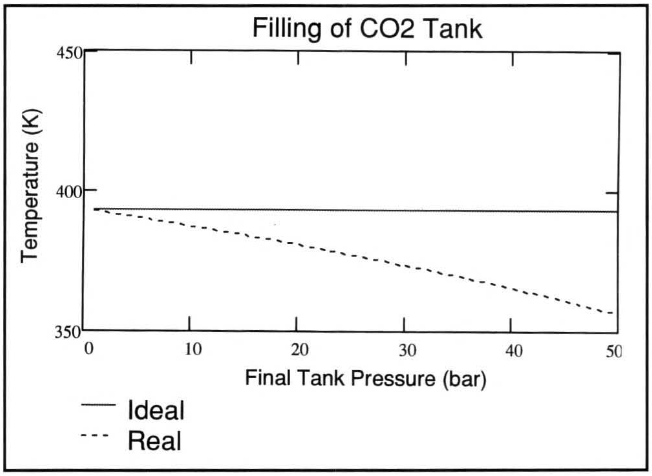

Figure 3. *Temperature of the tank as a function of the CO_2 final pressure.*

The above example illustrates several capabilities of Mathcad relevant to engineering education. (As mentioned previously, these benefits also apply to other equation-solving packages.) First, the software enabled efficient solution of engineering problems as shown in the initial "ideal" solution to the problem. Solution of the same problem using the Soave equation of state demonstrated a realistic solution that was not previously tractable, and use of both the ideal and real solutions allowed comparison of the two. Mathcad also permitted calculation of the temperature for a range of pressures and visualization of the results, providing physical insight that was previously unavailable. Qualitative questions were used to help develop this insight. Finally, calculations were easily repeated for a different gas, and students were asked to rationalize and evaluate the differences, illustrating the use of Mathcad to answer "What if...?" questions.

In short, Mathcad permitted extension of the original problem, at relatively little overhead, to enhance learning. This type of extension, however, requires effort on the part of the instructor; it does not follow automatically with the use of Mathcad. Using the "same old problem statements" with the new tool will do relatively little to enhance student learning. In fact, in some cases, it may even reduce learning.

There are other ways to use equation-solving packages to enhance the education of engineering students. The combination of powerful computational and graphical capabilities is ideal for exploring trade-offs between opposing factors in order to reach an optimal solution. Students might be asked to evaluate and recommend options based on economic considerations. Important physical insight can be gained by using software such as Mathcad to identify the most important variables or factors and then offering an explanation for

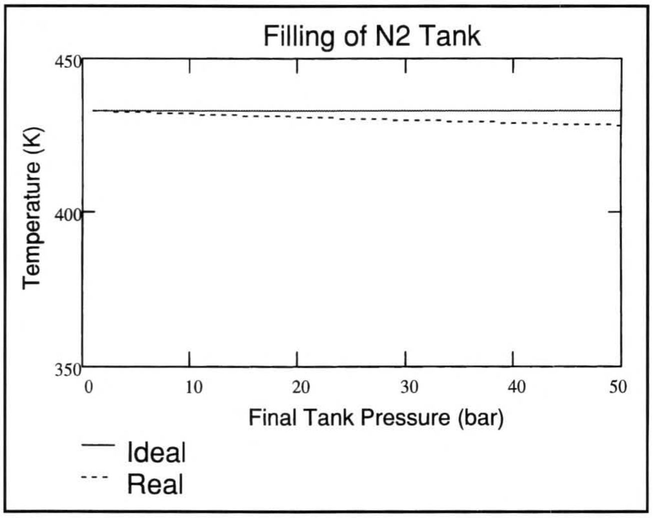

Figure 4. *Temperature of the tank as a function of the final pressure for N_2.*

their relative importance. Students might be asked to solve a problem and then use the software to explore an issue of their own choice related to that problem. These and other opportunities are made possible by the tool's capabilities.

Relationship to Learning Styles

We can use the tool's flexibility to teach to a variety of learning styles. Students have a variety of learning preferences or styles, and the needs of the individual learners are best met with a variety of learning activities.[3-5] Activities such as those described in the example problem can be used to help address different learning styles and to improve the learning of all students. For example, Mathcad provides an excellent opportunity for students to visualize information, to actively experiment with the concepts and ideas, to explore new ideas, and to solve realistic problems. As such, it represents another important addition to our instructional toolbox.

The following sections of the paper document our experience with the equation-solving package.

FACULTY PERSPECTIVE

The response of our faculty to the introduction of Mathcad into the curriculum varied from one person to another, but was generally positive. Individual responses were correlated with the level of awareness: awareness of the tool's features, awareness of students' capabilities with the tool, and awareness of how the tool can impact learning in and out of the classroom. Generally, the more familiar the faculty member was with the tool, the more positive the reaction. Our observations regarding the faculty have been divided into the following seven areas.

Faculty Involvement

Mathcad was initially introduced into the curriculum by a core group of two faculty members. Although the entire faculty voted in support of the program, there were no requirements for using Mathcad in specific courses other than the initial sophomore course. Consequently, only some of the faculty have learned the software and adapted their teaching to take advantage of the opportunities it provides. In fact, less than half (five out of twelve) of our faculty currently use the software, although some who have not used it themselves have required their students to use it in specific courses. The number of "users" appears to be growing as other faculty members have recently shown interest. We believe that more faculty will adopt the software as they become aware of the significant positive impact it can have on their courses and the value that students obtain from those courses.

Student's New Capabilities

Using Mathcad has enabled our students to efficiently solve a variety of engineering problems. Some faculty have been surprised by the new capabilities of our students. One faculty member teaching a junior-level class in our department commented that he didn't know exactly what we had changed in our sophomore class (where Mathcad is introduced), but "we are certainly doing something right!" He believes that the students understand concepts better and compute significantly better than previous classes. This same faculty member began using Mathcad because of the capabilities he saw in his students. A faculty member from another department found that our students were able to easily and quickly complete his traditional assignments. The students had asked his permission to use Mathcad on the assignments beforehand, and he had agreed. He was delighted and amazed at the ease with which they completed the work.

Math Skills

Some faculty members have sensed a decline in the math skills of some students, presumably due to their dependence on the software to do the math. They mention that students do not have the same "by hand" math skills possessed by previous groups of students. This is, in a real sense, both a practical and a philosophical issue. Are these math skills a means to an end, or do they have intrinsic worth to the students? This question is certainly not a new one, having been raised, for example, with regard to calculators. In fact, many "by hand" math skills once thought essential have been forgotten with the advent of the slide rule and the calculator. Similarly, the use of equation solvers may lead to another shift in the skills required of engineers and engineering students. It seems to us that the key issue is not the ability of students to manipulate equations, but their ability to solve engineering problems.

Exam Procedures

One issue of practical concern among the faculty has been the effect of Mathcad on exam performance. Exams have been influenced in several ways by the use of an equation solver. First, a couple of instructors have given exams that require students to use Mathcad. They have been given primarily as "take home" exams with a specified time limit. Additionally, the exam content has changed in some classes to focus more on problem definition and setup rather than on solution methods. Qualitative problems, similar to those discussed previously in conjunction with the Mathcad example, have also been used effectively on exams.

The exams in many of our undergraduate classes, however, remain unchanged. Also, for logistic reasons, most of our students have not had access to Mathcad during exams. In fact, use of the equation solver on exams has been largely restricted to a few upper-division courses. The unavailability of Mathcad has caused difficulties for a few students who felt it hindered their performance on exams. For example, they might develop a problem to the point of one or more equations and then state, "I could now use Mathcad to solve this problem." Such responses have raised a concern that the software may have a negative impact on students who have lost (or never developed) the ability to simplify problems, make approximations, or even solve relatively simple mathematical problems.

We view these concerns as a manifestation of the math skills issue discussed in the previous section where students have developed skills that differ from those expected by the instructor. *This mismatch between the students' skills and those expected by faculty can be avoided if faculty members are aware of the tools the students are using and if they clearly communicate their expectations to the students.* If we expect students to work a certain type of problem by hand (*e.g.*, on an exam), we should tell them so, encourage them to practice solving it that way, and reinforce our expectation by giving them problems of that type to solve.

Our need to explicitly communicate our expectations has increased as alternate methods for solving problems have been developed. As a general rule, students will solve problems in the way they deem most efficient (usually with the equation solver) unless they are required to do otherwise.

Impact on Course Content

Incorporation of an equation solver into our undergraduate curriculum has had, and continues to have, a significant impact on the content of several courses. For example, our separations course was recently restructured to take advantage of both Mathcad and a process simulator. We have also found that we spend much less time teaching numerical methods and solution procedures than was previously necessary, especially in courses that are computationally intensive.

Using an equation solver has also had significant impact on course content by providing the means for students to solve difficult, realistic engineering problems. The choice of problems is now less restricted by the means available for their solution, and this has allowed problems to be selected for their content and connection to real engineering rather than for their solvability.

Impact on Learning Concepts

Several faculty members have used Mathcad to help students learn concepts, with very positive results. It is their perception that the software has helped students to develop a better conceptual understanding of the material.

Other members of the faculty, however (particularly those who have not used the software), feel that the software has had an adverse effect on student learning. For example, one faculty member recently expressed a concern that students were losing touch with the physics behind problems. He expected students to use physical insights to make assumptions that simplified problems for solution on a calculator. Many of the students, however, simply solved complete sets of complex equations in Mathcad without thinking about the physics. In this case, the problems were designed to maximize learning when worked by hand and were therefore not ideally suited for advanced computational tools. Consequently, the educational value of the problems was short-circuited by the ability of the students to solve the complete set of equations without simplification.

This example illustrates the fact that faculty members should know what tools the students are using and should adjust instruction and/or requirements to maximize learning. In the above case, the professor could have required the students to work the problems by hand in order to achieve the desired results. Alternatively, the problems could have been restructured to take advantage of the available tools and still achieve (or exceed) the desired educational objectives. For example, students could have been required to calculate the magnitude of individual terms in the equations and to comment on their physical and numerical significance.

Group Assignments

There has been a movement in recent years toward more collaborative learning and teamwork. Consequently, we need to consider the effects on learning as we use computational tools in group assignments. We have observed, for example, that students in a group at a single computer do not derive equal benefit from an assignment. In particular, the individual actually at the keyboard appears to get more out of the exercise. The literature discusses creative ways around this problem.[e.g., 6] For example, each member of a group might be given instruction on a particular feature of the software and then be asked to teach that feature to their group. Additionally, the group might be asked to solve a complicated problem that requires the "skills" of all the group members to complete.

Summation

In summary, faculty who have used Mathcad have generally been pleased with the software and found it to be a valuable education tool. In spite of this, less than half of our faculty use Mathcad. It was also the perception of the faculty that a majority of the students used the tool, even when the teacher did not anticipate (or desire) its use. Some teacher and student frustration has been observed in courses taught as they had been in the past, with no modification of assignments or instruction to take advantage of Mathcad. This frustration can be avoided, however, by clearly communicating expectations to the students and/or adapting problems to take advantage of the educational possibilities that a math tool such as Mathcad makes available.

STUDENT FEEDBACK

A survey was conducted in order to evaluate the equation solver from the students' perspective. The survey consisted of ten questions, and we have chosen to discuss five of these (shown in Table 2). Three of the remaining five questions were actually subsets of the questions chosen for discussion; the responses to these questions have been grouped with the questions shown in Table 2. One of the last two questions was specific to our institution and was therefore not included. The last question was discarded because it was poorly phrased and did not yield any useful information. Responses were received from sophomores, juniors, and seniors. First-year students were not surveyed since Mathcad is not used as part of the curriculum in the first year.

Question #1: Overall Opinion • A combined total of just over a hundred responses from sophomore, juniors, and seniors was received for the question that asked students for their overall opinion of the Mathcad package. Of these, the responses from the seniors were overwhelmingly positive—in fact, none of the seniors responded negatively.

The response from the juniors was also very positive, with only about ten percent being negative. Several of the positive responses were also qualified with statements such as "I like it but I'm just not all that familiar with it," or "Great time-saving tool if you know how to use it." Responses from the sophomores were similar to those from the juniors.

It was evident from the responses that the seniors were more comfortable with the software package than either the juniors or sophomores. Incidentally, the positive opinions expressed by the students are strongly supported by the fact that they used the software in almost all of their courses, even when it was not required or expected by the instructor. In our experience, this has never been the case with FORTRAN programming.

Question #2: Benefits • Students noted several benefits in using Mathcad. The most frequently mentioned benefit was that using the software typically reduced the time required to solve a particular problem. Time savings were attributed to the package's ability to solve equations and to perform unit conversions. Students also noted that mistakes made early in the sequence of calculations could be easily fixed without having to "repunch" the numbers.

The students also recognized that Mathcad allowed them to solve problems that otherwise would not have been assigned. In addition, students noted that the software made it easy to see the equations and to follow the logic of the solution. Others mentioned that Mathcad allowed them to spend more time learning concepts and less time with tedious calculations. The graphing capability of the package was also noted as a benefit by students.

Question #3: Conceptual Understanding • The survey asked students to evaluate how the use of Mathcad to complete homework assignments affected their ability to understand the concepts presented in class. Most of the student responses to this question could be classified into three groups. Responses in the first group were from students who got lost in the solution procedure and felt that Mathcad actually had a negative influence on their conceptual understanding. Additional instruction would undoubtedly help these students. Some of the students who struggled were transfer students who did not have the same exposure and experience with Mathcad as students who began their studies in our department.

It was the opinion of the second group that Mathcad was merely a computational tool that did not have any effect, positive or negative, on their ability to understand concepts. The third and largest group felt that Mathcad enhanced their conceptual understanding by allowing them to focus on the concepts rather than on the math or mechanics of the solution and by providing them with tools to help increase their understanding.

TABLE 2
Sample Survey Questions

1. What is your overall opinion of Mathcad?
2. What are the benefits of using Mathcad?
3. The purpose of homework is to help you understand concepts. How has using Mathcad on homework affected your ability to understand the material presented in class or in the text?
4. Mathcad is typically not available on exams. How did this affect your performance on exams?
5. How can the Chemical Engineering Department improve the use of Mathcad in undergraduate education.

Student comments indicated that the software had a significant positive impact on their education. As far as overall distribution is concerned, just over half (42 of 83) of the students whose responses fit into one of these three groups felt that Mathcad was beneficial to their conceptual understanding (group 3).

Question #4: Influence on Exams • The survey also asked students to evaluate the impact that incorporation of an equation solver into the curriculum has had on their exam performance. Mathcad is not typically available for use on exams in our department so we expected this issue to be a sore spot with students. The response to this question was also divided. Some students felt that using Mathcad on homework assignments had a negative impact on their exam performance. In fact, several students referred to a dependency on Mathcad that weakened their math skills and altered their approach to problems, which was detrimental to good performance on exams. There were also students who considered it unfair not to allow use of the software on exams. In contrast, it was the opinion of a number of students that using Mathcad on homework had no substantial effect on their exam performance.

Finally, there was another group of students who thought the exams were actually easier because they had been able to solve more difficult, complicated problems as homework on Mathcad. These students felt they had a deeper understanding and a better command of the material than they would have had if they had not used the software.

Of the 76 responses that fit into one of these three groups, just over 40% thought that using the equation solver did not have a significant impact on exam performance. The remaining responses were split evenly between those who felt that Mathcad had either a positive or a negative impact on their exam performance. There was a substantial number of students (about 30) who provided responses that could not be classified. Most of them failed to address the question that asked them to evaluate the impact of the software on exam performance. For example, many of these students commented on whether or not they thought the equation solver should be used on exams, without evaluating the impact of the current implementation on their exam performance.

Question 5: Suggestions • Most students felt the department could improve the use of Mathcad by teaching the program earlier and/or better. Apparently many students perceive that Mathcad is difficult to learn, contrary to our expectations prior to implementation of the software. Students recommended that Mathcad be taught either in the freshman year or in the sophomore-level programming course that currently covers only FORTRAN. Other suggestions included integration of the software into more courses in the curriculum and making it available on exams. Additional tutorials and in-class examples using Mathcad were also suggested.

In response to student suggestions, our traditional FORTRAN programming class was expanded this past year to include parallel teaching of FORTRAN, spreadsheets, and Mathcad, with an emphasis on tool strengths for different types of problems. Toward the end of the semester, the students were asked to compare the strengths and weaknesses of the packages and to identify their preferences. Student preferences were: Mathcad, 64%; spreadsheets, 25%; and FORTRAN, 11%. Most students were perceptive enough to see the utility of all three programs for different applications. Many of them felt that seeing the problem in mathematical terms in Mathcad facilitated their understanding and solving of the problem. There was also a feeling that FORTRAN was out of date and that Mathcad is a more powerful and flexible tool than the others. The positive perceptions of these students toward Mathcad and the sense of ability to solve problems would be expected to enhance student learning.

SUMMARY AND CONCLUSIONS

This article examined the use of an equation solver, Mathcad, in the undergraduate chemical engineering curriculum. An example illustrated some of the capabilities of this tool and, more importantly, ways in which it can be used to enhance learning. As demonstrated by the example, equation-solving packages such as Mathcad are powerful and flexible tools that can be used to develop a variety of instructional activities designed to promote learning.

Students responded positively to the tool and used it in most of their classes, even when it was not required. Most students felt that using Mathcad enhanced their conceptual understanding of the material. Specifically, it allowed them to focus on the concepts rather than on the solution procedure and gave them a tool to "experiment" with the material. But other students struggled with the software and felt that it had a negative impact on their learning. Additional instruction and practice is needed to help these students. In general, students felt that Mathcad was difficult to learn at first and that formal instruction should be provided to beginning students.

Faculty who have used Mathcad have generally been pleased with the software; in spite of this, it is currently used by less than half of our faculty. Occasional frustration has been experienced in courses where no modification of assignments or instruction has been made to take advantage of Mathcad. These frustrations can be avoided by clearly communicating expectations to the students and/or adapting problems to take advantage of the educational possibilities that a math tool such as Mathcad makes available.

In conclusion, we have found that Mathcad can be used effectively by innovative teachers to promote learning, to deepen student understanding of concepts, and to provide experience with more realistic engineering problems. But it is not a panacea in this regard, and it can actually be detrimental to learning if used inappropriately. We have found that many students enjoy solving problems in Mathcad and therefore use it as a tool of choice, often in ways the faculty had not anticipated.

RECOMMENDATIONS

Based on our experience, we offer the following recommendations to departments considering implementation of Mathcad or some other similar package into their undergraduate curriculum:

1. *It is important that the faculty learn and use the software. Therefore, some method of training and encouraging the use of the software by faculty members should be implemented.*
2. *Students perceive the need for formal instruction on using the software. We recommend that the instruction be provided early, in the first or second year, and that at least a portion of a course should be dedicated to learning the software.*
3. *Implementation of such a package requires substantial numbers of adequately equipped computers. Such facilities should be available before implementing the software as a required part of the curriculum.*
4. *It is important that the software be used consistently throughout the curriculum in order for students to develop and maintain proficiency. We recommend that most, if not all, of the core courses actively incorporate the software. This will help students to be sufficiently comfortable with the software to go beyond the mechanics and use it as a learning tool.*
5. *Opportunities should be provided for faculty to share their experiences and ideas on using the software to promote learning. This could be part of a faculty meeting, a users' group, etc.*
6. *If possible, facilities should be provided so students can have access to the software during exams.*

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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 interns and coop assignments typify such experiences; however, reports of more unusual cases are also welcome. Description of 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, University of Texas, Austin, Texas 78712.

INTRODUCING GRADUATE STUDENTS TO THE INDUSTRIAL PERSPECTIVE

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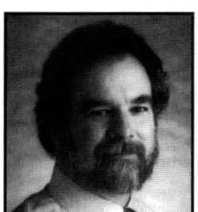
It has long been recognized that there is a wide gap between industrial practice and most university research and that this gap seems considerably pronounced in the field of chemical process control. In the extremes, academic researchers deal almost completely in applied mathematics, emphasizing proofs and theorems, while it is likely that a process control engineer has had no formal training in process control and his knowledge has come largely from on-the-job training. It is not surprising that there is almost no exchange of ideas between these two groups since they do not speak the same "language" and neither group, in general, appreciates the value of the other. The academic feels that the process control engineer does not understand the fundamentals of process control, which is generally true, while the process control engineer feels that the academician does not understand how to make process control work in an industrial setting, which is also accurate.



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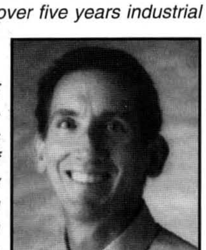

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The truth of the matter is that both the academic and the process control engineer could greatly benefit from the knowledge held by the other. Process control engineers could better perform their job if they had a fundamental understanding of the principles of process control. Likewise, the developments produced by academics would be more likely to have an impact on the practice of process control if they understood the key issues associated with the industrial implementation of process control.

In the Department of Chemical Engineering at Texas Tech University, the process control program is aimed at the industrially relevant study of advanced methods in chemical process control. Moreover, we strive to instill an industrial perspective of process control in our graduate students so they are prepared to perform industrially relevant research and upon graduation have the knowledge and skills to effectively perform in an industrial setting. This paper addresses approaches that we have found useful; these approaches involve a combination of classroom instruction, research activities, interaction with industrial control engineers, and summer internships.

ELEMENTS OF THE INDUSTRIAL PERSPECTIVE

The practice of process control is based on issues such as process knowledge, controller reliability and maintainability, and operator acceptance. A key distinguishing characteristic of chemical process control engineers is their reliance on process knowledge in the application of process control. This knowledge is based on understanding the operational objectives and constraints of a process unit and understanding how the units comprising the process are interconnected. With this knowledge, the control engineer can implement control approaches that are compatible with and even enhance the overall operational objectives of the process.

Teaching graduate students the fundamental principles of technology is obviously important, but putting these students in a position where they are prepared to function effectively in an industrial setting is also important. We have found that the industrial perspective can be effectively integrated into the on-campus program through the classroom, research group activities, and interactions with industrial representatives.

As a simple example, consider the problem of tuning a level controller. Without regard to the rest of the process, the level controller can be tuned to provide very tight level control. If, for example, the outflow from the level controller serves as the feed to a reactor, tight level control would likely be undesirable since it would result in sharp changes in the flow rate to the reactor. On the other hand, for certain cases tight level control may be required. Therefore, knowing how the controller fits into the rest of the process is a prerequisite to properly implementing control. In other words, overall process knowledge is important to insure that a cost effective solution to the control problem has been obtained.

Process knowledge is valuable as a consistency check for a process control application to ensure that the application will effectively fit into the overall process scheme. Researchers have recently shown that process understanding is very useful in designing control systems for complex units.[1]

Reliability is a major issue for industrial process control. A controller may perform well 99% of the time, but if it upsets the entire plant even 1% of the time, it is unacceptable. On-line factors of 95% are considered good, but it is not acceptable for a controller to create major upsets even occasionally.

The amount of effort required to keep a controller on-line with an acceptable service factor relates to the maintainability of the controller. Maintainability is a key issue with industrial process control. For example, a high-maintenance controller may function well as long as the control engineer who implemented it is maintaining it. But as soon as the original control engineer moves on to a new assignment, the controller will fall into disuse. Industrially, the KISS principle (Keep It Simple, Stupid!) is well established from a maintainability standpoint.

Finally, interpersonal skills have a tremendous effect on the effectiveness of a process control engineer. Being able to work effectively in a group setting is essential in today's chemical processing industry. There is no place where interpersonal skills are more important for a process control engineer than in dealing with operators. If an operator does not trust the ability of a process control engineer or does not like the engineer's attitude, the engineer's controller will not be used even when it works well. Control engineers who are effective are able to get the operators to assume "ownership" of the control project. This is usually done by soliciting information from the operators and listening to their input. Telling the operators what they should be doing or how they should do it is the fastest route to failure. Although we do not attempt to teach interpersonal skills directly, we do make sure that our students are aware of their importance, especially when dealing with operators.

APPROACH

There are a variety of ways to convey to graduate students the sense of an industrially relevant approach to process control. They include

- *Classroom and laboratory material and exercises*
- *Research projects*
- *Research group meetings*
- *Interactions with industrial process control engineers*
- *Summer internships in industry*

The classroom is an ideal venue for introducing the elements of the industrial process control point-of-view. At Texas Tech, we offer three graduate courses in process control: a first course, a course on model-based control, and a laboratory course. There are no specific lectures on the topic of industrial process control practice; instead, the topic is interspersed throughout each course. That is, as each topic and method is presented, a discussion of how it is addressed in industry is added. In addition, certain simulator software is used to give the student the feel of a dynamic process for controller implementation and tuning. To effectively integrate the industrial point-of-view into the classroom, it is essential to have instructors with significant industrial experience. This experience can come from full-time employment with industry or by working directly with industrial plant operations.

As the students perform their research, there are always a number of issues that come up in the pursuit of maintaining industrially relevant research. On many occasions, our weekly research group meetings involve discussions of research papers from other groups. During those times, a number of interesting issues arise that are related to industrial relevance.

One of the best ways to convey the industrial perspective is to promote direct interaction between the student and the industrial process control engineer. We have semiannual consortium meetings (discussed later) during which the leading control engineers from our member companies visit our campus. In addition, a number of our research projects require frequent input from industrial experts.

While the previous approaches have largely occurred on campus, the summer internship approach requires the student to join the company for a summer and to work as a control engineer in a plant. Obviously, for the students to be effective as summer interns, they must have been exposed to the elements of the industrial process control perspective on campus. The summer internship demonstrates first-hand the various elements of the industrial perspective, which greatly increases the student's understanding of these important issues. In addition, in several cases, a graduate student has gone on-site for periods of just one to two weeks to install control software (the result of their research projects).

CONSORTIUM

The Texas Tech Process Control and Optimization Consortium was established in 1992 as a mutually beneficial arrangement between industry and the Chemical Engineering Department. We currently have eleven industrial members representing the major sectors of the chemical processing industry: the leading refining companies, chemical companies, and control consulting companies.

The Consortium is an indispensable element in our effort to expose students to the industrial practice of process control. During the semiannual meetings, the industrial representatives of our member companies review and guide our advanced control research to keep it industrially relevant. In addition, they serve as a major source of research ideas and as a source of industrial data. During the fall Consortium meeting, graduate students present posters on their research and the industrial visitors have an opportunity to discuss the research approach and results directly with the students. The students are often inspired by the opportunity to interact with process control experts from these leading companies.

ESTABLISHING A SUMMER INTERNSHIP

The key to establishing a successful summer internship experience is ensuring that all parties involved benefit, *i.e.*, the student, the company, and the university. The first step is to establish an industrial contact who will sell the summer internship idea within the company. We have used our Consortium contacts and other professional contacts for this purpose.

Many companies have a summer internship program in place, but they are typically used for recruiting undergraduates. As a result, the industrial contact usually only has to convince a mid-level manager to use one of the allotted summer internship positions for a graduate student.

An advantage for the company is that with a graduate student they are more likely to have a summer intern who will actually accomplish something significant. Typically, undergraduate summer interns are not trusted with much responsibility. For example, an undergraduate is usually assigned to an engineer and given small tasks such as tracing utility lines or completing backlogged paperwork.

In order for graduate student summer interns to be successful, the company must be willing to give them enough responsibility so they can have a chance to make significant contributions during their three-month tenure. Before giving the student such responsibilities, the supervisor must have confidence that the student has the skills to be successful. Students are usually watched closely until they prove themselves.

It is best if at least a portion of the summer internship assignments directly relate to the student's university research. This is not always possible, but it is certainly desirable. It is usually easier to establish a summer internship for a graduate student if the student is a U.S. citizen.

The advantages to each of the parties involved for the summer internship program described above are

The Company • *The company is exposed to a highly qualified potential employee and to technology that it may not have.*

The Students • *Students are exposed to industry and industrial operations directly related to their research area.*

The University • *Projects of this sort enhance the university's interaction with industry, providing industrial results for control approaches, and in certain cases, industrial data on processes of interest. In addition, working directly with industry can lead to the identification of fundamental problems that can be assimilated into the university's research program.*

SUMMER INTERNSHIP EXPERIENCES

► *Student A*

Student A was an undergraduate who joined our graduate program after his graduation in the fall semester. During the spring semester we made arrangements for a two-summer internship for Student A. In addition, he took our first process control graduate course in the spring semester. The chemical company understood that his master's research project involved using neural networks for distillation control and that he would spend a portion of his time with them implementing the controller on one of their columns.

In discussions with supervisors from the chemical plant, the decision was made that the student would spend the first summer identifying the test column, closing material and energy balances around the column, bench-marking a steady-state simulator on the column, tuning the flow and level controllers on the column, and evaluating the on-line product analyzers. The first summer went as planned, with Student A spending approximately 20% of his time on the tasks relating to his control project and the remainder of his time on various plant projects (controller tuning, trouble-shooting, etc.). The student required about one month to become comfortable with the company's distributed control system.

The company was pleased with the student's performance since he was handling the typical responsibilities of a process control engineer for most of the summer. During the following school year, Student A took classes and worked with one of our PhD candidates on developing and testing the neural network controller.

Student A returned to the chemical plant for the second summer and installed and tested the neural network controller. During the second summer the student spent approximately 50% of his time on his control project. The controller used a steady-state neural-network model of the column combined with a simple linear-dynamic model. The industrial column exhibited much more complex dynamic behavior; therefore, even though the neural network controller understood the steady-state nonlinearity of the process, the complex dynamics of the industrial column undermined the effectiveness of the controller.

Although this control project did not result in a successful industrial controller, the student did identify a fundamental problem with the way that we were applying neural networks for control. As a result, we are currently studying neural network controllers that can handle highly complex dynamics behavior.

It is noteworthy to point out that the portion of the plant where Student A was doing most of his work had some of the oldest operators in the plant. In fact, this group of operators was well known for being difficult to work with. Through patient efforts, however, Student A was able to build a positive relationship with the operators so that by the second summer they were doing all they could to help him with his control project.

Finally, it should also be pointed out that upon graduation with his master's degree, Student A took a process control position with the same chemical company where he had done his summer internship.

► ***Student B***

One of the industrial representatives from our Consortium invited one of the authors (JBR) to attend a meeting on developing a company-wide approach for controlling C_3 splitters (propylene-propane separation). Since Student B's PhD research involved C_3 splitters, he also went to the meeting. We both made presentations on our research to the group and participated in the discussions that followed. An approach for controlling all the company's C_3 splitters was developed and endorsed by the membership of the committee.

Before we left, I proposed to the chairman of this committee that Student B be hired by the company for a summer internship so he could demonstrate the proposed control approach in their plant. About six weeks later, after a couple of follow-up calls, the student received an offer for a summer job with the company.

When Student B joined the company for his summer employment, he was assigned to an ethylene plant that contained a C_3 splitter. During the summer, he served as a control engineer for this ethylene plant and was able to implement the new control approach on the C_3 splitter. The new controller was successfully commissioned and then turned over to operations. The new controller remains in service while providing enhanced propylene recovery and reduced variability in the propylene product.

In addition, Student B worked with the temperature controls for the ethylene furnaces. His efforts resulted in reduced outages due to furnace coking. The company determined that the benefits of the C_3 splitter and ethylene furnace work is saving them in excess of one million dollars per year. Once again, a major reason for the student's successful summer internship was the positive relationship that he developed with the operators. The company offered the student employment for the following summer.

CONCLUSIONS

Teaching graduate students the fundamental principles of technology is obviously important, but putting these students in a position where they are prepared to function effectively in an industrial setting is also important. We have found that the industrial perspective can be effectively integrated into the on-campus program through the classroom, research group activities, and interactions with industrial representatives. A summer internship experience for our graduate students preceded by the on-campus preparations provides students with a comprehensive preparation for working in industry. Moreover, when the students return to the university from an internship experience, they typically become disciples of the industrial perspective and greatly facilitate the transfer and acceptance of the principles of industrial practice.

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AN EXPERIMENT TO CHARACTERIZE A CONSOLIDATING PACKED BED

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Packed beds are much used as contactors for interphase mass transfer and chemical reaction. An interesting example involves their use in the biofiltration[1] of air streams laden with volatile organic compounds (VOC). In this instance, the bed may consist of naturally occurring materials such as soil, heather, peat, or compost. The resident (or seeded) micro-organisms then digest the VOC in the incoming stream. With natural packing materials, however, the bed can collapse in time, leading to increased pressure drop and higher operating costs etc. In this short article we will describe an inexpensive modification to a standard undergraduate laboratory experiment that studies such consolidating behavior.

THEORY

The pressure drop in fixed beds can be predicted using the well-known Kozeny[2,3] equation for low gas flowrates:

$$\Delta p = 5a^2(1-\varepsilon)^2 \mu h v/\varepsilon^3 \tag{1}$$

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where the symbols are defined in the nomenclature. As these natural beds tend to collapse and compress, so the height, h, voidage, ε, and specific surface, a, change from the original values, h_0, ε_0, a_0, and hence the bed pressure drop increases.

If the structure of the bed is assumed not to alter, then

$$\varepsilon = \frac{hA - (1-\varepsilon_0)h_0 A}{hA} = 1 - \frac{(1-\varepsilon_0)h_0}{h} \tag{2}$$

$$a = \frac{a_0 h_0}{h} \tag{3}$$

Putting these back into Eq. (1), we find

$$\Delta p = \frac{5a_0^2 h_0^4 (1-\varepsilon_0)^2 \mu v}{\{h-(1-\varepsilon_0)h_0\}^3} \tag{4}$$

or

$$\Delta p = \frac{kv}{(h-G)^3} \tag{5}$$

where

$$k = 5a_0^2 h_0^4 (1-\varepsilon_0)^2 \mu \tag{6}$$

and

$$G = (1-\varepsilon_0)h_0 \tag{7}$$

Thus, for Eq. (5) we would predict an inverse cubic relationship between pressure drop and bed height for a given bed velocity. So a small change in bed height can have a profound effect on Δp.

Rearranging Eq. (5), we have

$$\left(\frac{v}{\Delta p}\right)^{0.333} = k^{-0.333} h - G k^{-0.333} \tag{8}$$

So, a plot of $(v/\Delta p)^{0.333}$ versus h will yield a straight line whose slope is $k^{-0.333}$ and the intercept is $Gk^{-0.333}$. From the intercept, we find G and then ε_0 from Eq. (7). Finally, Eq. (6) leads directly to a_0.

We can extend the analysis by calculating the mean equiva-

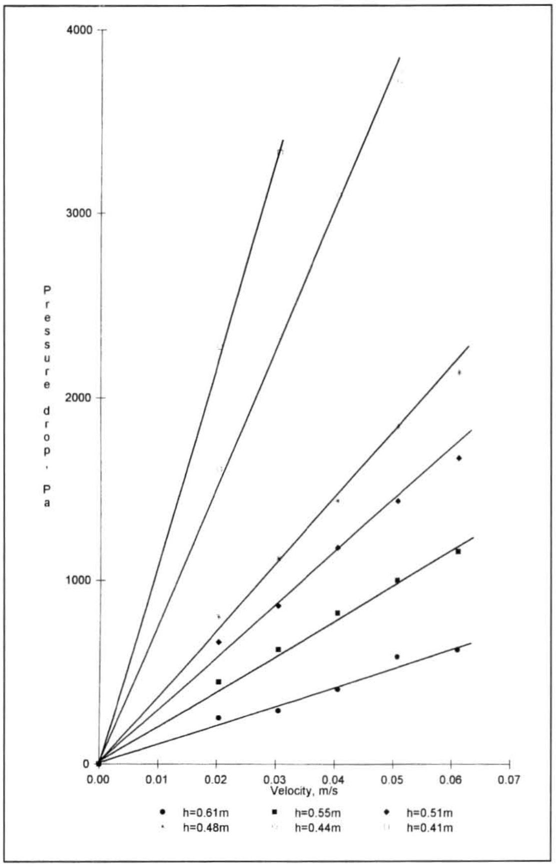

Figure 1. *Graph of pressure drop versus velocity for various bed heights.*

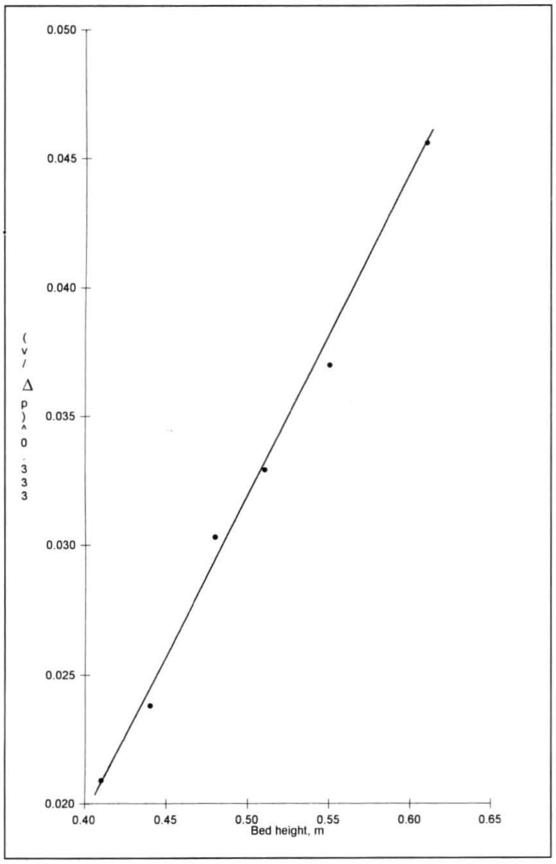

Figure 2. *Graph of (velocity per pressure drop)$^{0.333}$ versus bed height.*

lent particle diameter

$$D_p = \frac{6(1-\varepsilon)}{a} \tag{9}$$

and can also check to see if the Reynold's number is in the right range.[3]

EXPERIMENTAL

We used an existing 6-inch diameter glass column, complete with manometer and rotameter, which is usually used as a sand-air fluidized bed. The natural packing material was a commercial peat-moss-based potting soil purchased from a local plant nursery. An original packed height of some 0.61m gave reasonable results. The pressure drop-flowrate curve for the empty vessel was determined, then the column was filled with the compost, and the measurements were repeated. The contents were gently compressed by hand and the net pressure drops were again found. Some five compressions were applied, leading to Figure 1.

The gradients from Figure 1 allow us to calculate $(v/\Delta p)$, which when raised to the one-third power, can be plotted against the bed height, h, to give Figure 2, which is an excellent straight line. Finally, we compute the original voidage and specific surface to be 0.6 and 17000m^{-1}, respectively

CONCLUSIONS

Existing equipment can be used with unconventional packings to measure the effect of bed consolidation. The experiment gives the student an unconventional use of the Kozeny equation, together with an interesting opportunity to linearize Eq. (5). It is also an extremely inexpensive addition to the undergraduate lab.

NOMENCLATURE

a	specific surface area (variable)
A	bed cross-sectional area
D_p	mean particle size
G	constant defined by Eq. (7)
h	bed height (variable)
k	constant defined by Eq. (6)
v	superficial bed velocity
Δp	pressure drop
ε	voidage (variable)
μ	gas viscosity

Subscripts

0	indicates original value before compressions

ACKNOWLEDGMENT

This work is part of an EU-funded project on the purification of waste gases.

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USE OF SPREADSHEETS
in Introductory Statistics and Probability

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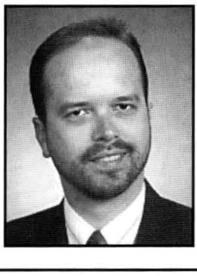
Statistical software packages such as Minitab, Statistica, or SAS are extensively used by engineers to provide descriptive statistics (mean, median, coefficient of variation, etc.) for a data set, to generate values to the various probability distributions, and to perform a linear regression or a Student's t-test. The use of these programs may be taught in various undergraduate chemical engineering courses, but their use in the chemical engineering curriculum is not standardized and there is no consensus on which, if any, of the programs is preferable.

Spreadsheets such as Microsoft Excel, Corel Quattro Pro, and Lotus 1-2-3 provide a convenient and standardized way to teach the fundamentals of statistical analysis and probability to undergraduate students. In addition to being able to execute the statistical analyses listed above, they can be used for everything from calculating numbers of combinations to constructing control charts for average ($\bar{x}$ charts). The standard user interface also reduces the time required to learn each new concept, and documents and features are virtually identical across not only platforms (IBM to Macintosh), but also across software vendors (Microsoft to Lotus).

The concept of spreadsheets in the classroom is by no means new. There are some very excellent examples of using spreadsheets for everything from general applications for first-year chemistry labs,[1] or teaching regression analysis,[2] to very elaborate applications such as calculation of X-ray diffraction patterns from crystallographic information,[3] but little information exists on how to bring spreadsheets into an introductory course in statistics and probability.



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Chemical engineering students at Tulane University are introduced to a variety of spreadsheet applications in their freshman course on the chemical engineering profession. The skills they develop there are used to a greater extent in the first semester of their sophomore year in a "Chemical Engineering Design I" course. This course, taught concurrently with stoichiometry, introduces the students to statistical analysis, probability, reliability, quality control, and engineering economics.

The book *Statistics and Probability for Scientists and Engineers*[4] by Mendenhall and Sincich is used in the course. It provides numerous example problems from all engineering disciplines, and although a software package is supplied with the textbook, we have opted to solve the problems using spreadsheets. This article describes how the spreadsheet can be used in a course such as this and presents example problems and solutions to illustrate the ease with which this can be accomplished.

We are fortunate to have an electronic classroom in our department that allows us to work example problems in class. With the use of a projection system that displays the screen from a laptop computer, the instructor can "walk through" the example while students perform the same functions at their own computer. The examples shown here are from Mendenhall and Sincich (hereafter referred to as MS) unless indicated otherwise, and all have been used either in the electronic classroom or assigned as homework problems. All spreadsheet solutions are from Microsoft Excel, version 7.0 for Windows 95.

DESCRIPTIVE STATISTICS

College sophomores should certainly be able to calculate a mean, median, and mode from a data set, but it's always best to begin at the beginning. Additionally, a simple problem that the students can easily check by hand helps introduce them to the use of a spreadsheet if they are not yet familiar with it.

Example 1 is such a problem, complete with the Excel solution. Descriptive statistics are generated by selecting the data set (in this case, A2..A51) and choosing "Descriptive Statistics" in the Analysis Toolpak under the "Tools" menu. (The Analysis Toolpak is included with Excel, but is not a default item and must be installed using the "Add Ins..." command under the "Tools" menu.) The confidence level for these calculations can be specified. This example illustrates not only how to generate the desired analysis, but also how a great deal of time can be saved with large data sets. In this example, even more time is saved because the data set is available on the textbook diskette in ASCII text format, so it can be readily imported into the spreadsheet. For most example problems, the data set is placed on a server that the students can retrieve using File Transfer Protocol (FTP). This saves a substantial amount of class time.

Close inspection of the data set in Example 1 points out one of the limitations of the spreadsheet; namely, that only one mode is specified for multimodal data sets. The example data set contains two modes: 128 and 131 (three values each). The spreadsheet displays the first mode it finds, in this case 128. This example also points out a "quirk" of Excel—data can be analyzed only in columns or rows. That is, con-

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Example 1 Descriptive Statistics (MS 2.48)

Industrial engineers periodically conduct "work measurement" analyses to determine the time required to produce a single unit of output. At a large processing plant, the number of total worker-hours required per day to perform a certain task was recorded for 50 days. Compute the mean, median, and mode of the data set. Find the range, variance, and standard deviation of the data set.

	A	B	C
1	Worker-hours	*Descriptive Statistics*	
2	128		
3	113	Mean	117.82
4	146	Standard Error	2.122896
5	124	Median	117.5
6	100	Mode	128
7	119	Standard Deviation	15.01114
8	109	Sample Variance	225.3343
9	128	Kurtosis	-0.69123
10	131	Skewness	0.00906
11	112	Range	62
12	95	Minimum	88
13	124	Maximum	150
14	103	Sum	5891
15	133	Count	50
16	111	Confidence Level(95.0%)	4.266116
17	97		
18	132		
19	135		
20	131		
21	150		
22	124		
23	97		
24	114		
25	88		
26	117		
27	128		
28	138		
29	109		
30	118		
31	122		
32	142		
33	133		
34	100		
35	116		
36	97		
37	98		
38	136		
39	111		
40	98		
41	116		
42	108		
43	120		
44	131		
45	112		
46	92		
47	120		
48	112		
49	113		
50	138		
51	122		

tiguous columns cannot be analyzed as one set, even if the data in them belong together. Quattro Pro, on the other hand, does allow for such analysis.

Histograms are also readily generated in Excel. In addition to the input data, the number and size of bins must be specified (see column B in Example 2, a modified form of MS problem 2.18). The histogram function generates the absolute frequency for each bin, as shown in columns C and D. A histogram is then generated automatically, but in this problem, a relative frequency diagram is requested. Some user intervention is required here (this is a good thing since it makes the students think about what they are doing). Relative frequency is calculated in column E by using the data from column D and the formula shown. Each of these calculations requires entering one formula only, which can then be copied to the remaining cells. Formula cell references automatically adjust, except for those "locked" with dollar signs ($). A relative frequency distribution chart can then be generated using Excel's graphing tool.

PROBABILITY

The fundamentals of probability are usually introduced using examples with decks of cards and rolls of the dice. Spreadsheets aren't a great deal of help here. They can be used at the next level, however—particularly for simple things like permutations and combinations. The number of permutations is the number of ways to put y elements in y distinct positions from a single net of n different elements, or

$$\text{\# of permutations} = \frac{n!}{(n-y)!} \tag{1}$$

The number of combinations of n distinct items taken y at a time is given by the binomial coefficient

$$\binom{n}{y} = \frac{n!}{y!(n-y)!} \tag{2}$$

Neither of these relationships is very complex, and either can be calculated fairly easily by simply typing the formula into a spreadsheet cell. All spreadsheets are able to calculate factorials, in most cases with the FACT function. Example 3 illustrates the use of built-in functions to accomplish the same task more easily, using the PERMUT and COMBIN functions of Excel. Two arguments are specified for each function: the total number of values to choose from (n, number) and the number of values taken at a time (y, number_chosen).

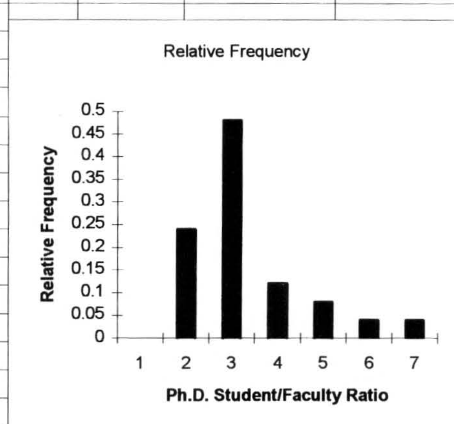
PROBABILITY DISTRIBUTIONS

Probability distributions are a vital component in the introduction of reliability analysis. There are many forms of distributions, though, and students often get hung up trying

Example 2: Relative Frequency Histograms (MS 2.18)

Each year, U.S. News and World Report surveys America's best graduate schools. The 1993 survey included a list of the top 25 graduate programs of engineering. The accompanying data include each school's overall score (based on a weighted average of rankings in five areas), total enrollment, dollar amount awarded for research, doctoral student-to-faculty ratio, and acceptance rate. Construct a relative frequency diagram for the doctoral student/faculty ratio and interpret the results.

	A	B	C	D	E
1	Doctoral Student/Faculty Ratio	Bin	*Bin*	*Frequency*	*Relative Frequency*
2	2.52	1	1	0	=D2/$D$10
3	5.24	2	2	6	=D3/$D$10
4	2.82	3	3	12	=D4/$D$10
5	4.66	4	4	3	=D5/$D$10
6	2.36	5	5	2	=D6/$D$10
7	2.63	6	6	1	=D7/$D$10
8	3.27	7	7	1	=D8/$D$10
9	3.3		More	0	=D9/$D$10
10	2.32		Sum	=SUM(D2:D9)	=SUM(E2:E9)
11	2.23				
12	3.7				
13	2.51				
14	1.75				
15	2.04				
16	1.96				
17	2.38				
18	4.88				
19	6.35				
20	2.41				
21	2.46				
22	1.27				
23	1.42				
24	2.7				
25	1.85				
26	1.75				
27					
28					



to memorize the formulas for five or six distributions rather than concentrating on the appropriate applications for each distribution. While a spreadsheet cannot totally eliminate this problem, it can reduce the anxiety of distributions a bit, and certainly eliminates the need for distribution tables, which can vary in terminology from book to book.

Most spreadsheets contain a number of distributions. Excel includes the binomial and Poisson distributions, among others. Generating values from these distributions is a simple matter of using a function with anywhere from two to four arguments. An example of the binomial distribution is given in Example 4, where the binomial distribution is given by

$$P(y) = \left(\frac{n!}{y!(n-y)!} \right) p^y (1-p)^{(n-y)} \tag{3}$$

Here P(y) is the probability that a known outcome occurs y times out of n trials, and p is the probability that an isolated event of the given outcome will occur. The example problem asks not only for the probability of 1-15 valves failing, which is just the binomial distribution evaluated at a single value of y in each case, but also for the cumulative probability of failure for 0-5 valves. First, values for n and p are entered in cells A2 and B2, respectively. For the first part of the question, all possible values of y are entered in cells C2..C17. This is easily accomplished by placing the value of zero in cell C2 and using the "Fill" command in the "Edit" pull-down menu to fill in the rest of the series up to 15. The values of the binomial distribution for each value of y are generated in column D using the BINOMDIST function. (Normally, this would be displayed as a number, but for instructional purposes, both the formula in column D and the number it returns in column E are shown.) The BINOMDIST function re-

Example 3: Probability Distributions (MS 3.40 and 3.42)

A security alarm system is activated and deactivated by correctly entering the appropriate three-digit numerical code in the proper sequence on a digital panel. Compute the total number of possible code combinations if no digit may be used twice.

	A	B	C
1	**Function Description**	**Formula**	**Numerical Result**
2	PERMUT(number, number_chosen)	=PERMUT(10,3)	720

Suppose you need to replace 5 gaskets in a nuclear-powered device. If you have a box of 20 gaskets from which to make the selection, how many different choices are possible; i.e., how many different samples of 5 gaskets can be selected from the 20?

	A	B	C
4	**Function Description**	**Formula**	**Numerical Result**
5	COMBIN(number, number_chosen)	=COMBIN(20,5)	15504

Example 4: Binomial Distribution

Consider a sample of 15 valves. The probability that a given valve fails is 0.18. a) Calculate the probability of failure of 0-15 valves. b) Calculate the probability that <u>at most</u> five valves will fail.

	A	B	C	D	E	F	G
1	n, total number of valves	p, probability of single valve failing	y	P.D.F., P(y) (formula)	P.D.F. (values)	C.D.F. (formula)	C.D.F. (values)
2	15	0.18	0	=BINOMDIST(C2,$A$2,$B$2,FALSE)	0.05095	=BINOMDIST(C2,$A$2,$B$2,TRUE)	0.05095
3			1	=BINOMDIST(C3,$A$2,$B$2,FALSE)	0.16778	=BINOMDIST(C3,$A$2,$B$2,TRUE)	0.21874
4			2	=BINOMDIST(C4,$A$2,$B$2,FALSE)	0.25781	=BINOMDIST(C4,$A$2,$B$2,TRUE)	0.47656
5			3	=BINOMDIST(C5,$A$2,$B$2,FALSE)	0.24524	=BINOMDIST(C5,$A$2,$B$2,TRUE)	0.72180
6			4	=BINOMDIST(C6,$A$2,$B$2,FALSE)	0.16150	=BINOMDIST(C6,$A$2,$B$2,TRUE)	0.88330
7			5	=BINOMDIST(C7,$A$2,$B$2,FALSE)	0.07799	**=BINOMDIST(C7,$A$2,$B$2,TRUE)**	**0.96129**
8			6	=BINOMDIST(C8,$A$2,$B$2,FALSE)	0.02853	=BINOMDIST(C8,$A$2,$B$2,TRUE)	0.98983
9			7	=BINOMDIST(C9,$A$2,$B$2,FALSE)	0.00805	=BINOMDIST(C9,$A$2,$B$2,TRUE)	0.99788
10			8	=BINOMDIST(C10,$A$2,$B$2,FALSE)	0.00176	=BINOMDIST(C10,$A$2,$B$2,TRUE)	0.99965
11			9	=BINOMDIST(C11,$A$2,$B$2,FALSE)	0.00030	=BINOMDIST(C11,$A$2,$B$2,TRUE)	0.99995
12			10	=BINOMDIST(C12,$A$2,$B$2,FALSE)	0.00003	=BINOMDIST(C12,$A$2,$B$2,TRUE)	0.99999
13			11	=BINOMDIST(C13,$A$2,$B$2,FALSE)	0.00000	=BINOMDIST(C13,$A$2,$B$2,TRUE)	0.99999
14			12	=BINOMDIST(C14,$A$2,$B$2,FALSE)	0.00000	=BINOMDIST(C14,$A$2,$B$2,TRUE)	0.99999
15			13	=BINOMDIST(C15,$A$2,$B$2,FALSE)	0.00000	=BINOMDIST(C15,$A$2,$B$2,TRUE)	0.99999
16			14	=BINOMDIST(C16,$A$2,$B$2,FALSE)	0.00000	=BINOMDIST(C16,$A$2,$B$2,TRUE)	0.99999
17			15	=BINOMDIST(C17,$A$2,$B$2,FALSE)	0.00000	=BINOMDIST(C17,$A$2,$B$2,TRUE)	1

quires four arguments, the first three of which are the values of y, n, and p, in that order, all of which can be referenced to their respective cells. Note that the value of y changes as it should, whereas n and p are fixed by the problem statement. The final argument is a "switch" that allows the cumulative distribution to be calculated. This argument is set to FALSE in column D so that singular values of the distribution can be calculated. Column E generates the answers to part a) of the statement. The cumulative distribution function is exactly what is required to solve part b) of Example 4, so the switch is set to TRUE in column F. Again, values returned by this function are shown in the following column, and the answer to the problem is shown in cell G7; the cumulative probability of zero through five valves failing is 0.961.

HYPOTHESIS TESTING

There are a number of useful null-hypothesis tests, including the Chi-square test, F-test, and Student's t-test, all three of which are covered in Design I. Most spreadsheets are capable of performing at least some of these tests, although much more interpretation of the results is required than for the previous examples. In particular, the final decision as to whether or not the null hypothesis has been verified is left up to the student.

An F-test is used here as an illustration of how null-hypothesis tests can be performed, at least in part, using a spreadsheet. Recall that an F-test compares the variances, s_i^2, of two data sets

$$F = \frac{s_1^2}{s_2^2} \tag{4}$$

The null-hypothesis is that the two variances are statistically equivalent at some specified confidence level, typically 95%. The value of F is calculated using Eq. (4), and compared with a value in a table at the specified confidence level and appropriate degrees of freedom for each data set. If the F-value in the table is greater than the calculated value of F, the null hypothesis is substantiated, and the two variances can be considered statistically equivalent.

A well-known problem from Peters and Timmerhaus[5] is used here as an illustration of an F-test applied to a chemical engineering problem and how the results from the spreadsheet manipulation must be interpreted (see Example 5). The data are entered in cells A2..A8, and B2..B6 for the revised and current analytical methods, respectively. The "F-test Two Sample for Variances" function is selected from the "Data Analysis..." option under the "Tools" menu in Excel. The cell indexes for both data sets must be provided, as must the cell assignment for the output, and the value of α, which determines the confidence level. The resulting table is shown in cells A12..C19. The calculated value of F appears in cell B17 and is the ratio of cells B14 to C14. In this instance, no formulae are present in the tables—only numerical values appear at the end of the analysis. The tabulated value of F for the specified value of α=0.5 is given in cell B19. The final step is left to the student. In this case, the calculated value of F is greater than the tabulated value, indicating that the two analytical procedures may not be equivalent. Once again, the spreadsheet is helpful, but the user must have a knowledge of the underlying principles to correctly interpret the results.

ANALYSIS OF VARIANCE

Analysis of variance (ANOVA) is a statistical analysis tool that provides a smooth transition from F-tests into a

Example 5: *F*-test (Peters and Timmerhaus Chpt. 17, Example 10)

A simplified analytical procedure is proposed for a routine laboratory test. It is necessary to determine not only whether the new procedure gives the same results as the old, i.e., whether the means of a duplicate set are the same, but also whether the precision of the new test is as good as the current test.

	A	B	C
1	**Revised Method**	**Current Method**	
2	79.2	79.7	
3	79.7	79.5	
4	79.5	79.6	
5	79.4	79.5	
6	80	79.7	
7	79.6		
8	79.8		
9			
10	F-Test Two-Sample for Variances		
11			
12		*Variable 1*	*Variable 2*
13	Mean	79.6	79.6
14	Variance	0.07	0.01
15	Observations	7	5
16	df	6	4
17	F	6.999999998	
18	P(F<=f) one-tail	0.040280016	
19	F Critical one-tail	6.163134003	

discussion of linear regression. Recall that an ANOVA table compares N similar data points from k different treatments by essentially performing an F-test on the variance between treatments (mean square treatment, or MST) and the variance within the treatments (mean square error, or MSE). The MST and MSE are calculated from the sum of squares (SST and SSE, respectively) and corresponding degrees of freedom for each type of error, as shown in Table 1.

TABLE 1
Analysis of Variance Table

Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Treatment	$\sum_{i=1}^{k} n_i(\bar{Y}_i-\bar{Y})^2$	k-1	SST/k-1	MST/MSE
Error	$\sum_{i=1}^{k}\sum_{j=1}^{n_i} n_i(Y_{ij}-\bar{Y}_i)^2$	N-k	SSE/N-k	-
Total	$\sum_{i=1}^{k}\sum_{j=1}^{n_i} n_i(Y_{ij}-\bar{Y})^2$	N-1	-	-

Example 6: Analysis of Variance (MS 14.27)

An excessive amount of ozone in the air is indicative of air pollution. Six air samples were collected from each of four locations in the industrial Midwest and measured for their content of ozone. Construct an analysis of variance table for the data. Do the data provide sufficient evidence to indicate differences in the mean ozone content among the four locations? Use α = 0.05.

	A	B	C	D	E	F	G
1		Location					
2	1	2	3	4			
3	0.08	0.15	0.13	0.05			
4	0.1	0.09	0.1	0.11			
5	0.09	0.11	0.15	0.07			
6	0.07	0.1	0.09	0.09			
7	0.09	0.08	0.09	0.11			
8	0.06	0.13	0.17	0.08			
9							
10	ANOVA						
11	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
12	Between Groups	0.006779	3	0.00226	3.498925	0.034527	3.098393
13	Within Groups	0.012917	20	0.000646			
14							
15	Total	0.019696	23				

Example 6 shows how an ANOVA table can be generated on the spreadsheet. In this case, there are k=4 treatments (locations, i=1 through 4), each with six data points (j=1 through 6), for a total of N=24 data points. By selecting the "ANOVA:Single Factor" function in the "Data Analysis..." option of the "Tools" pull-down menu, the input range can be specified, which in this example is A3..D8. The data is this case are grouped by columns, and this radio button must be selected on the menu. Once again, the desired confidence level can be specified, here as α=0.05, and the location for the resulting ANOVA table specified in the "Output Range" box. The ANOVA table appears in cells A10..G15. Additionally, this table not only shows the calculated F-value, but also the critical F-value for the specified degrees of freedom and confidence level. This makes comparison of the two F-values particularly easy for the student, who must once again arrive at the final evaluation. In this case, there is sufficient evidence to suggest that the ozone contents differ statistically for the different locations.

CONTROL CHARTS

The final example of spreadsheets in Design I deals with quality control. In the chemical process industry, this usually means control charts. Control charts for average ($\bar{x}$-chart), range (R-chart), proportion defects (p-charts), and defects per unit (c-charts) are introduced in this course. Example 7 shows how Excel can be used to generate a p-chart. In this case, the formulae for the lower control limit (LCL), upper control limit (UCL), and centerline must be specified as

$$LCL=\bar{p}-3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \qquad (5)$$

$$UCL=\bar{p}+3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \qquad (6)$$

Here

$\bar{p}$ = centerline = average fraction defectives = $(d_1 + d_2 + ...d_k)/nk$, cell C24

n = sample size, cell B2

k = number of sample periods.

There is nothing particularly involved about this application, but it does allow the introduction of IF/THEN-type statements into spreadsheet calculations. In this case, the calculated LCL may have a negative value, in which case it must be replaced by zero. Cell C27 shows how the IF statement can be used to compare the calculated LCL to zero and place the appropriate value in F3. The LCL is copied down column F (in this case it is zero), as are the UCL and centerline values down columns D and E, respectively, to facilitate plotting. The p-chart is generated by plotting the data in column B (shown as triangles), UCL, LCL, and centerline vs. the sample ID in column A. The resulting plot is shown at the bottom of the spreadsheet in Example 7, and the process appears to be in control. Time allowing, this example also provides an excellent opportunity to introduce the concept of spreadsheet macro commands that can automate the production of $\bar{x}$-charts every time a new set of data is generated.

Example 7: Control Chart (MS 16.44)

High-level computer technology has developed bit-sized microprocessors for use in operating industrial "robots". To monitor the fraction of defective microprocessors produced by a manufacturing process, 50 microprocessors are sampled each hour. The results for 20 hours of sampling are provided. Construct a control chart for the proportion of defective microprocessors. Locate the center line and upper and lower control limits on the chart. Does the process appear to be in control?

	A	B	C	D	E	F
1	n	50				
2	Sample	Number of Defectives	Fraction Defective	UCL	Centerline	LCL
3	1	5	=B3/$B$1	=$C$25	=$C$24	=$C$27
4	2	6	=B4/$B$1	=$C$25	=$C$24	=$C$27
5	3	4	=B5/$B$1	=$C$25	=$C$24	=$C$27
6	4	7	=B6/$B$1	=$C$25	=$C$24	=$C$27
7	5	1	=B7/$B$1	=$C$25	=$C$24	=$C$27
8	6	3	=B8/$B$1	=$C$25	=$C$24	=$C$27
9	7	6	=B9/$B$1	=$C$25	=$C$24	=$C$27
10	8	5	=B10/$B$1	=$C$25	=$C$24	=$C$27
11	9	4	=B11/$B$1	=$C$25	=$C$24	=$C$27
12	10	5	=B12/$B$1	=$C$25	=$C$24	=$C$27
13	11	8	=B13/$B$1	=$C$25	=$C$24	=$C$27
14	12	3	=B14/$B$1	=$C$25	=$C$24	=$C$27
15	13	2	=B15/$B$1	=$C$25	=$C$24	=$C$27
16	14	1	=B16/$B$1	=$C$25	=$C$24	=$C$27
17	15	0	=B17/$B$1	=$C$25	=$C$24	=$C$27
18	16	1	=B18/$B$1	=$C$25	=$C$24	=$C$27
19	17	1	=B19/$B$1	=$C$25	=$C$24	=$C$27
20	18	2	=B20/$B$1	=$C$25	=$C$24	=$C$27
21	19	3	=B21/$B$1	=$C$25	=$C$24	=$C$27
22	20	3	=B22/$B$1	=$C$25	=$C$24	=$C$27
23						
24		Centerline	=AVERAGE(C3:C22)			
25		UCL	=$C$24 + 3*SQRT($C$24*(1-$C$24)/$B$1)			
26		LCL (calculated)	=$C$24 - 3*SQRT($C$24*(1-$C$24)/$B$1)			
27		LCL (actual)	=IF($C$26 > 0, $C$26, 0)			
28						
29						
30						
31						
32						
33						
34						
35						
36						
37						
38						
39						
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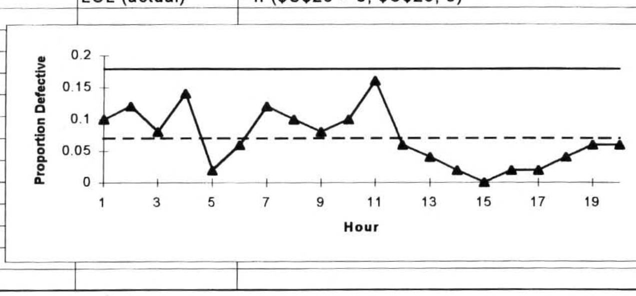

CONCLUSION

Spreadsheets continue to grow in popularity and availability, and their utility in solving everyday enginering problems develops with each new version. Some examples have been presented on how to incorporate spreadsheet use into a sophomore-level chemical engineering course on statistics and probability. Hopefully, these examples will inspire more of us to use spreadsheets to illustrate chemical engineering fundamentals in the classroom.

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