The 2007 ConocoPhillips Lecture
Oklahoma State University

Fundamentals: Wellspring for Adapting to Change

by

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ABSTRACT

Contemporary living must deal with manifold, rapid, and continuous change. Change demands adaptability. Adapting requires sustenance and skills. Are there limits to people's abilities to adjust and thrive? How do we make the whole process efficient and humane? The magnitude, complexity, and acceleration of current changes arise from integrated and sophisticated technologies and their consequences. We engineers are significant developers, functionaries, and maintainers of these technologies. Thus, sustainability demands maximum competence and wisdom of the individual and collective contributions of our profession. It is asserted here that the technological leaders and followers who most effectively preserve and enhance life, are those who best comprehend, visualize, and capably apply basic principles of natural and human behavior. It is better to know "always trues" than only “sometimes trues”. *To surmount the oncoming challenges, engineering teachers must guide their learners to possess attributes and foundations for critical thinking, wise decision-making, and effective communication.* Here, some fundamentals about Nature, people, and professionals are articulated, and suggestions are made of educational structures and experiences for their mastery.

Introduction

"**well•spring** *n***:** a source of continuous supply" [1]. Humanity is in the midst of transformations of greater magnitude and of faster rate than ever in history [2]. Human capabilities to manipulate Nature, *i.e.*, technology, continue to expand in depth and breadth in ways unimagined when I was in school. Breakthroughs are occurring in biotechnology, nanotechnology, materials science and photonics, information and communication, cybernetics, logistics, and energy utilization. Most of these terms were not in my student lexicon. Any success I have had required learning them and adapting to their technologies.

One consequence of technological change is "more of everything," including wide-ranging scales of constructive and destructive impacts on living things. To sustain and enhance the quality of our existence will require interweaving technological innovation and human values. There are particular urgencies for structural and communication infrastructures, environment, and aging populations [2].

The onrushing future puts special demands on those with engineering abilities, education, and experience. Only well-educated technologists can fully understand the opportunities, limitations, resources, processes, and outcomes of uncovering, developing and implementing technology. Therefore, their functioning must go beyond the mechanics of implementation; they must guide the transformation via the wisest choices and the optimal strategies. Without both elements, there will be degradation, and probably irreversible loss, of the benefits of technology.

Since it is in youth that the most influential stages of maturation occur, it is essential that engineering students, under the guidance of intelligent and caring educators, achieve maximum capabilities and readiness to provide the greatest value and positive impact in, and for, the future.

Innately, people want to make "sense" of what happens to them. However, technology is often not so intuitive, especially when multiple effects occur in the same system or event. Contemporary and future technologies involve many, and very subtle, interactions that can overwhelm and confuse the uninformed. Further, while the uses of technology for positive values are advancing with incredible rapidity, so is the ability to destroy. No wonder many people respond to contemporary changes with apprehension, consternation, and angst. We engineers who implement novel technologies are unlikely to have those responses, but we have our own pitfalls. For example, if we use oversimplified black-box analyses and avoid details, the unexpected and unintended consequences can impair, rather than improve, a situation. Sustainable societies will rely more and more on us to articulate the consequences of technical decisions involving conflicts of values, as well as to ameliorate harmful or inappropriate technologies.

I assert that the most effective technologists have assimilated, and can apply, the fundamentals, broadly and deeply. They can intuit, or be able to figure out, concepts, processes, qualities and quantities of maximum generalization and applicability, rather than being overly focused on simplification and specific knowledge. They are comfortable in reasoning about the variety and range of importance of the principles of the great variety of situations to be encountered. They know about the meaning and usefulness of information beyond its apparent content. Finally, they have the desire and capacity to overcome challenges, especially those technological, that appear in their own professional and personal lives, as well as in those of others.

Here I contribute my views about how engineers educators and students might think and act to maximize the benefits of technology in the current and coming world. These are not formulated in terms of curriculum, nor in specifics to Chemical Engineering, though I think they could form some of the broader elements of our courses, and are most easily applied to our discipline. There are 1) a few fundamentals of Nature, humans, and professionalism that I find helpful to keep in focus, 2) a brief justification about why fundamentals are of greatest value, 3) a review some of the challenges that learners and teachers encounter, and 4) some suggestions of ways teachers might use these thoughts for enhancing positive outcomes. I believe our most important educational task is to guide as many future engineers as possible to capably adapt to change and to fully promote professional values.

My format for an element will be to give one or more quotes of special meaning to me, usually followed by expansion of their content and implications. Unfortunately, many of them will not have full attributions or may not be precisely what was said or written by others. While their essence is with me, some of the details may be lost in the mists of my past.

What fundamentals should we understand?

About Nature

The possibilities of maxims are prodigious, and everyone has their favorites. My hope is to express some of the most valuable principles, so that they are memorable and can influence actions. I expect that only engineers can fully appreciate their significance. One of our professional responsibilities is to help others take them into account.

"The richness of Nature seems unbounded." We now see the incredible range of about 10^{40} orders of time and length scales existing and functioning in Nature. Chemical engineers are concerned with the number of atoms/molecules of interest, covering the nano, mezo, and continuum realms of systems as diverse as geological, biological, and informational. Even more, investigations and manipulations continue to uncover new combinations of scale and operation. While their complexity can obscure the fundamentals, taking full advantage of Nature's abundance requires characterizing the crosscutting basics and appreciating their similarities and differences.

"*Complexity rules, especially dynamics.*" We now know that time-varying systems, including all life forms, have intricate inter- and intraconnections that respond to their environment in an unimaginable variety of ways. To sustain activity, essentially all living creatures degrade useful energy via physical and chemical mechanisms, often by delicately balancing opposing forces. The diversity of species arises from each one finding a niche of utilization on the path from original solar input to ultimate heat output [3]. Chemical engineering deals with many such pathways, perhaps allowing us unique insights about sustainable forms, functions and innovations.

"Mother Nature cannot be fooled!" Regardless of the shell-game trickster's methods, the woman with the wand always selects the shell covering the pea [4]. Nature's processes continue regardless of what we think, feel or believe. Technologists manipulate Nature for human purposes; but regardless of the complexity of our schemes, reality is that we do not violate Natural Laws. *"Natural Laws are not like traffic laws, and true reality is not like reality TV."* Further, *"For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."* [5]. One should *"Believe in miracles, but don't depend on them"* [6].

"With mass & energy, you don't get something for nothing - AND you can't throw them 'AWAY'." Chemical engineers use fundamental material and energy balances to keep track of things. Historically, people struggled to get materials and usable energy for food, shelter, luxury and war. Nothing came for "free" but disposal was not an issue. The industrial revolution, based on fossil fuels, made extraction and utilization less labor-intensive. Now, however, humans are encountering the output side of conservation and "putting away" is clearly an illusion. The negative consequences range from toxic dumps and human-aggravated climate change to litter and local thermal pollution. Limited vital materials and useful energy sources, plus unacceptable disposal, force us to account for the complete life-cycle of objects and processes. This challenge is exacerbated by advances that quickly cause obsolescence, making it difficult to either maintain, or to get rid of, "old stuff". For example, there is now a tremendous difficulty in disposing and recycling obsolete electronic devices, including computers and peripherals, because of the sheer

bulk and variety of materials, including lead and other toxics [7]. "Throwaway" and "must-have the latest" mentalities intensify this challenge.

"Doing what comes naturally is easy; doing the opposite takes WORK - and more than you'd like." Chemical engineers recognize this as the 2nd Law of Thermodynamics. Manipulating Nature means constructing systems and executing processes that go counter to the way things work on their own. *"Remarkable things occur in accordance with Nature, the cause of which is unknown; others occur contrary to Nature, which are produced by skill for the benefit of mankind"* [8]. Work is measured by lifting a mass in a gravity field; historically, human and animal effort were used in exactly this way. Over time, clever technologists maximized efficiency to increase productivity and minimize pain. However, we now use enormous amounts of fuels to make electricity to light the dark, to level the hills and fill the valleys, to erect bridges and buildings, and to move people up, down, and all around. Interestingly, a consequence is that the real costs and effort become remote from most peoples' personal pain. Thus, "lost work" from inefficiencies and waste, or its consequences, often does not concern the public. But we know that a major contribution to the world's developing energy and environmental crises is humans behaving as if going counter to Nature is easy and can be carelessly done.

The last two fundamentals lead to several additional admonitions. *"The idea of a cow is to use green stuff and water to get white stuff; but there are always the yellow stuff and brown stuff."* [9] Even when we do the manipulation efficiently, there are still imperfections and we get unwanted side effects. *"The solution to pollution is not dilution."* [10] The lower the concentration, the more useful energy needed to purify. This is reflected in the correlation of cost of biologicals versus concentration [6] and the huge sewage treatment plants needed to remove water purposely added to human wastes. While landfills might ultimately be "mined" to recover metals and combustibles, the amount of work, and therefore the real cost, will be high. Besides, some easily made mixtures cannot be made wholesome. *"A barrel of sewage & a drop of wine make sewage; a barrel of wine & a drop of sewage make sewage."* [12] If disposal is not an option, even with the best original construction, maintenance cannot be ignored. *"Everything needs a little oil now & then."* [13] Bridges collapsing, machinery stopping, and people's joints wearing out, are all evidence that Nature degrades organized materials. If we wish to preserve their structure and function, we cannot let them go unattended. Besides just doing maintenance, informed thought is also needed to evaluate the timing and what "oil" to use.

"Driving forces make things happen - when they can." Chemical engineers recognize that spatial and temporal differences in properties such as temperature, pressure, concentration, and electric and magnetic fields - all of which can be lumped into the thermodynamic chemical potential - can cause physical movement and chemical reaction via transport and kinetic mechanisms. While some dynamics are straightforward, complex system behaviors with more than one force involved, or at the edge of stability [14], as in living systems, can be wondrous and confounding. However, knowing the fundamentals gives us the best chance to parse out and manipulate the most significant elements.

"Mathematics renders Nature." The most complete and useful descriptions of Nature are mathematical. While some technology can be done roughly, the most efficient ways have a precision that can only be utilized with mathematics. The techniques range from arithmetic to topology and beyond [15]. Quantitative descriptions of influences and effects are essential to

making complex systems accomplish our objectives. Fortunately, computers can solve the relations involved, even as we struggle for intuition.

"Accept primitives: things, properties and changes, including their uncertainty." Mathematics allows one to deduce relations, establish connections, and predict outcomes. However, at some level, elemental aspects of Nature must be accepted if we are to act at advanced levels. We can and should pursue knowledge and understanding of the origins of the universe, the meaning of life, and other great unknowns. But, for present practical purposes, we often need not know these in order to create and deal with the technology affecting our lives. Thus, while we may not get satisfying answers to many "why?" questions, we can carry out our tasks and objectives by building on apparently immutable things and actions. We just have to identify, and adequately characterize, those givens that we can, and should, deal with. We also must realize that perfect knowledge is not possible and, in fact, many phenomena can only be described probabilistically. Probabilistic and fractal descriptions of earthquakes, weather and utility demands are accurate, but the wisest consequent action is not obvious from knowing them [14].

About people

Said in engineering terms, "*Staying alive is a multimodal optimization problem with a dynamic fitness landscape."* As with other animals, most people do this instinctively, rather than develop and apply optimal strategies for dealing with life. However, by their work and experience, engineers know the nature of such situations and can develop techniques for solving that problem. *"Diversity of specialized species is Nature's way of sustaining life. Individual human survival requires one to know when & how to specialize & to diversify."* To achieve long life and social sustainability, people must optimize all aspects of their individual and species diversity and specialization. Because professional practice of technology involves such modes of operation, engineers can be models of optimization for others, and influence social policies and practices toward these objectives.

"Where there's a way, there's a will." If it can be done, it will be done, and may already have been done. This turning of an old phrase illustrates how people's minds and spirits love to explore. Novelty and escalation are part of our being. At this point in evolution, there have been enough humans to have worked on much of what Nature allows, but as technology expands the possibilities, people will continue to plunge in. We do not know for sure if there are limits to Nature, but it seems that, *“All the easy problems have been done.”* Unfortunately, *“The spirit’s willing, but the body’s weak.”* We encounter limitations after all. Physical and chemical realities ultimately impede the actuality of exploring and doing. This is not so obvious to students who are generally young, but their elder teachers are commonly very aware of this. Yet for both generations, *"The idle brain is the Devil's playground."* [16] The impact of this thought depends upon whether the creativity of the unfocused mind yields constructive, destructive, or useless outcomes. Maturing allows one to utilize “idleness” more effectively.

"Denial is not just a river in Egypt, and delusion is not just getting fewer points." *“Just because you think it’s that way doesn’t make it so.”* Unfortunately, it is easy for people to consciously or unconsciously substitute illusions for realities. As discussed below, technology is very effective in editing and distorting reality, leading us into unrealistic perceptions where logic, consistency and focus are subordinate to emotion and advertising. A vivid description of an ultimate reality based

on many technologies within reach was described by Aldous Huxley in the 1932 book, "Brave New World" [17]. Classes of humans were bred in test tubes to perform certain functions, and life was organized so to maximize “happiness” for those at every level by genetic makeup, structured activities, and drugs. The global leader says, "What's the point of truth [science] or beauty or knowledge when the anthrax bombs are popping all around you? After the Nine Years War, people were ready to have even their appetites controlled. Anything for a quiet life. Self indulgence up to the very limits imposed by hygiene and economics. Universal happiness keeps the wheels steadily turning; truth and beauty can't. People are never alone now." For decades, social critics have warned that life is becoming the “Brave New World”; it may be more true than ever.

"Humans have an incredible number of dimensions of capability and values. There is a bell-shaped population curve in each and every dimension, from world-class through professional to average and down to "not with it". Individuals must determine where on each curve they lie naturally, and where, with development, they can get to in life." Only very, very few reach world-class competence and morality in many dimensions. So the rest of us should consciously assess what to do for optimal personal satisfaction and social contribution, and then work at developing capabilities and performing accordingly. Unfortunately, it’s easy to be 'not with it' in multiple dimensions: just don't try or, even worse, ignore or interfere with others. *"The unexamined life may not be worth living, but it is surely more comfortable while you are living it.”* [18] However, operating that way is not likely to achieve ultimate satisfaction, or yield rewards from others - except in a "Brave New World".

"The reach of <u>individual</u>s has become truly global, as have the inevitable conflicts for wealth and power." It is now possible for every person to cause impact in any location of the world. Thus, those on the fringes of bell-shaped curves can reach far beyond themselves and their neighborhoods, though “*many acts of good are required to make up for a single act of evil*”. In addition, we can actually "see" from wherever we are, whenever we want, unprecedented numbers and levels of activities from celebrations and riots to extreme sports to murderous terrorism. “Entertainment on demand!” is possible and even desired. Personal ying and yang responses to such images may become even more conflicted as “information” transmission becomes more extensive and reliable, perhaps simulating those at the fringes even more.

"*Life should be spent doing what you find 'fun' within the constraints."* So what is "fun"?

fun - amusement ***<u>syn</u>*** absurdity, celebration, cheer, clowning, distraction, diversion, enjoyment, entertainment, escapade, festivity, frolic, gaiety, holiday, joke, laughter, merriment, nonsense, play, pleasure, recreation, rejoicing, relaxation, solace, sport; ***<u>ant</u>*** misery [1]

So what are the "constraints"? These start with our genetic position on our bell-shaped curves and our needs for adequate comfort and resources to avoid misery: shelter, nutrition, health care, interactions, and perhaps mobility and money or equivalent. In addition, we are constrained by everyone else deserving the same opportunities and respect we demand; one is not completely "free" because *"Your rights end where my nose begins."* Don Woods captures this last aspect extremely well with his Fundamental Rights and Guidelines for interpersonal interactions [19]. While we may prefer to pursue “fun” and to avoid “constraints”, sustainability requires both.

<u>About professionals and professionalism</u>

"The engineer, like the physician, is in a situation of incomplete information, but still must act." [20] Limited information is either because no one knows (research needed!) or one does not personally know while others do ("Well, I've never seen this before!"). The amount we can learn while in a set of circumstances depends upon the time available and how much of a "quick study" we are. We can enhance quickness with sharp focus and the critical thinking skills of assessment, analysis, synthesis and articulation. The goal should be actionable knowledge and mental processes that sort out the effects, follow Nature's logic, envision consequences, as well as recognize and enlist resources. While engineering actions are usually quantitative, to arrive at viable conclusions, as well as checking them out, we often just need qualitative and semiquantitative perspectives [21]. We need to know what form and content are needed for the wisest and timeliest action.

"*Operate via optimal procrastination & optimal sloppiness."* Do things when, and only when, they <u>must</u> be done - if ever - plus know how accurate and reliable the results must be. Doing all things is not possible, so priorities must be established. Since the temporal boundaries are now and never, the optimum time is somewhere in between, and depends in each case. Further, perfection is not achievable; in engineering we determine the applicable number of significant figures. In addressing a problem, the quality of answer should be determined in advance, consistent with the consequences of error, as well as the true amount of added value when compared to the personal, societal and economic costs.

"In engineering, the details are everything!" [22] Engineering failures and successes are thoroughly and interestingly described by many authors, especially Henry Petroski [23]. Commonly, failure appears from ignoring/omitting details vital to sustaining a whole system. This is a particular problem when the result is either the small difference of apparently well-defined large numbers or there is a tipping point [24]. Even small uncertainties of large effects can make small differences have large uncertainties. Delicate balances can be easily upset to yield a significant, and often negative, effect. Sensitivity to variations and error must be understood. Thus, "*If it doesn't matter, it <u>doesn't</u> matter; but look out when it does!"*

How do we find out what Nature will do? In the 13th century, Roger Bacon said, *"To learn the secrets of Nature, we must first observe"*. In the 20th century, Yogi Berra said, "*You can see a lot just by observing."* In between, Sherlock Homes said *"Developing theories without data is like making bricks without clay."* [25] Finally, a Murphy's Law can be stated as, *"Assumption is the mother of all screwups."* [26] A job is best done with keen examination, careful evaluation, creative integration of evidence and elimination of unjustified prejudice. Some evidence that this is not easy was presented by J.D. Fernie [25]. Galileo recorded data in 1613 that suggested the planet Neptune existed. He even put it into a drawing, but then ignored the observations. It only took 234 more years before Neptune was "found"! In the analysis of the exacting oil-drop experiments to determine the magnitude of the charge on electrons, Michelson decided *in advance* that charges could come only in integer values. There were many data in which the charge suggested one-third; these were thrown out. The result was that others discovered quarks. Finally, to confirm the payoffs of careful analysis, we should remember that *"A lot of patents came from outliers."* [27]

In general, we use models to describe, correlate and predict natural behavior. This has become a routine approach now that computers can solve the complex relationships that the models try to mimic. Much current technology has been refined with models for mechanical systems with well-defined structural properties, fluid flow with coarse-grained elements, and chemical systems with approximate quantum mechanics. The objective is to capture the essential responses of a system to varying conditions without needing to account for all complexities and ignorable effects. However, such efforts need to be done carefully. *"The problem [of beach erosion models] arises when we rely on quantitative models to find an accurate "when," "where," and "how much." We find that these types of applied models are frequently detached from reality - built on oversimplified and unrealistic assumptions about natural processes. Worse yet, we found that the modelers in many fields (global climate change being an exception) don't look back at the predictions to see if they were right."* [21] *"Simulation is seductive, but like most things seductive is not necessarily wholesome."* [28] The distinctions between a model and its reality must be known and appreciated. Does the model omit important aspects? Models need to be validated for internal consistency and compared with real data. Care should be taken that the values available are not just the results of other models or manipulations of measurements.

Beyond the above issues of modeling are their representations. I claim that *"It's not 'virtual reality', it's 'realistic virtuality'!"*. The visual images created by contemporary media - highly sophisticated technologies - can be powerful and compelling. But, even if they are representations of something real, they are restricted to the sample taken and to modifications via editing and transmission. If they are results of simulation, they can be incorrect because of the initial conditions chosen and assumed relations for interactions. The fundamental question in either case is whether we can tell if the photons from a screen are essential truth or not. *"Let the buyer beware!"*

Why Focus on Fundamentals?

Our main objective is to minimize mistakes. A translation of this is *"to supply as much truth as possible for the greatest value, through the most efficient use of resources"*. While the details are essential, their effect arises through consistent infusion of the fundamentals for validation. The idea is to start with basics that are "always true" for the situation, rather than relations that are "sometimes true". Though Big Bird of Sesame Street sings, *"Everyone makes mistakes, so why can't you?"*, we should apply that only for comfort after we've tried our best, not to justify a casual approach to professional and personal life.

"It is not enough to be right. You gotta know you're right!" [20] Being right in the face of doubt requires one to <u>sell</u> the truth. Warren K. Lewis' exhortation implies that the basis for being "right" has to arise from fundamental truths. In addition, our knowledge and skills must have a structure to be most effective. The descriptions of contemporary technology are so manifold, that only by having a well-defined set of pointers indicating priority and causality, can we expect to complete the logic and critical thinking needed for reliable adaptation [19].

Challenges to education

<u>To Learners</u>

First, there are the difficulties of assimilating the fundamentals. *"You gotta crawl before you walk before you run." "Like the development of a discipline, individual learning proceeds via induction to fundamentals then via deduction to particular situations."* [29] *"One must acquire many different ways to understand."* [30]

> **un•der•stand v. 1:** to recognize the existence of; **2:** to have thorough or technical acquaintance with or expertness in; **3:** have reason to believe; **4:** interpret; **5:** to have a sympathetic attitude; **6:** *<u>to accept as settled</u>* [1].

I think the last is the most relevant, even though acceptance does not guarantee correctness or comprehension. Haile thoroughly explores the issues of technical understanding [31], especially that there are several levels which individuals must develop in a structured manner.

Then there are the challenges of retaining, validating, and implementing fundamentals. Shulman [32] describes the learner pathologies as: *amnesia* (we forget), *fantasia* (we don't understand we misunderstand), *inertia* (we are unable to use what we have learned). In addition, there is the effort required to apply them. *"Perfect practice makes perfect."* [33] *"Don't practice mistakes!"* [34] *"You learn far more from your mistakes than from what you do right" "They will pay you the big bucks for what you can do, not for what you know." "No pain, no gain."*

Further, learners have unfulfillable expectations. *"I expect my teacher to make everything easy to understand."* [35] But what if something isn't easy to understand? While the major, and most exciting, advances are at the "edges" of a field or conjunctions of multiple fields, *"Interdisciplinary is meaningless without disciplines."*

And now there are so many distractions: media, entertainment, continuous interactions, travel; in short, a lot of "fun". In our era when comfort and diversion reign, taking the high road and the hard way has limited immediate appeal. In fact, there is evidence that young people around the world prefer not to exert the effort to learn and do science and engineering [36]. This may be evidence of De Zengotita's suggestion that little seems to matter to the young as they look around them. *"In a mediated world [of TV, iPods, etc.], the opposite of real is optional. In a virtualized environment, you are free to choose, because it doesn't matter what you choose – 'whatever'."* [37]

<u>To Teachers</u>

First, all the challenges that learners face must be of concern to teachers! Some additional subtleties that teachers also see are [32], *"there is a troubling absence of intellectual passion and commitment to ideas within our student populations."* There is the *"disconnection between intellectual learning and moral or civic learning in higher education."* In addition, we have the responsibilities of maturity and vision. *"Professions deal with parts of the world characterized by unpredictability. This includes teaching, where outcomes can vary for unexplainable reasons. We cannot remove the uncertainty, but we can grow much wiser about how to anticipate and deal with it."* A common response of unsuccessful teachers is *"Nostalgia: whatever the educational problem, combat it best by reinstating the ways we were taught when we were like our students."* and *"They have not been taught <u>enough</u> - teach them MORE."* As teachers, we profess the contradiction of rationality and evidence-based proof while we generally believe - unrealistically - that all our students can learn. Both perspectives are required, especially by our students.

What Teachers Might Do

Attitude Adjustments

First, *"Take learning seriously."* [32] As a teacher, profess the obligation, with a willingness to sacrifice, to serve by nurturing the knowledge, understanding and development of others. Teachers must "*view education as a calling*". "*To teach is to engage students in learning; thus teaching consists of getting students involved in the active construction of knowledge. . . . The aim of teaching is not only to transmit information, but also to transform students from passive recipients of other people's knowledge into active constructors of their own and others' knowledge. . . . Teaching is fundamentally about creating the pedagogical, social, and ethical conditions under which students agree to take charge of their own learning, individually and collectively.*" [38] Also, "*Do not ascribe to maliciousness what can be ascribed to incompetence, ignorance, or insensivity.*" [13] While malice may be intended, don't go there first.

Second, assess the situation realistically. What are the learners' personal and professional objectives? What are their motivations? *"You gotta wanna run to put up with the crawling and the walking."* Nobody puts out effort without justification. "*Going through the motions borders on being 'Not with it'.*" What levels are their knowledge and understanding? "*The first influence on learning is what the learner already knows. Ascertain this and teach accordingly.*" [39].

Students' engagement with learning usually depends on perceptions of educational style they and their teacher use, as well as their metacognitive awareness and strategies. Learning preferences should be assessed along with metacognition. Finally, levels of intellectual, social and moral maturity should be measured. There are useful instruments for these purposes, *e.g.*, [40]. Accumulation and connection among these data can be very useful for strategic individual guidance. Often, even the process of taking surveys is a growth experience for a student, since vital, but unconsidered issues may appear. Also, use periodic surveys such as the Minute Paper [41] to reveal the directions and amounts of change in individuals and classes. Occasional group discussions of growth, adaptation, and breadth of vision can also provide insights into relative success.

Finally, share the difficulties with students. "*All the challenges to learning are well known to engineering educators, but not commonly transmitted to students.*"

Set and Articulate Goals

Fundamentally both teachers and learners must recognize that, *"Education is a high word. It is not socialization. It is not training. It is not indoctrination. It is the internalization of the life of reason within a domain of purposes and problems. It is the cultivation of a variety of modes of thought. It is the development of the power of knowledge. We are educated only when we are able to think within multiple fields and have the ability to learn to think in other [field]s.*" [42]

The formulation should be in terms of learner outcomes and developments. The ABET 2000 *a-k* criteria is one articulation [43]. Another is the NAE Engineer of 2020 [2] who is to possess strong analytical skills; exhibit practical ingenuity; show skills in planning, combining and adapting, creativity, communication, business and management, and leadership; have high ethical standards and professionalism; demonstrate dynamism, agility, resilience and flexibility; and be lifelong learners. The Professional Development Attributes given by the University of Virginia School of Engineering and Applied Science for graduates [44] are: technological capability; leadership and cultural competence; industrial readiness; individual and team effectiveness; a commitment to ethics, values and service; effective communication skills; and a career vision. Note that required discipline-specific knowledge and skills are embedded in these overarching characteristics.

A formulation of the intended outcomes should be made manifest to one's learners and routinely referred to as expectations for them to achieve.

<u>Fashion the learning ambiance</u>

While learners often have definite ideas about the environment they wish to study within, they are usually not mature or assertive enough to independently optimize themselves or the learning situation. It is up to the teacher to do that, taking into account the people and goals at hand. To meet the pathologies, Shulman [32] suggests that *"Remedies for combating the illusion of understanding and persistence of misconceptions are to support learners in the active, collaborative, reflection reexamination of ideas in a social context. If we can teach learners to engage in active thinking about what they know and how they know it, and if we can create conditions where they can discuss what they know with others, we significantly raise the likelihood that the problems [of illusory understanding] diminish."* A common mode for this is by working in teams in both *ad hoc* and longer-term, goal-oriented projects. Teams make progress by members contributing diverse knowledge, perspectives, work methods, and styles. Each member educates the others about fundamentals and details for decisions that he/she uses. Synergistic multiformity enhances the product, while teaching others yields better individual understanding.

<u>Stimulate reasoning</u>

Engineering innovations depend on solid reasoning. There must be standards of clarity, precision, accuracy, significance, relevance, completeness, logicalness, fairness, breadth, and depth. These are applied to the purposes, inferences, questions, concepts, points of view, implications, information, and assumptions of the process. The required intellectual traits are humility, perseverance, autonomy, confidence, integrity, empathy, courage, and fair-mindedness [42].

<u>Structure the experiences of learners</u>

In undergraduate studies, it is the teachers, not the learners, who determine the learning activities. The University of Virginia Professional Development program advocated that all graduates should have the experiences of introspection and self-assessment (Who am I? How should I develop?), learning and growing (Build my competencies and recognize my changes.), performing and doing (Practice, practice, practice orally, in writing, physically, and computationally.), leading and following (What's my most effective role?), employment and service (Real work and how it's done.), interactions (Being and working with others.). *"These experiences and their lessons will provide confidence, wisdom & adaptability for lifelong service and accomplishment."* [44]

Of course, *"easier said than done."* I wish I had the time and energy to implement all of this advice, amid all the demands I see and respond to. Yet, my view is that however imperfectly and irregularly we carry it out, injecting these ideas and values into the learning environment is beneficial and satisfying to many students and to me.

Summary

Technological manipulation of Nature is transforming the human experience. Engineers do the real work of innovating advanced devices, systems, and processes. They also have the greatest appreciation of the opportunities, constraints, and consequences of technology. Their responsibilities are both to wisely advance technology and to sensitively interpret the outcomes. The teachers of engineers must structure learning to maximize their students' range of abilities, attributes, and attitudes to sustain and enhance the quality of life, to achieve personal and professional satisfaction, and to adapt. Knowing and applying the fundamentals of Nature, humans, and professionalism are the wellspring for all of these processes.

Acknowledgments

My life has been blessed with an incredible number of positive influences from family, teachers, colleagues, students, and contributors to the literature. There are so many that I cannot even recount them all, much less list them here. Hopefully, those that read this will recognize some of the values that they helped me assimilate.

I am very grateful to the Oklahoma State University School of Chemical Engineering and to the ConocoPhillips Company for providing me with an opportunity to contribute to their wonderful series of Lectureships.

References

[1] Roget's New Millennium Thesaurus, First Edition, Lexico Publishing Group, LLC, 2008.
[2] "The Engineer of 2020: Visions of Engineering in the New Century", National Academies Press, 2004. "Educating the Engineer of 2020: Adapting Engineering Education to the New Century", National Academies Press, 2005.
[3] E.D. Schneider & D. Sagan, "Into the Cool Energy Flow, Thermodynamics and Life", U. Chicago Press, 2005.
[4] Adapted from a "Spencer's Warbler" cartoon by Matt Campbell; date of publication unknown.
[5] Richard Feynman as quoted at http://www.quotationspage.com/quotes/Richard_Feynman/.
[6] H. Jackson Brown, Jr. as quoted at http://www.quoteworld.org/.
[7] http://www.thegreenpc.com/recycling_computers.htm.
[8] "Mechanica", Aristotle (384-322 BCE) as quoted in "Thermodynamics: Fundamentals for Applications", J.P. O'Connell and J.M. Haile, Cambridge University Press, 2005.
[9] A Ph.D. analytical chemist shoveling plastic for recycle into a BASF reactor in Ashville, NC.
[10] AIChE Houston Local Section motto, 1970's.
[11] G.E. Keller, AIChE Monograph Ser. 83 (17) (1987).
[12] "Marty's Rule of Mixtures" or, more seriously, "The Mixture Rule of toxic wastes," http://www.labtrain.noaa.gov/labwaste/section2/sec2-3d.htm, accessed October 21, 2007.
[13] An obscure Murphy's Law not found in on-line compendia.

[14] “How Nature Works: The Science of Self-Organized Criticality”, Per Bak, Springer, 1999.
[15] "The Road to Reality. A Complete Guide to the Laws of the Universe", R. Penrose, A.A. Knopf, 2006.
[16] “The Music Man”, Meredith Willson, 1962.
[17] “Brave New World”, Aldous Huxley, Harper and Brothers, 1932; reprinted First Perenniel Classics Edition, HarperPerennial, 1998.
[18] L.S. Shulman, J. App. Devel. Psych., 2000, *21*(1), 129–135.
[19] "Problem-based Learning: how to gain the most from PBL," D.R. Woods, 1994, D.R. Woods, Waterdown, ISBN 0-9698725-0-X.
[20] Warren K. Lewis (1882-1975), Chemical Engineering, Massachusetts Institute of Technology.
[21] Orin Pilkey and Linda Jarvis-Pilkey, http://www.columbia.edu/cu/cup/publicity/pilkeyinterview.html.
[22] Arnold Bondi (1916-1979), Senior Scientist, Shell Development Company.
[23] “To Engineer Is Human: The Role of Failure in Successful Design”, Henry Petroski, Vintage, 1992.
[24] “The Tipping Point: How Little Things Can Make a Big Difference”, Malcolm Gladwell, Back Bay Books, 2002.
[25] As quoted in John P. O’Connell, Chemical Engineering Education, Fall, 1997, *31*(4), 222-7.
[26] Wethern's Law of Suspended Judgment quoted at http://www.rijeka.com/phun/general/murphy.htm
[27] James D. Olson, Dow Chemical Corporation.
[28] Hans. C. Andersen, Department of Chemistry, Stanford University.
[29] Thermodynamics Fundamentals for Applications”, J.P. O’Connell and J.M. Haile, Cambridge University Press, 2005.
[30] “Society of Mind”, Marvin Minsky, Simon & Schuster, 1988.
[31] J.M. Haile, Chem. Eng, Ed., 1997, *31*(3), 152-7; 1997, *31*(4), 214-9; 1998, *32*(1), 30-9; 2000, *34*(1), 48-54; 2000, *34*(2), 138-143.
[32] L.S. Shulman, Change, 1999, *31*(4), 11-17. See also www.ce.umn.edu/~smith/docs/UM-Using_Cooperative_Learning-S2-106-2.ppt.
[33] James M. Haile, Macatea Productions, Central, SC.
[34] A piano teacher to a Master Class, 1974?
[35] UVa Undergraduates on a survey asking their assumptions about their teacher.
[36] “The World of Undergraduate Education”, Science, 2007, *317*, 63-77.
[37] “Mediated”, Thomas De Zengotita, Bloomsbury, 2005.
[38] “Education for judgment: The artistry of discussion leadership”, C. R. Christensen, D.A. Garvin, and A. Sweet (Eds.), Harvard Business School, 1991, as quoted at www.ce.umn.edu/~smith/docs/UM-Using_Cooperative_Learning-S2-106-2.ppt.
[39] “Educational Psychology: A Cognitive View”, David P. Ausubel, Holt, Rinehart and Winston, 1968, as quoted by Shulman [32].
[40] R.M. Felder and R. Brent, J. Eng. Ed., 2004, *93* (4), 269–77. G. Schraw and R.S. Dennison, *Cont. Ed. Psych.*, 1994, *19*, 460-75.
[41] http://teaching.berkeley.edu/compendium/suggestions/file95.html.
[42] http://www.criticalthinking.org/page.cfm?PageID=619&CategoryID=57#314.
[43]http://www.abet.org/Linked%20Documents-UPDATE/Criteria%20and%20PP/E001%2007-08%20EAC%20Criteria%2011-15-06.pdf.

[44] "Professional Development: A Document Articulating *Attributes, Experience and Initial Activities* for Enhancing Undergraduate Engineering Education", University of Virginia School of Engineering and Applied Science, 1995.