Does Engineering Education
Have Anything to Do with Either One?
Toward a Systems Approach
to Training Engineers[*]

by

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THE AWARD

The R. J. Reynolds Industries, Inc. Award for Excellence in Teaching, Research and Extension was established by the School of Engineering to honor a member of the engineering faculty who has demonstrated superiority in several areas of activity that relate to the University's three-fold mission of teaching, research and extension.

The annual award is supported by R. J. Reynolds Industries, Inc. through the North Carolina Engineering Foundation, Inc. to bring recognition to scientific and educational achievements in fields of engineering.

All engineering faculty members are eligible for the award. Nominations may come from any individual or group. A committee of engineering faculty, representing either academic, research, or extension areas, and representatives from other University schools reviews the nominations and recommends a candidate to the Dean of Engineering.

The following criteria are used in the selection of the candidate:

- Contributions to the education of students through excellent teaching, course and program improvement, advising, student project and thesis direction and participation in other activities that enhance the development of students.

- Scholarly activities, including research, design, writing, and speaking that are recognized locally, nationally, and internationally.

- Extension and public service activities, including assistance and advice to industry, business, government, and other educational institutions and contributions to professional societies.

The award recipient is asked to prepare a lecture on a topic related to his engineering activities, to be delivered during a special award ceremony honoring him with a monetary gift, a citation, and a framed certificate.

Each lecture will be published under a series bearing the title "The R.J. Reynolds Industries, Inc. Award Distinguished Lecture Series." The publications will be available upon request to the Office of the Dean.

RICHARD MARK FELDER

SECOND RECIPIENT

R.J. REYNOLDS INDUSTRIES, INC. AWARD
FOR EXCELLENCE
IN TEACHING, RESEARCH, AND EXTENSION

Dr. Felder, recipient of this $5,000 award, has won recognition in this country and abroad as a leader in chemical engineering education and research through his significant academic contributions and his writings. His strong commitment to upholding the highest of professional standards is reflected in his effective classroom teaching, his significant research contributions, and his dedication to serving the public in their continuing education needs. A colleague, describing the substance of Dr. Felder's distinguished career in chemical engineering, stated: "The collective quality of his research, teaching, and extension activities is, very simply, unprecedented."

A native of New York City, Dr. Felder received a Bachelor's Degree in Chemical Engineering *Summa Cum Laude* from the City College of New York in 1962. He earned both his Master's and Ph.D Degrees in Chemical Engineering from Princeton University, the latter degree in 1966. He then spent a year as a NATO postdoctoral fellow in the Theoretical Physics Division of the Atomic Energy Research Establishment, Harwell, England, followed by two years as a research chemical engineer at Brookhaven National Laboratory. He joined the North Carolina State University faculty in July of 1969.

Dr. Felder's research interests have spanned a wide range, and include such areas as the physics and chemistry of hot atoms, photochemical reaction engineering, computer simulation and optimization of chemical processes, modeling and environmental impact of coal conversion operations, air pollution monitoring and abatement technology, transport of gases and vapors in membranes, and applications of radioisotopes in the chemical process industry. He is currently principal investigator or co-investigator of seven research projects funded by grants totaling nearly $2 million. He holds a U.S. patent with Dr. J. K. Ferrell for a continuous in-stack pollution monitoring system. For his achievements in research, Dr. Felder received the N.C. State Sigma Xi Outstanding Young Scientist Award.

Dr. Felder's contributions to the literature in his field have been extensive. He has written over 60 technical papers and review chapters on his research interests. He is also co-author with Dr. R.W.

Rousseau of *Elementary Principles of Chemical Processes,* which serves as the text for the first course in chemical engineering. The text enjoyed widespread acceptance almost as soon as it was published in 1978. It has been adopted by more than 100 chemical engineering departments in the United States and has also been translated into Spanish and Chinese.

As Professor and Graduate Administrator of the Department of Chemical Engineering, Dr. Felder has played a major role in curriculum planning and course development. He has received repeated student acclaim for his inspiring lectures in courses ranging from the sophomore level engineering course to advanced graduate courses. In 1978, and again in 1981, he received the University's Outstanding Teacher Award. He was the featured "ChE Educator" in a cover story in the Winter 1981 issue of *Chemical Engineering Education.*

Dr. Felder is widely sought as a consultant by industry and research institutions. In recent years he has also been extensively involved with the presentation of short courses to industry, directing and lecturing in courses on process optimization, chemical reaction engineering, membrane separation processes, and chemical engineering principles for non-chemical engineers. He has served as a technical expert for the International Atomic Energy Agency, with missions in Brazil and Israel. He belongs to a number of honorary and professional societies including Sigma Xi, Tau Beta Pi, Omega Chi Epsilon, the American Institute of Chemical Engineers, and the American Chemical Society.

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Richard Mark Felder

FOREWORD

The custom at academic award presentation ceremonies is for the recipient to give a lecture on his or her research. There are three reasons for this. First, it's easy—most of us know more about our research than anything else. Second, and even more appealing, it's safe—we also know more about it than almost anyone in our audience. Third, 99 out of 100 academic awards that involve such things as presentation ceremonies are for research achievement, so that a lecture on anything but research would be inappropriate.

The R.J. Reynolds Award is the hundredth one, however, which is the principal reason I am so deeply honored to have been selected as the recipient. It is an award for "Excellence in Teaching, Research, and Extension," in that order. It is one of the few awards in existence that give more than token acknowledgment to the notion that education has a significant role in institutions of higher education.

I have some opinions on this subject. Rather than subjecting the audience at the award presentation to an exposition of research in an area few of them work in or particularly care about, I used that forum to express these opinions, accepting the risk that they would interest an even smaller group than would my research. This monograph is an expanded version of that talk.

My thesis is that many of the technology-related problems with which our society is now struggling are attributable in part to deficiencies in the way engineers are currently educated. In this paper, I suggest a series of modifications in the way engineering schools function that might help remedy the deficiencies. The first section contains a synopsis of my main points and a summary of the suggested modifications. Subsequent sections contain supporting arguments, elaborations, and references.

Before I begin, a necessary qualification. The points I make are generic: I don't intend to suggest that all the practices I criticize can be observed at North Carolina State University. Some can, and others cannot—and the same is true of every university in the country. My object is not to accuse or label, but simply to present ideas formed from my observations, conversations with colleagues at various engineering schools, and prejudices. To the extent that this monograph stimulates thought about the ideas—whether similar or different conclusions are reached—its preparation will have been worthwhile.

SYNOPSIS

Technology has been defined as the discipline that translates the discoveries of science into means of improving the well-being of society. If this definition is accepted and the well-being of society is taken as the measure of success, then technology in the United States in the early 1980s must be viewed as failing.

In recent years, we have been marching through an impressive array of crises: energy, environmental, and economic. The quality of our products and our ability to compete with foreign producers has been steadily declining. We keep finding new and more efficient ways to poison and irradiate ourselves, blow ourselves up, and give ourselves cancer. We have fallen behind a disturbing number of countries in our ability to provide adequate health care, efficient public transportation, and affordable housing. We are depleting our nonrenewable natural resources at an alarming rate, with little prospect of improvement. Growing percentages of our material and human resources are dedicated to increasing our destructive capability. We have the most energy-inefficient agricultural system in the world. We are last among the world's industrialized nations in annual rate of productivity growth.

It is true that the origins of many of these problems are political rather than technological in nature. Decisions about resource allocation and establishment of national priorities are not in the hands of engineers. However, it is up to the engineers to participate in the decision-making process; to inform themselves and the rest of the population about the potential social consequences of the decisions that are made; to judge whether implementation of the decisions is consistent with the stated objective of technology—improvement of the well-being of society; and to take appropriate action or inaction, depending on the outcome of the judgment. To our society's detriment, engineers as a class have failed to do this.

The blame for this abdication of responsibility cannot be laid to any one group, but a share of the burden must be assumed by engineering educators and their institutions. We have contributed directly to the technological developments that have brought our society, for better or worse, to where it stands today. Moreover, we educate the engineers. If they are failing to meet their obligations to society, we must ask whether the education we gave them adequately prepared them to do so.

I suggest that it did not. Engineering schools have undergone major changes in methodology and self-concept over the past several decades, reflecting the rapid and dramatic technological growth that has taken place during this period. Some of these changes were necessary and appropriate. I believe that several others were not well advised, however, and that reversing them could help restore a degree of balance to technology and society.

First, we have progressively shifted our focus from education to research. Our hiring practices and our incentive and reward systems all reflect this shift, to the point that we now tacitly discourage dedication to excellence in teaching. The quality of the training we give our industry-bound students has suffered in consequence.

Second, we teach primarily mechanics, and not reasoning methods; memorization and routine application, and not analysis, synthesis and evaluation. We don't encourage creativity and independence of thought, and in fact often do our best to discourage them. In short, we do not provide training in the skills needed to solve the most difficult technological problems facing our society.

Third, our curricula are largely based on a viewpoint which holds that any system can be analyzed entirely in terms of its component parts and functions. Physicists became aware of the inadequacy of this viewpoint 60 years ago, and now understand the futility of attempting to analyze a

system without taking into account the inevitable interactions between the system and its environment. Scientists in other disciplines, such as biology, medicine, psychology, sociology, and economics, are gradually becoming aware of the necessity of developing a systems approach to their disciplines. Some engineers, many of whom are involved with computers, have begun to integrate this philosophy into their work, but most of us are still bound to 17th-century thinking in our approach to our subjects. Many of the crises our society is now facing are direct reflections of the absence of a systems approach in our decision-making processes and our curricula.

These are my views of where the problems lie. To help remedy them, I propose the following modifications in the way engineering schools function.

* * *

1. *When hiring new faculty members for positions that involve both research and teaching, use both potential research ability and potential teaching ability as coequal criteria.*

We must acknowledge with more than rhetoric the concept that teaching engineering is at least as important a function of an engineering school as carrying out research. This means—among other things—not hiring someone for a teaching position who has no apparent ability or desire to teach, or who regards teaching as simply a necessary evil.

It is unfair to students to subject them to faculty members who have no interest in them. If a candidate for a faculty position seems to be incapable of giving a coherent lecture or indicates a distaste for teaching or a reluctance to assume his fair share of the department teaching load, either hire him with the understanding that he will only do research, or don't hire him regardless of his potential fundability.

2. *Abandon the requirement that both research and teaching must be done by all faculty members.*

The ideal faculty member is outstanding at both research and teaching, and top priority in hiring should obviously be given to such individuals. Unfortunately, they are relatively rare, and it is almost impossible to find enough of them to fill a faculty. Most faculty members enjoy and excel at either teaching or research but not both, and both teaching and research programs are now suffering because people with little interest in them are forced to participate in them.

If my first suggestion is adopted, some faculty members will be hired specifically to do research—appropriately, in view of their skills and the critical importance of outside funding to engineering departments. We should balance our faculties with professors hired specifically to teach. These individuals do not have to hold doctorates or have long publication lists; they do have to be experts in their fields of instruction, and excellent instructors. Since they would be expected to carry heavy teaching loads, the overall research and instructional requirements of the department would be met, only each function would be performed by individuals with both the skill and the interest to perform it.

3. *Hire some experienced engineers—with or without Ph.D.'s—as faculty members.*

If part of our function is to train practicing engineers and part to train research scientists and college professors, then we should hire for our faculties both industrial engineers and research specialists.

Opening our doors to experienced engineers would provide a variety of benefits. Our students would gain by being exposed to role models of experience and professionalism, who could serve as mentors to them. Reluctant researchers would no longer have to be dragooned into performing necessary but (to most of us) undesirable departmental functions like course scheduling, laboratory management,

staff supervision, and the like. Instead, these tasks could be performed by individuals with both the skill and enthusiasm for doing them, freeing the researchers to do what they want to do and what they do best. Finally, we would be utilizing an important element of our population—men and women with years of valuable, practical experience, who have the ability and the desire to pass on their knowledge.

4. *Restructure the academic reward system to put teaching and research on an equal footing.*

Our incentive and reward system is completely overbalanced in favor of research. When we write papers and get them published, and even more, when we write proposals and get them funded, we get congratulatory letters from administrators, promotions, tenure, merit salary increases, medals, awards with impressive financial stipends, invitations to visit exotic places, and national and international reputations. When we devote ourselves to being excellent teachers, we get personal gratification, and possibly an unframed teaching award certificate or two. The disparity is glaring, especially if we wish to maintain that teaching and research are equally important university functions.

The R.J. Reynolds award, which is given to reward a combination of teaching and research achievement, is a magnificent step toward eliminating the disparity. We should go one step further and provide the same level of recognition and financial reward for excellence in teaching alone as we do now for achievement in research alone.

5. *Carry out periodic departmental reviews of all courses to determine whether and how they should be updated or revised to improve their organization and clarity. Provide positive incentives—for example, lightened teaching loads—for new course development and existing course revision.*

Since our system provides us with little or no incentive to update and clarify our course notes, many of us teach from the same notes year after year, and sometimes decade after decade. As a result, our students are frequently exposed to obsolete, confusing, boring, trivial, or outright erroneous material, and the quality of their preparation for engineering practice suffers.

If the previous recommendations are adopted, there should be less of this sort of thing going on. In any event, we need to do whatever we can to minimize its occurrence. This means reviewing our courses periodically and making sure that their content reflects the current state of the field—that we are not spending a great deal of time deriving outmoded theories, for example, or teaching approximations that were necessary before exact solutions could be easily obtained on computers or hand calculators.

The courses as they are actually offered must be examined in this process—not simply the course syllabi that may or may not exist on paper. When new courses or course revisions are found to be necessary, planning and implementing them should be considered as important a function as carrying out funded research projects, and released time should be allotted accordingly.

6. *Incorporate peer and student review of teaching performance in evaluations of faculty performance.*

Teaching at the college level may be the only skilled profession for which absolutely no training is presumed necessary. The assumption seems to be that all those we hire come knowing how to teach, despite the fact that they have never had as much as an hour's training in teaching.

This assumption is false. New professors, like new members of any profession, need some guidance. I propose that we go back to the once-common practice of enlisting senior faculty members with proven teaching ability to review the performance of their junior colleagues and to suggest how it might be improved. Review of course notes and organization, as well as occasional observation of lectures, should be included in this process.

We should also pay attention to student evaluations of faculty and courses, rather than soliciting these evaluations and then ignoring them. Most systematic studies of student evaluation contradict the common view that the best evaluations go to the easiest graders. When an instructor gets superior ratings from most of his students, he is quite likely to be doing a good job of presenting the course material. By the same token, uniformly poor evaluations usually indicate poor performance: if students don't believe they're learning anything, they're probably right. We should treat the continued presentation of poorly organized or obsolete material the same way we treat failure to write proposals and publish papers when we make decisions regarding tenure, promotion, and raises.

7. *Recognize that we have an obligation to society to equip the exceptionally gifted students who come to us—those most likely to make the greatest contributions to engineering science and practice to make full use of their gifts when they leave us.*

This means becoming familiar with the characteristics of these students and the techniques that have been found effective at enabling them to channel their gifts in productive directions. We must recognize, for example, that the pace appropriate for some students is inappropriate for others; allow for self-study; and provide opportunities for extra credit through enrichment and acceleration of the normal course syllabi.

We should also help our gifted students develop their facility in the higher-level thinking skills of analysis, synthesis, and evaluation, decreasing the amount of pure memorization and routine drill in our courses. One way to do this is to give only open-book examinations. Another is to put more emphasis on cross-disciplinary approaches to solving problems, so that the students get used to the idea that what we teach them in one subject area may have applicability to problems that arise in other areas.

Cross-disciplinary methods are needed to solve most of the difficult problems facing society. If our students are never required to learn and use these methods while they are with us, the chances are slight that they will be able to do so in their jobs or research.

8. *Foster the development of creative thinking skills and acknowledge and encourage those who manifest these skills.*

The emphasis in our courses is placed entirely on solving well-defined problems that have one and only one correct solution. Unfortunately, unlike homework problems, real problems usually don't come so neatly packaged. Solving them often requires divergent thinking—being able to come up with a large number of possible solutions, including some that might initially seem absurd or infeasible.

Very often our most creative students—those with the greatest divergent thinking skills—go unrecognized, and their abilities remain undeveloped. When they come up with unexpected solutions to problems, our impulse is to prove them wrong—both the solutions and the students. Eventually the students get the message and turn off their creative impulses. If this happens often enough in their tenure with us, the impulses might never get turned back on.

We have a responsibility to help our students develop and improve their creative thinking skills. We should include some open-ended problems in each course we teach, and encourage the determination of alternative solutions. We should also provide exercise in defining problems, rather than simply solving them.

In addition, we should try to temper our criticism of innovative but incorrect answers. Appearing foolish and being wrong are risks taken every time a creative solution is ventured to a nontrivial problem. If we can make our students feel safe about taking these risks, we could be performing an incalculable

service to our society, which needs all the creativity it can get.

9. *Reverse the tendency of recent years to restrict our curricula to more and more specialized technical courses. Restore free electives that have been lost and broaden the curricula to include more of the social and behavioral sciences.*

The problems facing our society need broad social perspectives as well as technological expertise for their solution. We can't expect the social scientists to acquire the necessary technical expertise unless dramatic changes in the way they are educated take place relatively soon, which is unlikely. This places the burden on us to provide the necessary breadth of perspective. We won't do it by progressively narrowing our graduates' field of vision, as we have been doing for the past several decades.

Among other things, this suggestion requires encouraging our students to take electives in a wide variety of fields, including the social and behavioral sciences and humanities. Our job at the university is to provide an education, not merely vocational training. A graduate whose knowledge extends no farther than the boundaries of his technical field is not educated.

10. *Adopt a systems approach to engineering education. Teach that technological systems—like all other systems—do not exist in a vacuum, but are integrally related to and interact with their environment.*

Teach our students that decisions made in the name of technology and carried out by engineers have a dramatic impact on the entire fabric of society. Provide a sense of the legal and ethical responsibility that all members of the technological community carry for these decisions. Convey the idea that once possible solutions to technological problems have been advanced, they must be evaluated with this responsibility in mind. Impart this knowledge systematically, throughout the curriculum, so that it becomes a reflexive part of the thought processes of all those who have been with us.

* * *

Several of these steps can be implemented fairly quickly. We can hire engineers to teach engineering, researchers to do research, and teachers to teach, trying as much as possible to combine these roles in the same individuals. We can provide significant awards for teaching effectiveness. We can carry out reviews of curricula, courses, and teaching and use the results as part of our regular faculty evaluation procedures.

Once enough faculty members are available who can and will make the necessary effort, we can systematically incorporate problem-finding, synthesis, and divergent thinking skills in our courses, and we can infuse in our students a sense of social responsibility and the need to evaluate technological decisions in light of this sense. Making these changes will take time, and may cost us a great deal of effort and money. However, considering the problems we are now facing as individuals and as a society, it is likely that if we do not make the changes, the cost will be far greater to all of us.

THE DECLINE OF AMERICAN TECHNOLOGY

Technology has been defined as the bridge between science and society—the discipline through which the discoveries of science are translated into means of improving the well-being of society's members. If we judge by the well-being of contemporary American society, we must conclude that our technology is failing.

Let us consider where we are now and see what our technology has done to get us there. One thing it has done is to provide us with an impressive variety of ways to extinguish ourselves. We are poisoning ourselves with chemical wastes and herbicide and pesticide-tainted food. We are threatening to do the same with radiation emanating from nuclear weapons stockpiles and nuclear reactors and their byproducts. We are in possible danger of losing both coasts to the ocean as a consequence of the greenhouse effect resulting from the wholesale addition of combustion products to the atmosphere. Our rivers, lakes, forests, fields, cars, clothing, and lungs are subjected to infusions of sulfuric and nitric acid whenever it rains. We are constantly finding innovative ways to give ourselves cancer.

In other less lethal ways, our technology is also doing less than spectacularly. The costs of our principal consumer products, like automobiles, are going up, just as rapidly as the quality of these products is going down. Our ability to transport our citizens around their cities and around the country safely and economically is declining. We cannot build houses that we can afford to buy. We cannot meet our energy demands without continuing to import substantial quantities of petroleum. At the same time, we are subsidizing the elimination of farm production acreage that could be dedicated to the production of grain for fuel alcohol—over 20 million acres in 1982.[1]

Our technology is dedicated almost exclusively to one or the other of two guiding principles—destruction and consumption. In 1980, our government committed to spend for defense the sum of one trillion dollars over a five-year period, something on the order of a million dollars per minute. To spend this much money, substantial portions of our technological resources have been diverted to defense-related activities. In 1978 it was estimated that between a third and a half of our scientists and engineers worked for the military,[2] a fraction that continues to rise. We are developing weapons of unimaginable destructiveness—enough to destroy civilization as we know it many times over, and to contaminate the planet to an extent sufficient to prevent civilization's return.

The hysterical arms race in which we are engaged has every appearance of an Orwellian fantasy. The scope of the race is staggering. Existing stockpiles of nuclear weapons equal 16 billion tons of TNT, roughly 3.5 tons for every living human being. By way of comparison, it took only 3 million tons to kill 40 to 50 million people in World War II.[3] The fact that some of the more modern bombs would leave real estate intact while destroying life completely offers scant comfort.

What we have to look forward to in the future is even worse: a sky spangled with orbiting nuclear and laser arsenals which can instantly trigger wholesale destruction at the drop of a provocation. The grim prophecies of the science fiction writers of past decades have been surpassed. Even if by some miracle no one pushes the button in our lifetime, living under this many-bladed Sword of Damocles is quite likely to turn us into a race of paranoids.

The technological resources that we have not dedicated to the development of destructive capability are largely placed in the service of individual consumption. In the United States, we account for about 5% of the world's population and for about a third of its consumption of resources.[4] Those of us who account for most of this consumption— a relatively small percentage of the population—believe now that we NEED a new car every three to five years. We feel that we are underprivileged if our kitchen does

not boast an electric garbage disposer, dishwasher, trash compactor, food processor, blender, mixer, can opener, skillet, thermal oven, and microwave oven. We have at least two color televisions, one with attachments so we can play PAC-MAN in the comfort of our living rooms, and those of us without video recorders cast envious eyes at those who have them. We need new suits at least as often as a snake sheds its skin. We need freeze-dried reconstituted vitamin and protein-enriched stuff, which if eaten with closed eyes and a faulty memory can almost pass for food. We need new improved detergents that will get our clothes whiter than white, new improved toothpaste that will do the same for our teeth, new improved toilet paper that has the consistency of spun velvet, and a paper towel that can absorb a volume of liquid equal to that of Lake Erie and then support the weight of the Los Angeles Rams front four.

All this our technology has given us. But at what cost? An increasingly rapid depletion of nonrenewable resources. A growing scarcity of clean air and water in our most heavily populated areas. A buildup of toxic wastes, without safe means of disposing of them. An epidemic of industrial accidents that endanger growing segments of the population. A rising incidence of cancer, other lung, skin, and kidney diseases, and birth defects, And the increasing dehumanization of individual workers, who after enough corporate expansions, mergers, and takeovers have occurred no longer even know which machine they are cogs in.

Stories abound that dramatize the deterioration of our quality of life as a direct consequence of our technological development, and the same stories highlight technology's inability to correct the problems. The Love Canal story is the best known example of our self-poisoning tendencies. The toxic chemical wastes dumped into a trench near Niagara Falls eventually permeated into the groundwater and soil of a nearby residential neighborhood, and caused high rates of birth defects, liver, kidney, and lung diseases, and various forms of cancer among the residents. Denials and disclaimers of responsibility were routinely offered, until finally the weight of evidence became overwhelming, and the neighborhood was evacuated. It has recently been declared safe again. There has not been a great rush to move back in, however, by either the former residents or by those who have offered the assurance of safety.

Unfortunately, Love Canal isn't unique. In 1979, the U.S. Environmental Protection Agency estimated that there are more than 50,000 sites where hazardous materials are stored or buried, with less than 7% receiving proper disposal.[5] In New Jersey, four double-lined landfills built for hazardous waste storage within the last four years are now leaking, and the inevitability of eventual leakage from any such site has been attested to by a number of scientists, including several with the EPA.[6]

Nuclear power provides an unsurpassed example of the failure of technology. For ten years and more we have been barraged by propaganda proclaiming that nuclear power is reliable, safe, and cheap. It is becoming increasingly clear that it is in fact none of these, despite assurances from all those well-dressed and obviously well-financed people who inhabit major airports, babbling about sending Jane Fonda to the moon.

An example of the reliability and cost-effectiveness of nuclear power is provided by the experience of the Carolina Power and Light Company. The company runs three nuclear power units in two plants in North Carolina. Major shutdowns of these units occurred in three consecutive summers since 1978, the year when all three units became operable. In 1981, equipment failed an average of one day out of six at one unit, and one day out of four at another unit. According to a National Research Council report, during the period 1969-1979 there were 52 serious incidents in the CP&L plants that could have led to severe core damage and possibly a meltdown. As for cost-effectiveness, in 1980, the power produced by the Brunswick, North Carolina facility cost 56% more than the industry average for electricity produced from coal.[7]

The accident risks involved in nuclear power generation are made chillingly clear in a two-part

story on nuclear reactor technology in the *New Yorker* magazine (10/25/82 and 11/1/82), and in a study carried out by Sandia National Laboratories in 1982. The study includes estimates of the damage that would result from a "Group 1" accident—one involving severe core damage, melting of the reactor fuel elements, and massive release of radiation into the environment. If this occurred at a power plant in Salem, New Jersey, for example, as many as 102,000 people could die within a year from radiation. If it occurred at the Indian Point reactor near New York City, about $314 million in damage could result.[8] The estimated probability of such an accident occurring in a given plant is extremely low—roughly one in 100,000 reactor years. However, this translates to a 2% probability of occurrence in one of the nation's power plants before the year 2000 if nuclear power development continues at the projected rate.

The technological problems of radiation exposure and disposal of nuclear wastes are particularly troublesome. Everyone working in the nuclear industry is routinely exposed to radiation above naturally-occurring background radioactivity. Moreover, radioactive matter is invariably and sometimes deliberately released into the environment as part of the operation of a nuclear plant, so that everyone living in the vicinity of a facility is similarly exposed. The claim is that the level of the exposure is well below threshold limits for causing harm to living organisms, but most medical scientists now agree that there is no such threshold—even the smallest amounts of radioactivity are capable of producing mutations and diseases, and the effects are cumulative.[9,10]

The tons of radioactive waste produced by each nuclear reactor every year remain toxic for thousands of years. The most toxic of the wastes is plutonium, which has a half-life of 24,400 years. One-millionth of a gram of plutonium is carcinogenic. One gram of plutonium produced in a nuclear reactor will still be carcinogenic in 500,000 years, roughly fifty times longer than the time from the last ice age to now.[11] We do not have the technology to contain anything safely for a period within two orders of magnitude of half a million years, and there is serious question about our ability to contain wastes safely even within our lifetime. Despite millions of dollars spent on research, we still have no more than unproven and probably unprovable claims about the safety of proposed disposal methods.

In all of the areas I have addressed, when choices between economic expediency and the public interest are presented, the decision is generally made in favor of expediency, and the authority of technology is then exerted to justify the decision. Scientists and engineers were among those asserting that no harm would result from exposure to radiation from atmospheric testing of nuclear weapons in the 1950's, even as they saw rising incidences of various diseases and occurrences of strange phenomena such as animals turning blue in the vicinity of the tests.[10,12] Scientists and engineers were among those arguing that an incident like the Three Mile Island nuclear reactor accident could not possibly occur, until it occurred.

The same authorities who assure the public that there is no possible danger in whatever it is they propose to do are also right there to deny responsibility when their assurances prove erroneous. Some of the same scientists and engineers who defended the safety of atmospheric nuclear testing now claim that you can't *prove* that the extraordinarily high incidence of leukemia among residents of communities near the test sites has anything to do with the tests.[10] Other scientists and engineers argue that the 1 in 5 incidence of miscarriages and stillbirths among the wives of workers in a Baton Rouge refinery wastewater treatment plant can't be *conclusively* traced to plant conditions.[13] The same denial of responsibility is seen with respect to the contamination of Great Lakes fish with Toxaphene (a potential carcinogen); the contamination of 90% of the milk supply of Oahu, Hawaii with Heptachlor (which causes leukemia and liver disorders); the poisoning of wells in Long Island and Wisconsin with Temik (a nerve poison); the contamination of Missouri soils with dioxin (a poison and carcinogen, with cancer risks as high as 50% from chronic exposure); and so on.[14]

A legitimate function of scientists and engineers is to make the public aware of the risks involved

in technological policy decisions and to acknowledge responsibility in those instances where fears of hazards prove to be justified. If instead they use their stature as experts to support unjustified assurances of safety and subsequent denials of responsibility for mistakes, we must view this too as a failure of technology.

Another prominent failure is the ongoing depletion of our nonrenewable resources. Our energy consumption per capita is about twice as high as that in most European nations.[15] The drive to promote nuclear power intensified in the 1970's with the perception of a growing shortage of the fossil fuels—petroleum and natural gas—that had formed the basis of the nation's energy economy for most of this century. Our unrestricted growth in consumption has augmented this depletion along with that of our metal ore reserves. Faced with long and burdensome gasoline lines on several occasions, we acknowledged the need for conservation and have taken some steps in this direction, but most of the patterns which led to the problem of resource depletion have not changed...and our technology, which provides the means by which the resources are depleted, has not developed the means to abate the trend.

We are still operating on the "more is better" philosophy and dedicating our resources accordingly, regardless of the economic and social costs. We automate and mechanize our industries, increasing unemployment and decreasing per capita productivity. By 1980, the United States was last among the world's industrialized nations in annual rate of productivity growth.[16] We increase our agricultural output with the aid of energy-intensive machinery, pesticides, and herbicides, and end up with contaminated soils, contaminated food, an unprecedented farm failure rate, and the most energy-inefficient agricultural system in the world in terms of energy consumed per calorie produced.[17]

We are, in short, seriously out of balance. To be sure, the reasons for our problems are more political than technological. Decisions about such things as the determination of priorities for the allocation of nonrenewable resources and the need to regulate hazardous emissions are not in the hands of engineers. However, this is in part because most members of the engineering community have abandoned their responsibility to be aware of the social consequences of the decisions being made in the name of technology and to provide appropriate input to the decision-making process.

Moreover, the implementation of these decisions is the province of technology. Engineers develop the means for the consumption of resources, whether well or ill-advised, and for the production of enriched uranium, PCBs, dioxin, and the sulfur dioxide that either passes directly into our lungs or ends up as sulfuric acid in our soil and water. Decisions about priorities and funding may be made by politicians and economists, but if the decisions are detrimental to the well-being of society, and technology's function is indeed the furtherance of that well-being, then the engineers should question the decisions and proceed in accordance with their function.

I believe that many of the decisions that have been made for us in recent years have been detrimental—catastrophically so—and that technology has failed in its responsibility to reverse these decisions. The blame for this failure can be apportioned among all segments of our society—government, industry, and the population as a whole. But I speak now as a member of the engineering education community. We have contributed directly to the body of knowledge that has brought us to the point where we stand today—and more importantly, we are responsible for training the engineers.

We take credit for technology's considerable achievements. We must also examine our role in its failures. We must try to discover what we have done or failed to do that might have helped bring us to the precarious position we now occupy. Some ideas regarding these sins of commission and omission and possible means of avoiding their repetition in the future constitute the remainder of this presentation.

WE ARE HIRING NEITHER ENGINEERS
NOR EDUCATORS TO EDUCATE ENGINEERS

Not long ago I attended a department faculty meeting as a visitor. The purpose of the meeting was to choose one of several candidates for a vacant faculty position to receive an offer. The meeting followed a seminar given by one of the candidates, which I also attended.

The seminar presenter, whom I'll call Mr. X for lack of incentive to be more original, struck me as the best candidate for a faculty position I had ever seen. He had everything. He had a 3.9+ average as an undergraduate and straight A's as a graduate student. He was doing his dissertation research under a professor whose name is a household word in our field. His reference letters looked like entries in a contest to identify the most synonyms for "outstanding." His seminar was the best recruiting seminar, and one of the best seminars in any category, that I have ever seen. His delivery was lucid; his organization was impeccable; he fielded difficult questions gracefully and well; and he exhibited a fine sense of humor at appropriate points in the presentation.

At the faculty meeting, three candidates were considered. They were X; Y—a Ph.D. candidate with an outstanding record at another prominent university; and Z, an acknowledged expert in his field at a research institution, whose interview seminar was considered incomprehensible by most of those who attended it.

No one at the meeting questioned X's credentials or argued with the proposition that as far as teaching potential went, the other two candidates couldn't touch him. It was also agreed that if any of the candidates were to write a definitive textbook, it would most likely be X. The only negative point raised regarding his qualifications was that he was interested in several research areas rather than a single narrow area of specialization, which, it was claimed, could lead to a dilution of his research efforts. Y, on the other hand, did have such an area of specialization. It was argued that in the first few years of his residence at the university, he might write more proposals and get them funded than would X, who would need a little more time to get himself focused.

In short, for teaching and writing potential—X by several lengths. Short-range funding potential—maybe Y. Long-range research potential—tossup. I've been around long enough to know the importance placed on proposals and funding in engineering departments, but I couldn't believe that in this case the short view could possibly have that much of an impact.

I was wrong. The vote between X and Y was a tie, and several votes were also cast for Z. Someone suggested that if Z couldn't manage to present a coherent seminar on his own research, he might not be the best conceivable occupant of a faculty position with full teaching responsibilities. The rebuttal was, yes, but look how much money he'll be able to bring in with his industrial connections!

Who finally got the offer is irrelevant. The point of the story is the nature of the debate—which could have taken place at any engineering school in the country—and what it says about the view engineering faculties now have of their functions and responsibilities.

Most of the young people who come to us seek undergraduate training in engineering, and most of those who graduate go into industry, into jobs that don't involve research. In terms of demand for services, engineering schools should therefore be primarily undergraduate training institutions, as they were in past decades.

That's not what they are now, however. Judging by the way we hire faculty members—as illustrated by the story just concluded—and the way we recognize and reward those we have hired, we

consider our universities primarily research institutions. As engineering professors, our principal responsibility is to carry out research, and our secondary responsibility is to train graduate students to do the same. Whatever energy and resources remain after we have discharged these two functions go into teaching courses. Most of us teach, but we are expected to make sure it doesn't distract us from our more important jobs.

Consider our hiring practices. If we took seriously our responsibility to train engineers, you would think that we would make potential teaching ability at least as important as any other criterion when we evaluate candidates for faculty positions. But in fact it is a minor consideration at best, when it is considered at all. We require only that our new faculty members have a minimal ability to speak English. If they have the potential to become outstanding teachers, it is a nice fringe benefit but it is not really that important in our evaluation—and it could even be a drawback if we suspect that their dedication to teaching might interfere with their research performance.

You might also think that if our job is to teach engineering, we would need at least a few experienced engineers on our faculties. Regrettably, we have made it almost impossible for them to get through the door. Thirty years ago an engineer with a solid industrial background and the ability to communicate his knowledge would have been welcome at most engineering schools. Now, in requiring the Ph.D. of *all* new faculty members and in making publications and potential to secure research funding our primary hiring criteria, we have effectively ruled out most such individuals from being considered as faculty members.

Whom do we hire, then? Research scientists. Holders of Ph.D.'s in fields which may or may not be in engineering. A recent survey of engineering schools indicated that roughly 80% of all faculty members in Fall 1981 held doctorates, and in my own field of chemical engineering the figure was 92%. Although the survey did not indicate it, it is almost certain that most of the remaining 10-20% are close to retirement, so the percentage holding doctorates will increase in the coming years, approaching 100% unless the present hiring trend is reversed.

Most of us on engineering school faculties who are not close to retirement are thus cut from the same template. We more closely resemble physicists, chemists, and mathematicians than engineers. Our training, inclination, and interests intersect slightly or not at all with engineering practice. Most of us were taught by other individuals without engineering backgrounds, and we have rarely spent more than a summer or two, if that, in an industrial environment. Few of us are particularly gifted as teachers, and many of us view teaching as a necessary chore—dues to be paid for the freedom of conducting our research in an academic environment.

In short, we are hiring neither engineers nor educators to educate engineers. If the quality of engineering education suffers from this condition, it is hardly surprising. If part of our role in society is to train engineers, which it is, we should be hiring individuals with or without Ph.D.'s who know engineering and have the talent to teach it. If part of our role is to carry out research in pure and applied science and to train others to do so, which it is, then some but not all of us should have our training in pure and applied scientific research.

This is not a new issue. In 1968 the NSF-sponsored Goals of Engineering report lamented the increasing tendency of engineering schools to short-change engineering in their curricula. This report and subsequent reports by the National Society of Professional Engineers and a successor to the Goals committee called for the establishment of professional engineering curricula, which would emphasize engineering design and practice as opposed to engineering science and research.[19]

Nothing along these lines happened, of course. How could it? If we instituted all of these design

and practice courses, who would teach them? Most of the few qualified to do it are at or near retirement age, and others capable of replacing them can't get jobs with us.

If further justification is needed for the idea of hiring practicing engineers who may not have Ph.D.'s, consider the host of essential departmental functions for which the Ph.D. is supremely irrelevant: planning and supervising laboratory courses; scheduling classes and seminars; serving on school and university committees and boards; supervising department staff; administering the undergraduate program; orienting freshmen; providing hospitality to department visitors; and on into the night. Most of us have relatively little interest in these activities, regarding them (rightly) as diversions from the things we want to do and were hired to do—but we recognize their necessity and submit to being dragooned into doing them in the name of departmental citizenship. As a result, they often don't get done very well.

At North Carolina State we recently brought onto our faculty a man with 30 years of industrial experience, who made it clear that he had no interest in research. It was one of the cleverest things we've ever done as a department. He has taken over, enthusiastically and expertly, many of the responsibilities from which most of us instinctively recoil, including the undergraduate laboratory. His technical experience has proved to be a rich resource for both his students and his colleagues, and his managerial background and skill enable him to do gladly and well what most of us would do reluctantly and, at best, adequately.

Our profession needs more of this sort of individual. There are many engineers who have worked in industry for years and who have the skill and desire to pass on what they have learned. Opening our doors to them would serve everyone's interests: theirs, ours, and our students'. The new faculty members would gain the opportunity they seek to put their knowledge to continued use. The researchers on the faculty would be free to do more of what they want to do and what they do best. The students would gain access to role models of experience and professionalism who could serve as mentors to them. Considering these benefits collectively, the ultimate beneficiary would be society.

WE DISCOURAGE GOOD TEACHING
AND DEDICATED TEACHERS

Just as we make it difficult to hire dedicated teachers, we discourage those on our faculties from pursuing teaching excellence. In fact, our system provides implicit incentives for poor teaching.

The initial motivation for this presentation was a news story in the *Rocky Mountain News* of May 19, 1982. The headline read, "Tutor gets honor, then he's a goner." The story began, "On Saturday, art history professor Jose Arguelles was named to share the teacher-of-the-year award by the University of Colorado at Denver. On Monday, he was fired because University officials were not satisfied with his research."

Additional details provided in the story were that Arguelles had published four books on his research, one of them with the University of Chicago Press, and that he was selected to win his teaching award by a committee consisting of faculty members, students, and alumni, on the basis of student nominations and personal classroom observation. He was told by his dean that the college president chose to dismiss him because his research was "too non-traditional." The dean added that the teaching award did not make a difference in the decision, since Arguelles' teaching "was acknowledged by all parties as outstanding."

I don't want to make too much of the unfortunate Professor Arguelles...perhaps there really were good reasons for letting him go that I don t know about. But this is not a unique story: faculty members who gain teaching plaudits and are then let go because of alleged research inadequacies abound in this

country, in all fields. However, if any faculty member doing an outstanding or even adequate job in research has ever been dismissed because of poor teaching performance, I have never heard about it.

To be a good teacher—one who teaches, not simply entertains—takes a tremendous amount of time and dedication. Course notes must be continually revised, both to keep the material up-to-date and to improve the clarity and effectiveness with which it is presented. There are 100 muddy ways to say something for every clear way. Finding the clear way is a painstaking trial-and-error process, requiring hours of preparation time for each lecture hour.

What incentive does our educational system provide for us to put in this kind of effort? Little or none, and our performance shows it. Some of us teach from course notes we wrote 10 or 20 years ago. We plow through elaborate derivations of outmoded theories. We teach slide rule techniques and approximations that were necessary before computers became readily available and then send our students out to industries in which production planning, process control, inventory management, and routine desk calculations are all done with computers. We use laboratory equipment the likes of which have not been seen in industry for decades. And we repeat the same confusing, boring, trivial, and outright erroneous material year after year.

This is clearly an unsatisfactory situation. We are attacking it to a limited extent—especially problems like antiquated equipment, which require money more than faculty time for their solution. But there is no visible effort being made to solve the problems—like the obsolete course material and the obscure and erroneous notes—for which the burden of solution falls squarely on us, the individual faculty members.

I became sensitized to this subject when I was an undergraduate chemical engineering student at the City College of New York and arrived at the point where it became necessary to take CHE 161—Chemical Process Industries. In those days, 20 years ago, this was a standard course in the chemical engineering curriculum. It has since been mercifully eliminated at most schools.

Three times a week in CHE 161, the elderly professor who always taught the course would bring in his voluminous tattered notebook with its yellowing pages, open to where he had left off, and begin transcribing facts about the chemical process industries onto the blackboard. We would then transcribe these facts from the blackboard into our notebooks. Before tests, we would transcribe the same facts from our notebooks into our short-term memories (or in some cases onto small sheets of paper or readily accessible portions of our anatomy), and on the tests we would transcribe them from whatever storage bank we had chosen into test booklets. We then forgot it all, which was the only reasonable thing to do with it.

Not all, though. Over the years I have retained three pieces of information from the course.

Fact 1: *DuPont has 14 functional departments.* That is, it had that many in 1960, when I took the course—or perhaps in 1938, when the notes were written. I never bothered to find out which was the case, since it clearly made no difference.

Fact 2: *Whale oil is produced by distilling whale blubber in an open digester.* I made a special effort to remember this one, since I knew it would be one of the best trivia contest entries I would ever find.

Fact 3: *The letters CAWSLSSSPSIPOFW are the first letters of something very important in the chemical process industry.* I have no idea what, but I'll never forget the letters, since they are also the first letters of the phrase "Call a waiter, Sam. Let's see some service, please, since I plainly ordered fresh watermelon."

So much for the lasting benefits of CHE 161! I think there may also have been something in the course about the four basic elements of matter being earth, air, water, and fire, but I couldn't swear to it.

Several questions are raised by this nonsense. Why was this man allowed to waste the time, year after year, of students in the toughest curriculum in the school—students who had no time to waste? Why did he choose to do so? Why do many of us subject *our* students to more or less similar abuse in some of our courses every year?

Because there's no institutional incentive for us to do otherwise. The only incentive at all is an internal sense of dedication to teaching, which is lacking in many of us and is a costly luxury to those of us who have it. Our universities, schools, and departments give us no motivation, reward, or even acknowledgment for spending the time it takes each year to update our knowledge and prepare new notes, examples, problems, and examinations. If we do the work we may or may not get good student evaluations, but aside from the ego gratification they afford us, they don't do us a great deal of good.

And what penalties do we pay for putting in the time it takes to do a thorough, conscientious job of teaching? Ah—that's another matter. Each minute we spend on the relatively reward-free task of course preparation is a minute taken away from the activities—research, consulting, and administration of one kind or another—for which the rewards are handed out.

The boundary condition we work with is that we all have the same 168 hours in each week, of which a limited number are available for work. Of these, a fair number are taken up by functions like meeting classes, attending meetings, advising students, attending faculty meetings, reading letters, memos, and bulletins of every color of the rainbow, writing reports, filling in survey forms, and if time permits, attending to necessary physiological functions. There is a limited time left, and we must decide how to use it.

What are our choices? We can write papers on our research and proposals to do more research. There are direct rewards for these activities—they lead to raises, tenure, and promotions; congratulatory letters from department heads and deans and provosts, chancellors, and congressmen; medals, prizes, and national and international reputation. Or, we can spend our time studying and writing course notes on material about which we have no intention of writing papers and proposals. We get no reward for this other than personal satisfaction and possibly a teaching award certificate or two.

All of us know which choice makes more sense. As the university reward system has tilted increasingly toward publications in the middle part of this century and toward fund-raising in the past decade, the decision to dedicate our time and energy to teaching has become increasingly irrational. We are not irrational beings. Most of us do not make the irrational decision.

Given this situation, how much time do we actively devote to teaching? In a recent National Science Foundation survey,[20] roughly 10,000 engineering school faculty members at doctorate-granting institutions report an average of 49 hours per work week, of which 11 are spent on instructional activities outside the classroom. These activities include meeting and advising graduate and undergraduate students outside of class, making up tests and assignments, and in some cases grading them, cutting the number of hours available for course preparation down to perhaps four or five.

As low as this value is, I believe it is inflated. The respondents certainly include faculty members whose functions involve only teaching and departmental administrative chores. Faculty members active in research—a good percentage of us now, and all of us in a few years if current hiring practices continue— spend on the average about two hours a week on course preparation, and the number for many of us is closer to zero.

However, we can't fully condemn ourselves for assigning course preparation this low a priority. Faculty members are a highly diverse group, as any veteran of department faculty meetings can attest, but we have several features in common with our fellow humans. We all have material needs—we must support ourselves and possibly others. We need recognition, praise, rewards. In these circumstances, who would dedicate himself or herself to the activity that offers the lowest prospect of either material or intangible gain?

Few without tenure, certainly. Those who try might succeed in the required balancing act by putting in 80-hour weeks, and I know outstanding junior faculty members who are seriously risking burnout by doing this. More fail, however; most who come in dedicated to the pursuit of excellence in teaching have to give up either their dedication or the prospect of securing tenure.

And just as few with tenure choose to devote their energies to class preparation. The upwardly mobile among us still need the rewards that come from research alone, and the minority of us who are content to rest on their laurels don't want to exert effort of any kind that is not mandatory. If this means teaching from decades-old notes, so be it.

Who is left? Some, certainly. There have always been teachers whose sense of responsibility and devotion to their students provides the motivation they need to teach the best courses they can, regardless of the effort required and the personal cost to them. How many are there? 20% of us? 10%? No more than one or two in each department, in my experience. Not nearly enough to serve our students properly.

WE ARE NOT MEETING THE NEEDS
OF OUR MOST GIFTED STUDENTS

Solving the problems currently besetting our society—some of which I addressed in my rather grim opening remarks—will require considerable giftedness and creativity. If easy conventional solutions were available, someone would have come up with them by now. To the extent that the problems are technological in nature, gifted engineers are needed to solve them. We are in the business of producing engineers. It would seem to be our responsibility, then, and also in our best interest, to produce some gifted ones. More precisely, we should try to avoid extinguishing the sparks of giftedness our students bring to us as part of their natural equipment.

The characteristics of gifted students have been studied extensively in recent decades, and a variety of ways to meet their educational needs have been developed. Although the emphasis in most of this work has been on primary and secondary school education, many of the results can be extrapolated to higher education. An outstanding reference on this subject is the text *Gifted Education*[21] by Linda Silverman, from which much of the material that follows is drawn.

A review of the literature on the gifted makes it clear that the deficiencies in many or most of our courses—the obsolete and trivial material, the incoherent notes—are severely counterproductive to the development of intellectual talent. Gifted students should be challenged by course material, not made to memorize and repeat cookbook formulas. They should be encouraged to question and challenge their own and others' ideas and concepts, not simply forced to swallow predigested material.

A characteristic of gifted students is that they often work fast—some can absorb and apply material at a rate two, four, or ten times faster than can their less gifted counterparts. There is ample evidence to show that when you force a gifted student to follow the pace of a class geared to the average student, you are apt to lose her—she is likely to become bored with the subject, and while she may do well and get her A, her giftedness will be channeled in other more interesting directions. If all her courses

fall into the same tedious category, the profession is likely to lose a potentially valuable contributor—and we have to accept the primary responsibility for this loss.

Additional needs of gifted students are suggested by a consideration of what constitutes giftedness. A widely-used pedagogical model is *Bloom's Taxonomy of Educational Objectives*,[22] which proposes a hierarchy of thinking skills. Beginning at the lowest level, the categories are knowledge (memorization), comprehension (understanding), application (using), analysis (taking apart), synthesis (putting together), and evaluation (judging). The last three—analysis, synthesis, and evaluation—are sometimes collectively referred to as the higher-level thinking skills. Giftedness might be defined as the ability to utilize these skills when it is appropriate to do so.

I suggest that the difficult problems facing technology now can be solved only through the systematic application of the higher-level thinking skills. Unfortunately, most education at the primary and secondary levels, and an unfortunate amount at the college level, involves the lowest of the thinking skills—pure memorization. I offer as Exhibit A the course that taught me how whale blubber is distilled. I offer as Exhibit B the institution of the closed-book examination.

By their very nature, closed-book tests place a premium on memorization and in doing so create an environment different from any real-world environment. No industrial situation requires people to transcribe a bunch of facts and derivations from memory within a rigidly specified time period. Open-book tests, on the other hand, eliminate memorization as a factor and force the students to exercise higher-level thinking skills in an environment that comes a great deal closer to simulating reality. I would argue that every engineering examination should be open-book.

Returning to the thinking skills, almost all undergraduate education stops at the level of application: we present formulas and try to make our students understand when and how to use them. We may or may not go into detail on where the formulas originate. Most of that sort of thing, which would fall into the category of analysis in Bloom's Taxonomy, is reserved for graduate school, and the derivations we present to undergraduates are generally glossed over by us and ignored by them.

The higher-level thinking skill of synthesis—taking concepts and ideas from a variety of sources and putting them together in a new way—is generally omitted from both undergraduate and graduate curricula. Course subject areas are rigidly compartmentalized—you learn about thermodynamics in the thermodynamics course, solid mechanics in the solid mechanics course, and seldom do the twain meet.

Unfortunately, the problems we face now don't lend themselves to single-discipline solution methods. To attack the problems associated with hazardous waste disposal, for example, takes skills generally associated with the areas of chemistry, chemical, civil, and mechanical engineering, soil science, toxicology, meteorology, and economics. One individual obviously can't be expected to have all of the requisite skills—but unless there are *some* individuals who have cross-disciplinary backgrounds and the ability and training to synthesize cross-disciplinary methods, the problems will not be solved. Since our students are not required to go through such thought processes in their education, the chances are slim that they will be able to do so in their jobs or research.

In summary, I don't believe we are providing suitable stimulation and challenge to the most gifted of our students. We force them to wade through material at an inappropriate level and pace and fail to exercise them in the higher-level thinking skills they will need to solve the problems we would like them to solve after they graduate.

I should add that I am not recommending "upgrading" our courses by introducing sophisticated theoretical and mathematical development early in the curriculum. I see no virtue in subjecting

sophomore thermodynamics students to elaborate statistical formulations, for example, or junior fluid mechanics students to tensor calculus and detailed derivations of the Navier-Stokes equations. For every exceptionally gifted student who gets excited by this sort of thing, there will be 50 others, some of whom are also gifted, who wrongly conclude that this is what engineering consists of and they want no part of it.

What should we be doing for these students, then? Clearly, we can't provide five different teaching tracks in our courses—with as many as 200 students in some of our classes, it's difficult enough to manage the homework and test grading for a single track. It isn't necessary to do so, however. The following procedures could be implemented with relative ease and would go a long way toward providing the type of educational environment that brings out the best in the best of our students.

- Distribute detailed course syllabi, notes (a complete set, or handouts covering routine factual material), and a dated schedule of tests and homework assignments at the beginning of each course. Require only that the students meet the test and required assignment schedule; make everything else, like class attendance, optional.

- Emphasize understanding rather than rote memorization, e.g., by giving only open-book tests.

- Routinely provide particularly challenging problems to be done for extra credit, preferably in place of less challenging drill-type exercises.

- Extend the syllabus to provide a substantial amount of optional advanced material and provide extra credit for covering this material and completing assignments on it.

- Be sure that each course builds on its prerequisite and corequisite courses and that some problems are given which require the students to synthesize material from several courses and disciplines.

If these measures were adopted consistently, I believe we would begin to see undergraduates who better understand and are more interested in hydraulics, thermodynamics, computer design, etc., than are most of our current graduate students and some of our faculty. We would also retain a greater percentage of the highly gifted students who come to us and better equip them to utilize their gifts once they leave.

WE ARE NOT FOSTERING THE CREATIVITY NEEDED TO SOLVE SOCIETY'S MOST PRESSING TECHNOLOGICAL PROBLEMS

Having considered giftedness, we turn our attention to the related but separate topic of creativity. While there is no universally accepted definition of the term, many of those who have studied it agree that certain processes or skills are involved in creative thinking. In general, the more opportunity one has to practice skills, the better one gets at them. It seems reasonable, then, that what we should be doing to foster creativity in our students is giving them as much opportunity as possible to exercise themselves in the skills that constitute components of creative thinking.

An important concept in this field formulated by the psychologist J.P. Guilford[23] is that of divergent and convergent production. In oversimplified terms, convergent production is the determination of a single correct solution to a problem, and divergent production signifies the generation of a number of possible solutions. Several divergent production skills are considered by Guilford to be indicators of creative thinking ability. These skills include fluency, or the ability to produce many responses to a given question; flexibility, or ability to see many categories of possible responses (i.e. to shift one's perceptual set); originality, or ability to produce responses that few others would think of; and elaboration, or ability to provide a richness of detail in a response.

Considering these skills together with the thinking skills of Bloom's taxonomy, we may deduce

that the individual most capable of solving the technological problems facing our society today must be both intellectually gifted—adept in the use of the higher-level thinking skills of analysis, synthesis, and evaluation—and creative—adept in divergent thinking skills such as fluency, flexibility, and originality. The gifted but noncreative individual may be skilled in convergent thinking but is not likely to come up with the innovative solution required when conventional approaches fail. The creative but non-gifted individual will think of a great many innovative ideas, but may lack the analytical ability to carry them through to their final form and the evaluative ability to discriminate between good and bad solutions.

I have suggested several ways in which we are failing to meet the needs of our gifted students. What of the creative ones? Creativity, unfortunately, is a much more elusive and ill-defined concept than intellectual giftedness. Before we can examine the question of how to foster it, we must consider the problem of identifying the creative among our students.

This is not a question that has occupied the attention of a great many engineering educators. One who has thought about it is Professor Robert Reid of the Massachusetts Institute of Technology, who has surveyed the psychological literature on creativity and considered applications of creativity research to engineering education.[24] Reid suggests that the following traits indicate the possible presence of creative potential in students:

1. High level of independence
2. Erratic grade record—mixture of high and low grades
3. Broadness of background and interests
4. Evidence of creative performance, in or out of course work

Studies of creative individuals also refer to the possible presence of such personality traits as self-confidence bordering on arrogance, introversion bordering on misanthropy, and indifference bordering on hostility directed at anything that diverts the individual from his immediate areas of interest—such as courses in unrelated areas. Of all of these characteristics, only the fourth of those numbered above provides a direct indication that the individual's contributions might be valuable; the first three and those mentioned subsequently are usually regarded in a negative light.

The oddball makes us uncomfortable. The student in the next-to-last row, chin in hand, looking bored or apparently sleeping, who suddenly pipes up in the middle of a phrase with the killer question that zeroes in on the flaw in our logic, our unstated assumptions, the exception we never thought of…this is not someone we welcome in our classes with gladness in our hearts. Those of us without exceptional degrees of self-confidence don't particularly want to see him coming, and if there's a way to put him down or shut him up, it's tempting to grab it. Failing that, we go to the delay game: "Good question, but we really don't have time for it now. I'll get back to you later," and that's often the last anyone hears of it, unless our nemesis is pushy enough to come back with it.

Obnoxious behavior may in fact be the negative sign we take it to be; however, it could also be an indicator of the type of thinking ability needed to solve problems that defy conventional solution. When we give out grades in our courses or projects, and when we advise students and either encourage or discourage them from continuing in our programs, and when we evaluate applications for graduate school, we might look twice at the individuals who display the traits we have been discussing and hunt for evidence of a creative spark in the erratic or socially unacceptable behavior with which they often confront the world.

Suppose we agree that it is in our interest to help our students develop their creative abilities. What does this mean we should be doing that we are not now doing? Again, it seems reasonable to suggest that the more provision we make for exercise of the components of creativity—divergent

thinking, generation of alternative solutions to problems—the better we prepare our students to utilize whatever abilities they may have along these lines when they go out to work.

Here, we are failing abysmally. In my entire educational experience, from the first grade through my last year of graduate school, not once was a word breathed to the following effects:

- *Some problems do not have unique solutions.*

- *Some problems may not have solutions at all.*

- *Problems in life, unlike problems in school, do not come packaged with the precise amount of information needed to solve them—some are overdefined, and most are underdefined.*

- *Problems in life, unlike problems in school, are open-ended.*

- *The more possible solutions you think of for a problem, the more likely you are to come up with the best solution.*

- *Sometimes the solution that sounds most foolish is the best solution.*

Appearing foolish and being wrong are risks we take every time we venture solutions to nontrivial problems, and being creative requires taking these risks. Another thing nobody told me in my education is that in engineering, as in the rest of life, risk-taking is often necessary—what is important is to take the risks consciously, weighing the consequences of failure against the rewards of success.

The educational process has not changed that much since I was in school. We still require purely convergent thinking from our students. We make the basis of all of our teaching the precisely defined, closed-ended problem with one and only one correct solution. We tend to get annoyed when students generate something other than what we had in mind—it confuses the grading terribly. When students come up with off-the-wall ideas, our impulse is to prove them wrong—both the ideas and the students.

Eventually the students get the message. In the best of cases, they'll simply stop telling us the ideas and instead concentrate on figuring out what we want and giving it to us. In the worst case—when they find no outlet in the educational system for their creative impulses—they'll turn these impulses off, perhaps for the rest of their careers and lives. More losses to society, for which we have to accept a major share of the responsibility.

There is considerable evidence that creative thinking skills can be developed through suitable classroom techniques of the types suggested below:[21,25]

- In every course, assign some open-ended and underdefined problems, and regularly include more information than is needed to solve problems with unique solutions.

- Assign problems that require the generation of alternative solutions, and give credit for fluency and originality as well as ability to discriminate between alternatives.

- Be on the lookout for solutions—correct and incorrect—that show clear signs of creativity, and take care not to discourage the imaginative impulses that gave rise to them. Reward innovation. Reward ideas drawn from fields other than that of the course in progress.

- Encourage constructive self-criticism and the habit of working out the full implications of solutions.

- Introduce creative problem-solving techniques, such as brainstorming. Emphasize the idea that in the initial stages of such activities evaluation must be suspended—the wilder the ideas, the better, as long as they keep coming.

- Provide case histories of creative problem solutions. Show how incomprehensible the process seems when only the final solution is presented; then show the steps—including false starts and blind alleys—that led to that result. In Torrance's phrase, "Dispel the sense of awe of masterpieces."[26]

- Provide exercise in problem-finding and problem-formulation, rather than exclusively problem-solving. (This is particularly important for graduate students but should not be confined to graduate curricula.) Encourage the development of problems that cannot be solved by routine single-discipline methods.

Our society needs all the creativity it can get. If our students are encouraged to use their creative abilities when they are with us and they grow accustomed to doing so, they are much more likely to be able to apply them to the problems that will confront them when they leave us.

A SYSTEMS APPROACH TO ENGINEERING EDUCATION

I began this presentation with a survey of assorted problems facing contemporary society and went on to discuss several deficiencies in the way engineering schools currently function. In this final section I propose an approach to engineering education that encompasses the areas I have discussed—faculty hiring practices, faculty incentive and reward systems, educational needs of the gifted and creative, etc.— and links the problems I perceive in these areas with the social problems cited in the introductory section.

The linkage has to do with a profound conceptual change taking place in several scientific disciplines. From the Renaissance to the early years of the present century, science had as its basis a mechanistic world view which held that any portion of the universe could be isolated and studied as an independent system. Given sufficiently clever experimentation and data interpretation, the system could be understood entirely in terms of the properties of its individual components: the whole of the system was no more or less than the sum of its parts. This philosophy, which Fritjof Capra has termed the *Cartesian paradigm*,[27] was dealt a fatal blow by Einstein and the architects of quantum mechanics, who showed the theoretical impossibility of studying a system without taking into account the inevitable interactions between the system and its surroundings, including the experimenter.

The view of the universe currently held by physicists is extraordinarily different from the traditional mechanistic view. There are no longer such things as isolated entities, whether they are called systems, processes, molecules, atoms, or subatomic particles. The fiction of the independence of a system from its surroundings is a convenient approximation for many applications, but ultimately the approximation must fail. The only way to understand a system fully is to understand all the relationships between the system, its components, and the rest of the universe. This is of course a practical impossibility, but it provides a valid conceptual basis for all scientific effort.

In *The Turning Point,*[27] which I would propose as required reading for every university curriculum, Capra observes that the inadequacies of the Cartesian paradigm in the physical sciences are paralleled by failures of this viewpoint in such fields as biology and medicine, psychology, and economics. He gives numerous examples of the ways in which the social and economic problems faced by contemporary society result from a rigid adherence to the mechanistic world view and provides extensive validation of the assertion that systems cannot be fully understood by considering only subsystems. The whole is always greater than the sum of its parts.

One of the major intellectual endeavors of this century has been the development of a theoretical framework for this viewpoint—general systems theory[28–31]—that articulates principles of system organization and the interactive processes that occur among systems, subsystems, and supersystems. The

theory has been applied successfully to the study of systems ranging in scale from biological cells to nations.

This essay is not the appropriate forum for a general discussion of systems theory, although I would observe that anyone who has had some exposure to concepts of process engineering—inputs and outputs, state variables, feedback and adaptive control, equilibrium, even entropy—would find himself right at home with many expositions of the theory and its applications. My point is that even though many of us have been trained to study the dynamic interactions of complex systems, we are not doing enough of it in contemporary technology. In engineering practice the obsolete Cartesian paradigm still holds sway. We isolate systems and ignore their interrelations. Decisions are made on the basis of narrow economic considerations, and there is bewilderment or resentment when these decisions lead to unrest over questions related to health, safety, or the financial well-being of those affected by the decisions.

Industries increase their level of automation or shut down plants to consolidate operations, eagerly anticipating the enhanced productivity that should result, and are surprised at the social upheaval that results from the consequent increase in unemployment. Companies faced with temporary declines in profits resulting from natural economic fluctuations respond by imposing hiring freezes, and are surprised when the engineers they need when the inevitable recovery occurs are not there. The federal government and the power industry push for increased reliance on nuclear power generation, looking at the economic benefits that should result, and are surprised at the public outcry that follows each newly perceived threat to health and safety associated with nuclear power.

The current severity of these problems follows directly from the absence of a systems viewpoint in the decision-making process. If the decision makers had considered the interactions between the systems of immediate interest and the other systems—individual and social—their decisions were bound to affect, the problems could have been anticipated and either minimized or avoided altogether.

The lack of a systems view in engineering practice may in turn be traced to the institutions where the engineers were trained—and here I suggest that general systems theory provides a useful framework for the analysis of engineering school practices. I propose that engineering schools may be collectively considered a system, subject to the general principles that govern system behavior. With this model as a basis, this entire monograph can be summarized as follows:

- The principal function of engineering schools in society—the only one no other entity can fulfill—is to educate engineers. We are failing to do this adequately, primarily because of the diminished role we have accorded education in our assignment of priorities. This failure may be viewed as a system malfunction.

- If any system—mechanical, biological, or social—fails to perform a vital function properly, the consequences affect all systems with which the malfunctioning one interacts. The failure of engineering schools to fulfill their primary function adequately creates problems in American technology, which contains the engineering schools as a subsystem. This in turn leads to problems in American society, of which technology is a subsystem.

- The deficiencies in our current practices mentioned in this paper—the way we hire new faculty, our incentive and reward system, the way we fail to meet the educational needs of our most gifted students—all contribute to the primary system malfunction and hence to the global problems cited in the first section of the paper.

The paragraphs that follow outline several properties of ideally functioning systems, both in general and specifically referring to the operation of engineering schools. In the presentation, specific criticisms and

suggestions made in previous sections are repeated in the context of the systems model.

The ideal state of a system involves a dynamic balancing of complementary functions—input and output, production and consumption, supply and demand, anabolism and catabolism. While a perfect balance can be approached, however, it can never be reached and maintained. In any system—mechanical or living—fluctuations in external conditions invariably occur, and the internal properties of the system consequently change with time. In some cases, a system perturbed from its ideal state is self-regulating and takes corrective action to bring itself back to that state. In other cases the system is unstable and the deviation perpetuates itself, whereupon the system either reaches a new and generally undesirable condition or destroys itself in the process of getting there. If the system is a chemical reactor, for example, in the best case the reactor quenches itself—turns itself off. In the worst case, it explodes.

If we view engineering schools as a system and consider our steady decrease in teaching effectiveness as an upset, we must conclude that the deviation is of the unstable, self-perpetuating variety. As the balance in our priorities began to tilt away from teaching and toward research, our hiring practices came increasingly to reflect this shift in emphasis. People whose principal concern was teaching found it more difficult to join faculties; the faculty population came to include a greater proportion of researchers; the tendency of the faculty and administration to give primacy to research was augmented, making it still more difficult for non-researchers to join; and so it has gone.

Similarly, the way we have discouraged dedication to excellence in teaching has added to the instability. As we gave increasing weight to the *Publish or Perish* rule, and then to the more modern *Get Funded or Perish* version, we forced more and more talented teachers away from teaching—either into research or out of the university altogether. Other faculty members got the message and responded by voluntarily withdrawing their energies from teaching. The limiting state we are now approaching is one in which 100% of engineering school faculties are fully committed to research. In this state, there is no possible way the system can work effectively to produce its desired product—educated engineers.

Another characteristic of an optimally functioning system—the best example being a healthy living organism—is that the system components do just what they were designed to do and what they do best. The heart functions as a heart, the liver as a liver. A body in which one organ had to do its own work and at the same time double up for another organ would not function very well for very long. This reasoning applies as well to engineering school faculties, which also have different functions to perform—teaching and research. Forcing faculty members to perform one of these functions when they have no particular ability or desire to do so guarantees inferior performance of the function and hence inferior operation of the system.

The sum total of these arguments is that engineering schools have deviated from their ideal state of being able to provide education and professional training of the highest possible quality. From the systems point of view, the remedy is clear: apply corrective measures (feedback) to counteract the deviation. Since part of the problem is a shift in emphasis toward research and away from teaching, these measures should promote restoration of the balance.

Steps of this nature include using teaching ability and interest in teaching as primary criteria in hiring new faculty members; providing incentives for faculty members to put at least as much energy into teaching as they do into research; and having the teaching done by expert teachers and the research by expert researchers. The ideal is to combine the functions in the same individuals; however, since most faculty members have strong leanings in one direction or the other, hiring some individuals primarily to do research and others primarily to teach will generally be necessary if both teaching and research are to be performed at the optimal level.

Still another mark of a properly functioning system is that its components work as required for the most efficient operation of the system, with a minimum of wasted effort. In the engineering school, obsolete or poorly-taught courses clearly represent wastes of effort, both for the faculty who teach them and the students who take them. Students—particularly engineering students—have a prodigious amount of material to learn in a limited number of class hours. If it is necessary to cram trivia into their heads, like the 14 functional departments of DuPont or the location of the university placement office (I didn't make this up—it was asked on a closed-book test in a freshman engineering course), then we should at least cut down on the time spent on this function: simply give out handouts containing the information, give tests on the handouts, and spend the class time on things for which in-class instruction is appropriate.

To minimize wasted effort in our programs, we need a suitable mechanism to detect its occurrence. Faculty and student review of courses and instructional quality is such a mechanism. We must also impose corrective feedback to remedy the problems disclosed by the reviews. One way to do this is to provide guidance and role models of teaching excellence to new faculty members and to reward excellence in teaching in the same manner and to the same extent that we now reward achievement in research. Another is to treat inadequate performance in teaching in the same manner that we now treat inadequate performance in research when decisions are made regarding tenure, promotion, and raises.

Our chronic failure to address the needs of the most gifted and creative of our students further reflects the absence of systems thinking in our functioning. Maintaining a system in its ideal state requires understanding how all system components work and providing for each component an appropriate working environment. All of us who deal with students, for example, know that they are not all equivalent—we're reminded of this every time we give a test. And yet, we assume that the same educational environment is appropriate for all of them. If we followed a systems approach, we would recognize that different groups of students have different needs and should therefore be provided with differentiated instruction.

This argument can of course be pushed to its absurd extreme by stating that every student is a unique individual and so should be exposed to an individually tailored curriculum. This approach is not supported by the systems view, however—it would clearly benefit the students, but it would also strain available system resources well past the breaking point. What is required—what is always required by the systems approach—is a balancing of costs and benefits.

There are ample precedents for selectively aiding specific groups of students, whether they are outstanding scholars, outstanding football players, members of selected minorities, or offspring of wealthy alumni. The benefits that result from such provisions are usually financial: rightly or wrongly, most universities routinely provide special treatment to students in the second and fourth of the categories just mentioned. Recently, social benefits have also been recognized, with special treatment appropriately being granted to members of minorities historically deprived of adequate primary and secondary education.

The question then becomes, what special provisions should engineering schools offer to meet the needs of selected groups of students, and to which students should they be offered? The systems answer is, provisions consistent with the primary function of the engineering school—to produce engineers capable of contributing to the solution of the technological problems facing society. It seems obvious that if any group qualifies under this criterion it is the highly gifted, who are most likely to make the greatest contributions. Our failure to meet the needs of this group—our failure even to recognize that the needs exist—has seriously detracted from our ability to fulfill our responsibility to society.

A natural outgrowth of the systems approach to engineering education would be the development of interdisciplinary programs and the inclusion of cross-disciplinary methods in individual courses. Our

failure to incorporate the thinking skills of synthesis in our instruction clearly illustrates our continued adherence to the Cartesian paradigm. We teach rigidly compartmentalized courses, generally ignoring the interconnections between different subject areas and disciplines. The type of global thinking required for the solution of society's most pressing problems cannot be fostered by this approach. If we want our students to be able to synthesize problem solutions by crossing disciplinary boundaries, we must give them practice in doing so while they are with us.

Another illustration of the Cartesian nature of our system is the progressive narrowing of our educational base—and with this point, direct links emerge between our practices and the problems of our society. In recent decades, engineering schools have systematically eliminated courses in non-technical areas, replacing them with specialized technical courses in an attempt to keep up with the growing sophistication of modern technology. Foreign language requirements have been dropped at all levels. Instruction in the social, behavioral, and economic sciences has declined steadily, and education in the humanities has all but disappeared.

Many, but not all, of our students will practice engineering after they graduate. Most of them will enter skilled professions of one kind or another. All of them will take their place as educated members of their society. We are supposed to prepare them for all of these roles, not just the first one—to provide them with broadly-based educations, not simply job training programs. If necessary, we should defer instruction in highly specialized material to graduate school and industry. Alternatively, we should consider extending the time required for the bachelor's degree from four to four-and-a-half years.

If our recent graduates fail to appreciate the social, economic, and psychological implications of their decisions, it's small wonder: our curricula are much too narrow in scope to give them a basis for doing so. Moreover, we haven't even hinted that such implications might exist or that it might be the students' responsibility to consider them. If we slight the higher-level thinking skill of synthesis in our educational structure, we completely ignore the even higher skill of evaluation—and this, in my mind, is our single greatest failure.

In the Cartesian mode of instruction, evaluation plays little part. Problems tend to be convergent, and solutions are narrowly focused. You simply define your system, solve whatever problem you're trying to solve within the context of that system, and move on to the next problem.

This approach is no longer adequate. In every course we teach, we should present some divergent problems and require the students to generate alternative solutions and to evaluate the alternatives. We should also ask them to come up with possible drawbacks of any process or product they design. *A problem solution reached without considering its impact on systems other than the one under immediate consideration should not be considered a complete solution.* Our goal should be to make the use of critical, evaluative thinking almost a reflex.

If we can do this, the consequences for society could be profound. Engineers who are trained to question and evaluate in their coursework will continue to do so when they go out to work for industry and government. When they make decisions regarding alternative energy sources, they will weigh considerations such as safety, health, and potential environmental impact equally with short-range economic considerations. When they assign priorities for natural resource allocation, they will balance the immediate benefits of the products against the potential costs of the resource depletion, both to present and future generations.

Engineers accustomed to the systems approach will view their career decisions more critically than their predecessors have. They may decide that there are good reasons to produce specific hazardous wastes and work on the processes involved, or they may reach the opposite conclusion and decline to do

so. They may choose to engage in the production of either plutonium or solar-derived methane; clean natural food or chemically processed material that tastes like the plastic it is sealed in; artificial kidneys or electric can openers. They may decide that the continued buildup of our destructive capability is justified and participate in it, or they may decide that it is not and refuse to participate. There is no guarantee that these engineers will make the correct decisions from the standpoint of society's well-being. What is significant, however, is that they will have arrived at their decisions consciously, rather than out of ignorance of the alternatives. Bringing them to the point of being able to do so is our challenge, and our responsibility.

The goals I have proposed in this essay are clearly not all attainable by next Tuesday. I believe they are realistic, however, and many of them can be implemented fairly quickly. We can hire researchers to do research and engineers and teachers to teach engineering. We can institute significant rewards for teaching effectiveness. We can carry out reviews of curricula, courses, and teaching and use the results as part of our regular faculty evaluation procedures.

Other changes I have suggested will take longer and can only be done effectively once we have a full complement of dedicated teachers on our faculties. Modifying our instructional methods to take into account the needs of the highly gifted and creative; systematically introducing cross-disciplinary approaches and synthesis skills into our courses; and infusing in our students a sense of social responsibility and the need to evaluate technological decisions in light of this sense, will take time and may cost us a great deal of effort and money. However, thinking back to my opening remarks and reflecting on the problems we are now facing as a society, it is likely that if we do not make these changes, the cost to all of us will be far greater.

ACKNOWLEDGMENTS

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