CAN WE TEACH OUR STUDENTS TO BE INNOVATIVE?

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I claim no special expertise on creativity, discovery, or innovation, and this paper does not purport to be a review or scholarly treatise on any of those subjects. Throughout my academic career, however, for practical as well as philosophical reasons, I have strongly encouraged my students to be creative in their experimentation, modeling, analyses, problem-solving, and designs. This paper describes techniques and subject matter that have proved successful in that regard.

Scientific and technical articles in the archival literature, even the most influential ones, rarely illuminate the creative process itself, because the misdirections, irreproducible observations, false inferences, and discarded conjectures that are common to most investigations go unmentioned. My primary sources of guidance for students have therefore been the autobiographies and biographies of famous innovators, wherein the "dirty linen" of their daily lives and their failures as well as their successes are described. A second and perhaps equally important set of sources has been the detailed experiences of my own students and associates, from which I am only once removed.

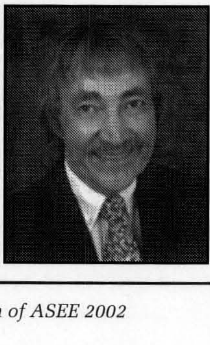
The creative process in chemical engineering differs somewhat from that in music, painting, literature, and even science, but we can learn from the more extensive and better documented experiences in those fields if we are careful to keep the differences in mind. Also, we do not need to conceive of ourselves as being on the same intellectual plane as Beethoven, Rembrandt, Shakespeare, and Newton in order to benefit from the study of their paths of creativity and discovery. In that sense I have chosen four well-known personalities from science as primary examples.

ILLUSTRATIVE EXAMPLES FROM SCIENCE

Functioning in his manifestation as an artist, Leonardo da Vinci in 1515, at the age of sixty-three, drew a sketch of himself watching the flow of a river past obstructions.[1,2] In his manifestation as an acute observer of natural phenomena, Leonardo noted the chains of stationary vortices generated immediately downstream from the obstructions, while in his manifestation as a scientist he included in a descriptive caption a mechanistic explanation for this behavior. That sketch and caption illustrate not only his universal genius, but also the sometimes complementary roles of observation, graphical representation, and science.

Invention of the telescope in the Netherlands inspired Galileo Galilei in 1609, when he was forty-five years old, to construct a greatly improved one for himself. His early observations included discovery of the four largest moons of Jupiter, the phases of Venus at different times of the year, and the existence of sunspots. From the periodic disappearance and reappearance of some of the latter, he inferred that the sun rotated and estimated its rate. In an even greater intellectual leap, he recognized that his observations of Jupiter and Venus provided an irrefutable confirmation of the Copernican theory of the solar system.

Issac Newton was only twenty-three years old in 1666 when he conjectured that the same force that causes an apple to fall to the earth might extend to the moon. Seeking an explanation for the failure of the moon to fall led him, by means of very intense and extended cerebration, to conceive of a mechanistic description and explanation for all kinematic phenom-



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ena. The story of the apple may be apocryphal, but it originated from Newton himself.

In 1928, Alexander Fleming (at the age of forty-seven) was probably not the first to observe the destruction of bacteria in the laboratory by a contaminant, but he had enough perception and initiative to identify the agent in this instance as *penicillium rubrum* and to successfully explore its potential as a therapeutic agent. This led others to pursue the production of an antibiotic drug.

The recurrent pattern in these four episodes is the recognition of anomalous behavior by a perceptive observer and the persistent intellectual pursuit not only of an explanation, but also of the possible consequences of that explanation. This is the most important commonality of discovery and innovation in the physical sciences and engineering. We can, however, learn many other lessons concerning the process of innovation from the experiences of these and other recognized masters of the arts and sciences.

CHARACTERISTICS OF INNOVATION

The common and salient characteristics of the great innovators provide useful insight and guidance for would-be innovators. Some such characteristics and circumstances are identified in the following paragraphs.

◧ *Resilience and Self-Confidence*

Most discoveries and new ideas are greeted with skepticism, misunderstanding, lack of appreciation, or outright rejection. The writings of the great innovators reveal that they all encountered such reactions but had sufficient self-confidence to persist.

For example, the opening lines of *Sonnet LV,* "Not marble not the gilded monuments of princes, shall outlive this powerful rhyme," demonstrates that Shakespeare knew that he was not just another poet and playwright, and indeed was not inferior to the royalty or the wealthy in true worth.

Beethoven's own pupil, Czerny, neither understood nor appreciated the sublime music of his final period, saying, "Beethoven's third style dates from the time when he became gradually completely deaf.... Thence comes the dissimilarity of style of his last three sonatas.... Thence many harmonic roughnesses...." But Beethoven, in 1817 at the age of forty-seven, is reported to have said of this same period, "Now I know how to compose."

Rossini clearly understood his place in the musical hierarchy, saying "I know I am not Bach, but I also know I am not Offenbach."

The trilogy, *Joseph and His Brothers,* by Thomas Mann[3] is an inspirational study of the constructive behavior of a solitary genius surrounded all of his life by people whom he knew to be intellectually and morally inferior.

When Gladstone, then Chancellor of the Exchequer, interrupted a description by Faraday of his work on the then-new subject of electricity with the impatient inquiry, "But, after all, what use is it?", the latter is reported to have responded with, "Why sir, there is every probability that you will soon be able to tax it."

Galileo recanted before the Inquisition in order to save his life, but he never stopped trying to educate the leaders of the Church and he never lost confidence in the ultimate recognition and acceptance of his findings and conclusions by his peers in science.

Newton was perhaps more fully recognized and appreciated for his scientific accomplishments in his own time than anyone except possibly Einstein in his time, but even so he was virtually paranoiac concerning the rejection of his findings or the perceived usurpation of credit for them by others. On the other hand, he never questioned his own intellectual superiority or the significance of his contributions, and indeed finally produced his *Principia*[4] to remove any doubt about that for all time.

Lord Kelvin is reported to have told an incredulous Lord Rayleigh that as his predecessor as President of the Royal Society he had rejected for publication the now-famous paper by Josiah Willard Gibbs, "On the Equilibrium of Heterogeneous Substances," because the *phase rule* that it introduced was too simple to be correct or significant. This rejection led to its publication in the obscure *Transactions of the Connecticut Academy of Arts and Sciences.* But Gibbs himself never doubted the significance of this work, as is evident from his subsequent submission of a reprint to virtually every famous scientist in the world and his reciprocated correspondence with many of them.

These experiences suggest that a would-be innovator must have sufficient self-confidence and resilience to persist in the face of skepticism and rejection.

◧ *Patience and Refinement*

Leonard Bernstein demonstrated vividly in the early television program *Omnibus* that Beethoven composed his *Fifth Symphony*, not in an explosion of inspiration but rather by incessant revision and refinement.

Newton conceived of his mechanics in 1664-1666 in a great burst of creativity, but eighteen years of incubation passed before he was provoked by the threat of loss of priority to publish this work. Even then, three more years of intense mental labor were required to correct, complete, and update these ideas for the *Principia.*

Seventeen years were required for the critical observation of Fleming to be translated into the first treatment of a human patient with penicillin, and that period of time was undoubtedly shortened by the urgency and high priority imposed by World War II.

Subrahmanyan Chandrasekhar, whom I was privileged to know (and whose book on creativity, *Truth and Beauty: Aesthetics and Motivations in Science,*[5] has been singularly helpful in formulating this paper) encountered so much hostility from his mentor Eddington and others for his theories on black holes that he abandoned the subject for other aspects of astronomy. But when he received the Nobel Prize forty-some years later in 1983, at the age of seventy-three, it was in part for that early, now-accepted work on cold stars.

The lesson here is that an innovator should not expect immediate acceptance of his initial discovery. Rather, he should be prepared to be patient and willing to persist, even if years of further work in the sense of refinement and confirmation prove necessary.

Age and Creativity

The opinion that all important discoveries are made at a relatively young age is widely held among mathematicians and physicists. For example, G.H. Hardy[6] in *A Mathematician's Apology,* an essay said by C.P. Snow to be "The most beautiful statement of the creative mind ever written or ever likely to be written," asserts that "No mathematician should ever allow himself to forget that mathematics, more than any other art or science, is a young man's game.... Galois died at twenty-one, Abel at twenty-seven, Ramanujan at thirty-three, Riemann at forty. There have been men who have done great work a good deal later,... [but] I do not know an instance of a major mathematical advance initiated by a man past fifty.... A mathematician may still be competent enough at sixty, but it is useless to expect him to have original ideas." He further says, quite unkindly, of his own, far greater protege, "The real tragedy about Ramanujan was not his early death. It is, of course, a disaster that any great man should die young; but a mathematician is comparatively old at thirty, and his death may be less of a catastrophe than it seems." For someone who criticized some of Ramanujan's proofs for their lack of rigor, this is a strange conclusion. What evidence is there that Galois, Abel, Ramanujan, and Riemann would not have continued to be creative if they had lived for a longer span?

The inclusion of ages in the preceding paragraphs and the focus on age here has the objective of throwing light on the possible productive span of creativity for engineers. No one would seriously assert, in the face of overwhelming evidence to the contrary, that creativity in painting, music, and literature is limited to the very young, but the evidence in science is somewhat contradictory.

Newton is often cited as the prime example of a scientist who did all of his greatest creative work while very young. Indeed, he did first conceive of his greatest contributions in mechanics, optics, and calculus at a very young age. But, he greatly improved and extended this work at the age of forty-five and demonstrated his unique mathematical acuity a decade later at the age of fifty-five when provoked by a challenge concocted by Leibnitz and Johann Bernoulli. Although Newton submitted his solution to their test problem anonymously, Bernoulli commented upon receiving it that "*tanquam ex ungue leonem,*" or, loosely, that "the lion may be recognized by his paw print." Newton's celebrated hiatus from science and mathematics at the age of thirty-three was not really due to his advancing years, but rather to his greater interests in religious history and alchemy. He subsequently welcomed the opportunity to leave Cambridge University and become Warden of the Mint because of the greatly reduced danger of his exposure and persecution as a religious heretic.

Thomas Huxley, a famous contemporary of Darwin, asserted that "A man of science beyond sixty does more harm than good," even though the latter was sixty-two when he published *The Descent of Man.* Perhaps Huxley did not count the period of reduction of ideas to print. When Lord Rayleigh, at the age of sixty-seven and still active, was asked by his own son to comment on this statement by Huxley, he replied, "That may be, if he undertakes to criticize the work of younger men, but I do not see why it need be so if he sticks to things he is conversant with." Rayleigh's own work supports this opinion; in a memorial lecture upon his interment in Westminster Abbey, J.J. Thomson emphasized the uniformly high quality of his creative work up to his death at the age of seventy-seven.

The span of creativity of engineers is perhaps known with even less certainty than that of scientists and mathematicians, but is presumably not so short as to discourage us from trying to develop an innovative outlook by our students.

Concentration and Freedom from Distraction

The power and exercise of concentration is an aspect of creativity that is sometimes overlooked. An ability and willingness to focus single-mindedly on a narrow topic for an extended period of time has often been cited as an essential attribute of Newton. It is probably not a coincidence that his *anni mirabiles* overlapped his hiatus from Cambridge owing to the threat of the plague. Again, when completing the mathematical components of *Principia* some years later, Newton went days with almost no food or sleep. An unwillingness to continue to make such a commitment and the related sacrifices with increasing age and acquired social obligations may be an uncited factor in the context of the previous subsection.

The loss of hearing and the virtual loss of human companionship by Beethoven may have been essential to his final greatest burst of creativity.

The self-portrait of Leonardo mentioned earlier implies the leisure to concentrate mentally on a single aspect of nature.

Although such extreme commitments as that of Newton, such trauma as that of Beethoven, and such relative freedom as that of Leonardo are not necessarily a prerequisite for creativity, it is not unusual for most of us lesser mortals to have our best new ideas when we are temporarily free from the distractions of our everyday life—for example when we take a long solitary walk, awaken in the middle of the night, or daydream at a symphony concert.

◧ *Interactions and Challenges*

Despite the popular image of the solitary lonely genius, interaction with one's peers as conferees or collaborators or even as competitors, often plays an important role in innovation. Again, Newton serves as a prime example. Although he protested bitterly over his perceived harassment by Hooke, Leibnitz, and others, had he not been provoked and challenged by them over priorities, and had he not been urged and assisted by Halley, he might never have completed or published his work. Although Newton rarely gave any public credit to his associates and correspondents, he tested his ideas on them and pestered them for their own derivations and experimental data.

Mozart was certainly spurred in his own operatic compositions by the competition and greater popularity of Gluck and others.

The implication is that innovators are apt to benefit from interactions, challenges, and competition, and should seek rather than avoid them.

◧ *Fallibility*

Even the greatest geniuses have proven to be fallible. For example, Leonardo sketched symmetrical pairs of vortices instead of the antisymmetrical ones that are now known to be formed. Newton made countless minor errors in his zeal to explain and model all physical phenomena. For example, he derived an erroneous expression for the velocity of sound in gases because of the premise that the behavior is isothermal. Lord Kelvin estimated the age of the earth by thermal modeling, but was in error by several orders of magnitude (thereby appearing to contradict the then-new theory of evolution) because of the neglect of heating by radioactive decay, neglect of the effect of pressure on the melting point of the magma, and several other simplifications.

These examples of fallibility by truly great men illustrate two fundamentally different sources of error. That of Leonardo is simply one of misobservation. Those of Newton and Kelvin were, on the other hand, the result of incomplete models; the concept of isentropy and the existence of radioactive decay had yet to be discovered. The latter examples provide a warning that is still valid today...predictions based on a model are no more reliable than the model (or, in the jargon of computing—garbage in, garbage out). They also suggest a revived opportunity for innovation when newly discovered phenomena are incorporated in old models.

Acknowledgment of Error

Progress in science and engineering occurs primarily by replacement of the old with the new and improved; that is, by innovation. But resistance to change is deep-seated in human nature. Sometimes that resistance has religious or philosophical roots. Nietzsche has said, "Convictions are more dangerous foes of truth than lies." Sometimes resistance is visceral; it is painful to have to replace knowledge acquired only after long and arduous study. The greatest resistance to scientific innovation, however, often comes from those whose cherished contributions are thereby consigned to the dustbin of history. The resistance may then be purely defensive and less than objective.

Newton serves as a bad example in this respect. When his prediction of the velocity of sound did not agree with experimental measurements, he inexcusably manipulated the data in order to produce conformity.

Acknowledgment of error by one's self as well as by one's icons is often the first step to further innovation.

◧ *Simplification*

Considerable understanding of the most complex concepts of science may often be achieved by means of simplifications, analogies, and rationalizations, even though their original derivations followed a much more complex path. For example, the proportionality of energy to mass in the most famous expression of Einstein is an obvious necessity. It follows that the proportionality constant must have the dimensions of velocity squared. It is then a reasonable conjecture that this velocity is that of light. Similarly, Planck's equation for the spectral distribution of radiation may be recognized as the simplest one that reduced to the previously known asymptotes for short and long wavelengths.

It may also be inferred that complex problems in engineering, such as the behavior of an automobile engine, may be most easily understood qualitatively and quantitatively if they are reduced to their component parts for asymptotic conditions or special cases. Skill in simplification—that is, in identifying and modeling the most important factors while eliminating the secondary ones tentatively or temporarily—is a common characteristic of successful innovators. Newton recognized the importance of three-body interactions, but realized that he had no chance of solving them until he had mastered two-body interactions.

◧ *The Prepared Mind*

Leonardo's experienced eye as an artist assisted him in his scientific observations and designs.

Although Newton was relatively unschooled in mathematics and science when he came to Cambridge, part of his genius is reflected in his recognition of the need to acquire a knowledge of these subjects extending to their very frontiers, in his willingness to make the corresponding commitment and effort, and of course in his accomplishment of this goal in an incredibly short time.

Fleming was prepared for his discovery of penicillin and for its internal application by his experiences in treating infected wounds in World War I and his recognition, even then, that bacteria could hide in the edges of a wound and thereby resist external treatment.

Recognition of an anomaly implies knowledge of and an expectation of somewhat simpler behavior. The explanation of an anomaly in engineering often requires knowledge of particular aspects of mathematics and science and/or of experimental techniques beyond those required for the originally anticipated behavior.

TEACHING INNOVATION IN A RESEARCH PROGRAM

Finally, let us turn to teaching innovation and other forms of creativity in the process of guiding research. Looking back over my academic career reveals that my largely intuitive efforts in this respect have been surprisingly successful. Over eighty percent of my research students, both undergraduate and graduate, have made identifiable innovations or significant discoveries in methodology or results. These accomplishments are mentioned because innovation in the sense considered herein is welcome, but not required, in doctoral work; a contribution to knowledge may be new, meaningful, and significant without necessarily involving innovation.

Whatever success I have enjoyed in motivating my students may have been in large part a fortuitous consequence of my predilection for exploratory research and of my insistence on a simultaneous combination of experimental and theoretical work. A third, more subtle factor has been a persistent effort to convince students that they are capable of innovation and that they can afford to take risks while within the relatively sheltered academic environment. These charcteristics of my own work are cited because of their possible relevance to the subject at hand—not because they necessarily have any special merit in the greater scheme of things.

Exploratory Research

Exploratory research is here defined as an open-ended problem for which the behavior to be determined is unknown, perhaps even in a gross sense. A further characteristic of exploratory research is the freedom and willingness to abandon, at least temporarily and tentatively, the initial objective in order to pursue the explanation of an anomaly and to speculate on its possible consequences. Anomalies are more likely to be observed in open-ended problems, and students are then more likely to be on the alert for them.

The distinction between exploratory and more-narrowly constrained research did not arise with Leonardo, Galileo, Newton, and Fleming and does not with most current scientific research. It is, however, often an important distinction and inhibiting factor in industrial research because of considerations of time, cost, and risk, and even in academic research in engineering because of the conservatism of the sponsoring agencies and their almost exclusive favoritism to a few currently anointed topics of the moment.

Those doing exploratory research often encounter an obstacle that did not exist or was less formidable in the past. The diversion to a new objective in midstream often requires utilization of topics in mathematics and science beyond those encompassed by the original objective. Doctoral students are nowadays generally discouraged by their advisor and academic department from taking any advanced course work that is not viewed as directly relevant to their preplanned research. At the time of recognizing the need for such specific extended learning, it is usually impractical to undertake the appropriate formal course work even if it exists. This imposes a serious burden of self-study that is not always pursued. The guidance, encouragement, and patience of the advisor is critical at this point.

Opportunities for Exploratory Research

Discoveries beget further discoveries. New developments in mathematics and science suggest improvements in engineering. New and improved materials, new and improved devices, and new societal concerns provide opportunities, motivations, and incentive for exploratory research and thereby innovation. For example, the research of my students has been stimulated and supported in part by concerns with such then-current topics as nuclear weapons, nuclear reactors, accidental chemical detonations, jet-engine noise, ignition of solid propellants, storage and transport of cryogenic fluids, fluid-mechanical behavior in space flight, reduction of air pollution from combustion, incineration of toxic substances in airplanes and hospital rooms, improvement of solar collectors, more efficient heating of working and living spaces, the Strategic Defense Initiative, enhanced rates of steam generation, controlled extrusion of Plexiglas®, and the growth of improved silicon crystals. A practical motivation of current societal interest is usually inspiring to engineering students because it provides a sense of relevance without necessarily restricting the freedom to explore innovative approaches.

The combined improvement of computer hardware and software has greatly impacted our ability to solve complex models numerically. For example, the development of direct numerical simulation has stimulated a new interest in turbulence, while methods for sensitivity analysis and methods for solving the sets of stiff differential equations that describe free-radical chemistry have greatly abetted the modeling of combustion. The development of lasers and spectrophotometers has greatly improved our ability to make experimental determinations of all sorts. It follows that students undertaking exploratory research must be alert to and if appropriate, master, new developments in contiguous fields. They cannot and should not depend wholly on their advisor in this respect.

The Synergy of Experimental and Theoretical Work

The advantage of a combination of experimental and theoretical work was recognized by Newton who, according to Chandrasekhar,[5] said (rather awkwardly to modern ears), "For the best and safest method of philosophizing seems to be, first to enquire diligently into the properties of things, and of establishing those properties by experiments, and then to proceed more slowly to hypotheses for the explanation of them. For hypotheses should be subservient only in explaining the properties of things, but not assumed in determining them; unless so far as they may furnish experiments...".

In the past, unexpected behavior was most often identified from experimental measurements, but now, because of the increased capability for solving mathematical models numerically, previously unobserved or unrecognized behavior is often predicted. For example, in our own work, multiple stationary states in thermally stabilized combustion and a finite time of induction for the onset of thermally generated sound waves were both first identified from numerical solutions and subsequently confirmed experimentally.

Students often resist a commitment to both experimental and theoretical work because of a personal predilection, but more often, in truth, because of their lack of experience and/or confidence in doing one or the other. They invariably end up most proud of their work in the resisted category. Their opportunities and capabilities careerwise are obviously enhanced thereby.

Guidelines for Innovation

Students are not ordinarily inspired by a detailed prescription or discussion of how to innovate, and are either intimidated or amused if told that they should emulate universally recognized geniuses such as Leonardo, Galileo, and Newton. On the other hand, they respond very positively to the anecdotal experiences described above, which emphasize the influence of everyday human factors and foibles on the lives and work of the great ones. I do not present such material in lecture form, but rather on an *ad hoc* basis when appropriate and relevant, and then only informally during individual or group discussions.

Establishing the Proper Environment for Innovation

Innovation usually involves some courage and risk. In order to be willing to take such risks, students must sense that their ideas, however incomplete, unrealistic, or naive, are welcome and will be given fair consideration. Criticism from their peers in small informal groups, such as the weekly gatherings of all my research students, is more easily accepted than from their advisor, and particularly so when it becomes a normal procedure. Surprisingly, students who are working on quite different topics often make very constructive and even innovative suggestions in that format. Interaction with other students who are clearly doing innovative work is both encouraging and challenging.

Students should be expected to justify their new concepts or interpretations, at least after some time for incubation, but a defensive posture on their part is to be avoided if possible. One of the most delicate tasks of an academic advisor is to redirect the efforts of a student from a blind alley or unproductive path.

Presentations

Presentations by my students at departmental seminars have engendered one surprising, but perhaps significant, response. On several occasions, other students have remarked that, because of the exploratory nature of the research and the focus on innovation, "your students have more fun than the rest of us." The joy and satisfaction in doing innovative work is not to be underestimated. Such experiences may have a career-long positive influence.

In addition to exposing their innovative work for recognition and criticism, presentations by doctoral students at professional society meetings are of critical importance in terms of raising their self-confidence. The implicit acceptance of the successful performance of innovative research at the frontier of their field provides a great boost in that respect at a critical time in their career.

Association with the Immortals

New findings, either experimental or analytical, often call for the extension, correction, or displacement of some aspect of the work of the great scientists and engineers of the past. At first, this is somewhat frightening. On the other hand, the psychological rewards of success in this respect are immeasurable. Such experiences by my students include successfully challenging the advice of G.K. Batchelor, disproving a theoretical expression of Einstein, displacing results of Rayleigh, Boussinesq, Prandtl, von Kármán, Colburn, Spalding, and Zel'dovich, correcting the model of Fourier for transient conduction, and extending solutions of Birkhoff, Debye, Schwarzschild, and Chandrasekhar.

Reviews and Rebuttals

Apart from appropriate criticisms and challenges, innovative results sometimes engender an apoplectic response from a reviewer whose work is being corrected or displaced. In addition, physicists are sometimes enraged by the audacity of an engineer who even attempts to correct or displace the work of their icons. On the other hand, the famous scientists themselves with whom we have been privileged to interact on a personal basis, including George Uhlenbeck, S. Chandrasekhar, Peter Debye, and John von Neumann, have invariably welcomed and encouraged our attempts to extend their own earlier work.

Detailed Examples

Reviews of the research of my students and associates in the context of innovation have previously been published in two categories: theoretically stabilized combustion[7] and heat

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transfer.[8] Those articles are suggested as supplements for the present one.

TEACHING INNOVATION IN A SEMINAR

For many years I conducted a seminar for doctoral students, both my own and others, in advanced topics in fluid mechanics and heat transfer. The format consisted of three assignments for study, oral presentation, and written presentation, first on some classical topic, second on some new analytical development in the recent literature, and third on a theoretical investigation of their own of limited scope. This process may be regarded as a three-step initiation into innovative analysis. Many of the students in the seminar achieved a publishable result, with the same psychological benefits mentioned above in connection with innovation in doctoral research. This seminar eventually fell victim to the unwillingness of the other faculty members to tolerate such a distraction from the sponsored doctoral research of their students. Indeed, the participants were often inspired to make a significant, perhaps excessive, commitment of time to their analytical investigation because of the excitement of doing innovative work as compared to the more routine work of their doctoral research.

TEACHING INNOVATION IN THE CLASSROOM

Teaching innovation in the classroom is almost certainly more effective within the context of a regular technical course rather than in a special course or special designated segment of a course on that topic. Even within the context of a regular course, the task is more difficult than in the context of research or a graduate seminar. Within the courses and topics in chemical engineering that I have taught through the years, speculative dimensional analysis proved to be the most effective vehicle for illustration of the process of innovation with undergraduates (see Churchill[9] for a description of this methodology). The development of theoretically based correlating equations[10] as well as speculative dimensional analysis have been found to serve this role successfully with graduate students. For both undergraduate and graduate students, the Socratic method was found to be most effective on these topics.

CONCLUSIONS

The concept of innovation is highly esteemed in our current culture, but its genesis and performance are not given much direct attention. Furthermore, innovation is not always welcome when it conflicts with old habits, common wisdom, well-established practices, or deeply held convictions. In addition, innovative ideas and findings may be neglected or rejected in industry because of constraints of cost and time and in academia because of the restrictions imposed by their sponsorship.

It is, of course, easier to impart the science and art of engineering to our students than to teach them to innovate. Discovery and innovation are not programmable and are thereby difficult to formalize, but we can stimulate innovative thinking by establishing an atmosphere in the classroom, conference room, and laboratory in which it is encouraged, welcomed, and rewarded.

The experiences of my own students indicate that innovation can be fostered by proper choice of an objective and development of the proper mindset. Exploratory research is conducive to innovation because it implies a willingness to take risks and to pursue a new direction when appropriate. Establishing confidence in their own ability to innovate is a first prerequisite.

The anecdotal experiences of the great innovators serve educationally as a useful guide and source of inspiration for students, since it is evident therefrom that they too often experienced doubt, failure, and rejection, and only triumphed by persistence.

Innovative thinking is more difficult to teach in the classroom than in research, but it can be induced within the context of technical subject matter and, most effectively, by the Socratic method.

The psychological gains from innovative work may be as important both for students and for practicing engineers as the technical and intellectual contributions.

Despite the favorable image of innovation, it is invariably resisted, not only by those whose contributions are displaced, but also by those who are forced to discard common wisdom and relearn.

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