TOWARD TECHNICAL UNDERSTANDING

Part 5. General Hierarchy Applied to Engineering Education*

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

In the first papers in this series, I presented a *special* hierarchy of technical understandings[1-3] based on my experience in trying to help students learn and informed by our current knowledge of the structure and function of the human brain. In the previous paper,[4] I showed how the special hierarchy is related to a more *general* hierarchy developed by Donald[5] and, independently, by Egan.[6] In discussing the general hierarchy, I adopted Egan's nomenclature, which identifies five levels of human understandings: somatic, mythic, romantic, philosophic, and ironic. Each level corresponds to a specific mode for getting thoughts out of the mind and into forms by which they can be dissected, analyzed, and reassembled. To recapitulate, the somatic level includes tactile learning, mythic corresponds to oral learning, romantic involves graphics and written learning, philosophic refers to learning by formal reasoning, and the ironic level encompasses exceptions, limitations, and learning by modeling.

It is the philosophic level that encompasses the basic cognitive skills required of engineers; these include use of formal logic, mathematical reasoning, critical thinking, and problem solving. But the special and general hierarchical models are both integrative; that is, progression to a higher level requires the individual to master skills and reorganize knowledge gained at lower levels. Consequently, students cannot develop facility with philosophic activities until they have mastered lower-level cognitive skills.

In this paper we illustrate how the five cognitive levels can be used to guide teaching and learning activities appropriate for engineering students. To do so, we apply each level to the concept of energy. As noted previously,[4] energy is already a highly abstract concept characteristic of those employed at a philosophic level of understanding; however, the word energy is common in daily discourse and, therefore, it is familiar to students. Nevertheless, freshman and sophomore engineering students generally have only vague notions of the concept, and often confuse energy with force and pressure. For these reasons, energy is a good concept for showing how the hierarchy could be applied.

We emphasize that the suggestions here are fragmentary and superficial; they are intended only to offer a flavor of the kinds of activities that could be pursued. Note that our goals are not so much to *develop*, say, somatic and mythic modes of technical understanding, but rather to *appeal* to such modes for understanding a particular concept.

SOMATIC UNDERSTANDING

At the most basic level, our objectives are to help students obtain a "physical feel" for kinds and quantities of energy. For example, we might have students try to increase the temperature of water in a bowl by using a hand-driven egg beater. Or we might have them manually compress air in a piston-cylinder device, such as a large medical syringe. To test whether energy is extensive, students could measure the time required for a 500-watt microwave oven to bring a cup of water to boil; then they could repeat the heating using two cups.

More elaborately, we could invert a bicycle, attach a friction-driven electric generator to the rear wheel, and run an

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J.M. Haile, *Professor of Chemical Engineering at Clemson University, is the author of* Molecular Dynamics Simulation, *published by John Wiley & Sons in 1992 and is the 1998 recipient of the Corcoran Award for the Chemical Engineering Division of ASEE.*

electric circuit from the generator to a light bulb.[7] Students would then be asked to keep the bulb burning by cranking the pedals by hand. If we add a voltmeter and ammeter to the circuit, students could determine the amount of power they generate. Such exercises need be only semi-quantitative, for the intent is to help students connect physical effort to measurable changes in temperature, volume, and current flow.

At the most basic somatic level, students confront physical situations and devices; at a higher level, we try to appeal to their somatic experiences without further direct contact. Such attempts might take the form of simple questions requiring modest computations. For example, if the cost of electricity is $0.1 per kilowatt-hour, how much does it cost to burn a 100-watt light bulb for one hour? The energy density of a typical gasoline is about 45 MJ/kg; if your car gets 25 mpg, estimate the amount of energy (kJ) your car uses per mile. The energy density of ethanol is 30 MJ/kg; estimate the amount of energy (kJ) in a 750-ml bottle of white wine that is 12% alcohol by volume.[8] The key here is to contrive questions that make contact with situations that are familiar to students, else the somatic advantage is lost.

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MYTHIC UNDERSTANDING

An important binary alternative that is fundamental to any study of energy is this: Does energy come in only one form, or are there many forms? If there are many, can we convert among them? Can the students cite examples of conversions in both directions between two forms? For example, electric motors convert electrical energy to mechanical, while electric generators convert mechanical energy to electrical. Similarly, solar cells convert radiant energy to electrical, while light bulbs convert electrical energy to radiant.

Are some conversions between energy forms easier than others? Do some conversions occur naturally? Are some conversions undesirable so that we seek to prevent or restrict them? Are some forms primarily for energy storage? These can lead to such questions as: What common devices are used to store energy? What is the defining characteristic of a machine? Is there a distinction between a motor and an engine?

One way to exercise the oral and narrative components of mythic understanding is to discuss with students old misconceptions about energy and forms of energy. Examples include the ancient idea that fire is an element, or, in an updated version, that heat is a thing ("caloric") that is conserved. Other common misconceptions surround the distinctions between quantity of heat and the intensity of heat; thus, it is a difference in intensity (temperature), not quantity, that drives heat transfer. More subtle confusions are attached to the possibilities of changing temperature without heat transfer and transferring heat without a temperature difference.

As another exercise of the oral component, each student could be asked to give a three-minute presentation on the origin, etymology, and historical significance of one piece of energy-related jargon. Appropriate words could include energy itself, horsepower, Btu, watt, Joule, kinetic, potential, efficiency, and friction.

ROMANTIC UNDERSTANDING

To identify the principal features on the energy landscape, we can have students list various forms of energy: kinetic, potential, chemical, nuclear, radiant, electrical, magnetic, heat, work, etc. Can these be distributed among certain categories? Students should also list kinds of molecular energies: kinetic, potential from intermolecular forces, electronic, and nuclear.

To exercise the narrative component of romantic understanding, students could be asked to contrive a chain of conversions; for example, living plants convert radiant energy to chemical, people eat plants to convert chemical energy to other forms of chemical energy, human muscles convert the stored chemical energy to mechanic energy, the muscles might crank a hand generator that converts mechanical energy to electrical, and the generator might be wired to a light, which converts electrical energy back to radiant.

To identify extremes, we would offer students numerical examples of situations involving large amounts of energy: the potential energy behind the Hoover Dam, the energy required to launch a Saturn V rocket, the energy consumed by all automobiles in the U.S. in one year. At the other extreme, we might cite the energy required by one light-emitting diode (LED), the amount to depress one key on a keyboard, or the amount used by a hummingbird during five minutes of flight.[8]

To appeal to human interests and motivations, we could start by working out an estimate of the energy—hence, man-years of effort—required to construct one of the Great Pyramids of Egypt.[9] Then we could note that the desire to replace man-power with machine-power motivated the in dustrial revolution. This leads to a description of socio-economic conditions prevailing in Europe in the early 1800s, and, in particular, to a discussion of Joule's careful, systematic, extended, experimental studies of the relations between heat and work. We could describe Joule's paddle-wheel experiments, which illustrated the equivalence of heat and work and led to an identification of internal energy. We would emphasize that these crucial experiments discredited the caloric theory of heat and laid the foundations for articulation of the principal of conservation of energy.

Another instructive story is that of the Haber-Bosch process for the catalytic formation of ammonia from its elements under high temperatures and pressures. That process was first used to make nitric acid for explosives and thereby enhanced Germany's ability to prosecute World War I, but after WWII, it made possible large-scale production of fertilizers that sustain the world's growing populations. Thus, we have an example of the common dilemma of technology being used and misused. But in the context of energy usage, this story illustrates one way in which technologies evolve: the fundamentals of the Haber-Bosch process are unchanged, but improvements have reduced the energy costs of the process by more than an order of magnitude—from 380 MJ/kg of NH_3 in 1930 to 35 MJ/kg in 1990.[8] Many important chemicals have histories that can be exploited to appeal to students' romantic understandings; another example is the story of the Leblanc soda process, nicely told by Cook.[10]

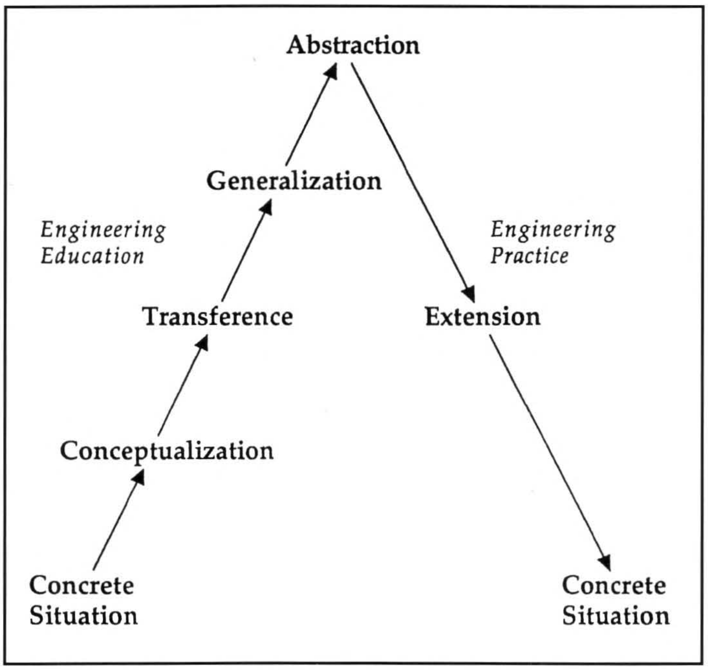

Figure 1. *Understandings of abstractions* develop *in a bottom-up strategy from concrete situations to abstract concepts; thus, in helping students learn new concepts, we should start with concrete and specific examples and move toward abstract generalizations. We* apply *abstractions in a top-down fashion, however, from abstract notion to concrete situation. Thus, in helping students learn to solve problems, we should teach them to identify the generalized concept that applies and then to proceed deductively to their particular situation.*

Still another aspect of romantic understanding is embedded in the graphical representations of physical objects and processes—plots, schematic diagrams, and flowsheets. An effective initial exposure to these tools is to confront students with objects and have them create schematics: cooling cycles in refrigerators or room air conditioners, the cooling-water cycle on an automotive engine, the steam cycle at a power generating plant, the water lines through their houses or apartments, etc. The educational advantage here comes when students can see and touch objects, and they attempt to represent relations among those objects abstractly on paper.

PHILOSOPHIC UNDERSTANDING

At the philosophic level, our first goal is to find those unifying generalizations that connect the things and concepts encountered at the somatic, mythic, and romantic levels: the stories, the devices and equipment, the many concepts, the transformations among concepts, the extremes, etc. The cognitive hierarchy guides us in how this is to be done. We emphasize that we do not, at this point, confront students with the answer—the generalized energy balance. Rather, we proceed systematically from concrete situation to abstract generalization, following the left leg in Figure 1. Our second goal is to help students develop the ability to *use* the generalized energy balance, which is represented by the right leg in the Figure. Thus, our pedagogical goal is distinct from the practical one.

We might start a philosophic discussion of energy with equations that define individual energy forms, such as mechanical work, electrical work, and changes in kinetic and potential energies. Then students would exercise those definitions by applying them to relatively simple situations: a) estimate the speed of a crescent wrench as it hits the ground after a free fall from the top of a 30-foot distillation tower; b) estimate the work performed by an adiabatic air compressor; c) estimate the heat required to raise the temperature of 1 kg of water from 20°C to 100°C.

(a) Concrete Situation • To start the progression on the left in Figure 1, we choose one of the concrete situations that the students have already encountered; a possibility is the compression of a gas in an insulated piston-cylinder apparatus. Many choices are legitimate here, so long as the one chosen arises from a situation for which students have strong visual images.

(b) Conceptualization • We now lead the students to identify the concept associated with the concrete example. We ask, what is it we, as engineers, are likely to want to know about the compression? Presumably, the amount of effort required. That effort is conceptualized by a particular form of energy—the work; here it is adiabatic work, because the apparatus is insulated. Note that because of the groundwork laid by the earlier somatic, mythic, and romantic exercises, the students should be able to participate actively in this discussion. Inversely, if those lower-level understandings have been ignored and instruction starts here at the philosophic level, then many students will be immediately overwhelmed. Once students have recognized work as the appropriate concept, we then have them calculate values for the adiabatic work under various sets of parameters applied to the piston-cylinder device.

(c) Transference • At this stage we want students to apply the concept of adiabatic work to situations other than the piston-cylinder apparatus. For example, we could pose problems involving adiabatic compressors, adiabatic turbines, and adiabatic pumps. The objective is for students to recognize that all such problems belong to the same conceptual class.

(d) Generalization • Now we come to the difficult stage at which we generalize away from the special case of adiabatic work processes. Thus, we first relax the adiabatic constraint and consider workfree heat transfer situations; then we introduce processes involving both work and heat transfer. We emphasize the extent to which these situations are conceptually the same as, but practically different than, the adiabatic work processes considered earlier. Then we consider steady-flow processes, with the introduction of flow work and the possibilities of changes in kinetic and potential energy. Finally, we end with a completely abstract consequence: the general energy balance, which applies to any process. This establishes the important connection among the various forms of energy; that is, this step relates the principal features of the energy landscape as identified at the romantic level.

Our second goal is to help students learn how to use the general energy balance; our strategy is now top-down, as on the right in Figure 1. Thus, we want students to appreciate that *any* situation they encounter is a special case, but we attack that special case by starting with the completely general energy balance and identifying the assumptions that are appropriate to the situation at hand. Thus, we would exercise the general energy balance applied to such situations as adiabatic processes on closed systems, to workfree processes on closed systems, and to steady-state processes on open systems. The latter would include illustrations of the special forms known as the mechanical energy balance and Bernoulli's equation. The concrete applications would include heat duties for heat exchangers, sizing of pumps, turbines, and compressors, analyses for thermal efficiencies, etc. These kinds of activities are addressed in modern textbooks and many current learning strategies, so they need little attention here.

IRONIC UNDERSTANDING

To develop ironic understanding of energy, we would revisit the assumptions and limitations that pertain to the equations used at the philosophic level. For example, most calculations of mechanical work can be done only for idealized processes in which the driving forces are differential. For real processes, in which the driving forces are finite, we need an efficiency, obtained either from measurement or by estimation. To calculate changes in internal energy and enthalpy, we often need an equation of state that models the PVT behavior of the working fluids. Many texts restrict such calculations to the ideal-gas model, but students must be introduced to more realistic models, and they must be instructed in the engineering task of selecting a model that is appropriate to their problem. Thus we must confront issues associated with model processes and model substances. For example, we may be able to perform an exact analytic calculation of the required heat duty for a heat exchanger design, under the presumptions of particular model processes and model substances. However, such exact calculations are still approximate to the degree that the assumed models fail to represent the real situation. Students often have difficulty in reconciling how an approximate answer can be obtained from an exact calculation.

NONLINEAR INSTRUCTION

For purposes of clarity, the suggestions in the foregoing sections were presented in a linear progression that builds from somatic to ironic. In practice, however, instructors of college students need not—indeed, should not—proceed in such a linear fashion. Of course, somatic activities should generally be performed well before philosophic activities, but this does not mean we should avoid somatic and mythic digressions in an otherwise largely philosophic lecture. For example, continuing with energy as the focal point, the listing of types of energy (romantic) could be done as soon as students acknowledge that energy comes in many forms (response to the mythic binary). Calculation of the velocity of the falling crescent wrench (philosophic) could be embellished with the observation that the answer is independent of mass, so the velocity would be the same for a manhole cover or a pocket watch; this harks back to the tale of Galileo and the Leaning Tower of Pisa (a romantic reference). The discussion could be further extended by noting that the terminal velocity is independent of mass only when the air resistance is negligible; thus, we have done a model calculation that yields an approximate answer (ironic).

It is appropriate and beneficial to include somatic, mythic, and romantic allusions in a largely philosophic presentation;

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however, the inverse procedure is counterproductive and should be avoided. That is, we accomplish little when we introduce abstract generalizations (such as the generalized energy balance) and models (such as Raoult's law) before somatic, mythic, and romantic contexts have been established for those generalizations and models.

At this point, kind Reader, you might indulge in the following reflective exercise. Pick a course you have taught recently; can you identify the cognitive level at which you did most of the teaching? For example, if most of the instruction took the form of anecdotes based on your industrial experience, then you were functioning at the mythic level with appeals to the somatic. If the instruction depended heavily on students reading the text, technical reports, research journals, and on their making and interpreting plots, schematic diagrams, and flowsheets, then you were working at the romantic level. If the instruction emphasized derivations, problem solving, and calculations, then you were at the philosophic level. If the instruction involved liberal doses of all of these, plus efforts to sensitize students to the uses and limitations of models, then you were teaching at the ironic level.

Any of these approaches may be right or wrong, effective or not, depending on the situation—that is, depending on what your students needed at the time. So now ask yourself, why did you choose to instruct at the level you did? Was the choice made implicitly for your own convenience and comfort, or was it made explicitly to address the needs of the students? What was the outcome of your work? If the students were generally frustrated, then your teaching level failed to match their needs. If the students were generally happy, comfortable, and secure, then your efforts probably were limited to reinforcing their current levels of understanding. If the students were apprehensive but stimulated, then they were probably growing toward higher levels. (If only the reality were as simple and clear-cut as these idealized comments imply.)

COMMENTS

As an individual grows through levels of understanding, lower-level understandings are not lost or displaced; rather, they are reorganized and subsumed into high levels. Nevertheless, there is a loss associated with each transition;[6] for example, the admonition to "be objective" means to strip away mythic and romantic associations, such as emotion and anecdotal evidence, and reason logically.[5] But if the basic somatic and mythic understandings are not lost, what is? Part of the process of solidifying understandings at one level includes the creating of mental scaffolding that will support the transition to the next level.[3] Once the transition is complete, the scaffolding collapses. But some people become attached to the scaffolding and experience a sense of loss when it collapses. Such is the nature of mental growth.

How much understanding does an individual need at one level before he can move to the next? The answer must be that it depends on the individual and the extent of his earlier experience with understandings at that level. For example, we conjecture that an individual who has developed somatic understandings of some concepts will find it easier to develop somatic understandings of other concepts. The situation must be much like the learning of a foreign language (or a computer language), which is made easier if the individual has already learned another. In higher education, we appeal to somatic, mythic, and romantic modes of thinking to solidify the foundations for philosophic and ironic understandings. Successful generalization (concrete to abstract) and extension (abstract to concrete) depend on facility with manipulating objects and concepts at somatic and mythic levels.

To illustrate let us consider the value of somatic thinking. Marvin Minsky[11] asks why we insist on thingifying abstractions. It can only be because thingifications help our thinking. Thus, we think about energy as a thing, even though most forms of energy are abstract mathematical functions and are not objects at all. We do this so we can draw fruitful analogies between energy and mass: mass can flow into and out of systems, so can the energy-thing; mass is conserved, so is the energy-thing; mass is a resource whose use incurs cost, so is the energy-thing. The power of such analogies is so well accepted that we take it for granted. But our familiarity with such analogies must not blind us to the significance of the achievement nor to the difficulty students have in accepting such analogies and using them.

In recent years, engineering educators have renewed emphasis on the development of oral (mythic) and written (romantic) communication skills. But, according to the cognitive hierarchy, these skills are valuable not merely for communication; rather, they are important because they support subsequent development of understandings at the philosophic level. Further, the hierarchy asserts that oral skills develop before written skills; this reverses the order employed at many institutions, where oral skills are addressed late in curricula and after written skills have been exercised.

Students come to us at many different levels of understanding, and our obligation is to help them grow to higher levels. It may be that many people in our society cannot become philosophic thinkers in any mathematical sense. Such people cannot become engineers, and their talents should be developed and applied in other ways. Further, some people can function at the philosophic level, but they may be more *effective* at some other level. These people can fulfill important and even creative roles in engineering; however, they cannot make informed judgments about the best use of their talents until they have acquired some skill in philosophic thinking.

Good teaching meets students at their current levels of understanding and attempts to push them to higher levels. This requires that instructors be able to cross readily among levels of understanding: this is an attribute of the ironic thinker. An obvious general rule-of-thumb is: If the student seems perplexed or confused, the instructor should push the discussion to a lower level of understanding. Equally important, but often overlooked, is the inverse: If students seem confident and secure, then the instructor should push the discussion to a higher level of understanding. One of an instructor's goals is to find the level of understanding at which students are balanced between perplexity and confidence; at that point of creative tension, teaching is most effective and learning most rapid. This goal is relatively easy to achieve for a single student (a graduate student), but exceedingly difficult to achieve for a group of heterogeneous talents and personalities (an undergraduate class).

Between, say, 1950 and about 1990, engineering education developed along ever-increasing theoretical, mathematical, and abstract lines; that is, engineering education came to be practiced almost completely at the philosophic level. Such is the natural progression that mirrors cognitive evolution. But in recent years we have come to realize that solely philosophic modes of instruction fail to help today's students. The typical reaction has been to dilute philosophic instruction in various ways. For example, some chemical engineering departments have reduced the philosophic content of the curriculum by removing physical chemistry, quantum mechanics, transport phenomena, or computer programming. In the courses that remain, the philosophic content has, perhaps, been diluted by over-emphasis on "practical" applications and flowsheet design. But too much attention to applications produces a catalog of special cases, when the objective should be development of organizing principles that generalize across individual situations. Further, today's flowsheet design tends to be accomplished with the aid of process-simulation programs; but without sufficient command of philosophic and ironic thinking, students can only allow such exercises to devolve to syntheses of black boxes, with issues of engineering judgment relegated to default settings of the software. Such dilutions of philosophic instruction actually make matters worse:[6] not only do they fail to develop philosophic thinking, but they also leave students with confused and useless somatic, mythic, and romantic understandings of technical material.

Rather than dilute the philosophic content of engineering curricula, we should be moving in the other direction. As a rough generalization, our goals might be to use early engineering courses to solidify understandings at the somatic, mythic, and romantic levels. But though the levels would be emphasized, higher modes would not be neglected; some foreshadowing of philosophic and ironic thinking must also be done. Then, once students begin the transition to philosophic thinking, the curriculum should develop that thinking by being *more* abstract and theoretical, not less. This is the direction of growth for individuals, cultures, and even engineering.

Finally, we ask, is there any level of understanding beyond ironic? I think the only proper answer is, we don't know. Donald notes that each level of understanding incorporates a particular mechanism for off-line processing—for getting thoughts out of the mind so they can be more readily manipulated, dissected, and reassembled.[5] At the somatic level, the off-line processor is the human body; at the mythic level, it is speech; at the romantic level, it is graphics and writing; at the level of (technical) philosophic and ironic thinking, it is mathematics and written chains of logic. So the question is, can we find another mechanism for out-of-mind processing? Can the computer fulfill this role? I think we can only wait and see.

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