TOWARD TECHNICAL UNDERSTANDING

Part 4. A General Hierarchy Based on the Evolution of Cognition*

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

As their principal role, institutions of higher learning are to develop and extend those high-level cognitive skills that people need to function productively in modern society.[1] Such skills include complex abstract thought, logical and mathematical reasoning, synthesis and analysis, and the ability to recognize and apply patterns, generalizations, theories, and schema to solve problems. Such skills are developed by immersing students in a community whose members explicitly attempt to pass those skills to other segments of the society. This difficult job is attempted only at institutions of higher education. But though we, as institutions, have been at this job for centuries, we still do not have effective methods for accomplishing it.

In previous papers in this series, I presented a hierarchy of technical understandings[2,3] based on my experience in trying to help students learn and on our current knowledge of the structure and function of the human brain.[4] I will refer to this as a *special* hierarchy of understandings.

But in addition to using observations of college students and brains to obtain evidence for how learning occurs, we can also pursue other routes. For example, Merlin Donald studied the evolutionary history of culture from apes to *homo sapiens sapiens* to show how high-level cognitive skills probably developed.[5] And in another study, Kieran Egan used mental growth in youngsters as the basis for a theory of how humans learn.[6] Both these studies result in cognitive hierarchies. That by Egan contains five levels of human understandings: somatic, mythic, romantic, philosophic, and ironic. I will refer to this as a *general* hierarchy of understandings.

In this general hierarchy, it is the philosophic level that encompasses the critical thinking skills required of engineers. However, we cannot immediately begin instruction at the philosophic level, because the special and general hierarchies are not merely sequential, but integrative: in such models, mastery at any level requires assimilation, reorganization, and generalization of understandings gained at lower levels. Hence, unless students have attained adequate facility with somatic, mythic, and romantic thinking, they cannot progress beyond a superficial level of philosophic understanding. Unfortunately, most students now entering engineering schools in the U.S. are ill-prepared to develop technical understandings at the philosophic level. Moreover, various strategies currently in vogue for addressing this problem—such as problem-based learning, discovery-based learning, group work, and web-based learning—are primarily attempts to exercise thinking at the philosophic level. As such, they fail to meet student needs at lower levels in the hierarchy and therefore they are generally not as effective as they could be. For some students, such learning exercises are, in fact, counterproductive.

As engineering instructors, we are masters of philosophic understanding, and we naturally want to teach what we do best. But many engineering students are not prepared to enter into philosophic modes of instruction. If those students are not properly prepared, then philosophic instruction is largely frustrating, and such students fail to develop the skills we want them to have: ability to solve novel problems, ability to extract meaning from data, ability to develop technical narratives that are well-reasoned and convincing, abil-

***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 from the Chemical Engineering Division of ASEE.*

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ity to exercise sound engineering judgment. The question is, can we do anything about it?

EPISODIC LEARNING

Before identifying levels of human understandings, we consider the demarcation between human and animal cognition. In animals, the highest levels of cognitive skills are found in chimps and the great apes. Beyond the instinctive and procedural-habits characteristic of all animals, chimps and great apes are masters of the moment; they can contrive creative solutions to problems as they arise. For example, they can combine available objects in new ways and they can use available objects as tools to achieve goals. Further, some individual apes have been taught a subset of American Sign Language.[7] Donald refers to these achievements as *episodic* learning. These kinds of achievements are remarkable; nevertheless, they are limited to the current situation—animals live in the present. They do not plan for the future. For example, they do not make tools of their own. Although they may have used an object repeatedly as a tool, they do not set it aside for future use. Even though they may learn some sign language, they have never made original contributions to their vocabulary, much less created a grammar. In short, animals with the most highly developed cognitive skills appear incapable of abstract thought.

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SOMATIC UNDERSTANDING

The first step beyond episodic learning is prelanguage and relies on the sense of touch to gain and convey understanding. For engineers, its important characteristics are tactile learning, toolmaking, and communication by manual gestures and body motions. Donald calls this *mimetic* learning, but we follow Egan and call it *somatic* understanding. At the somatic level, we have already taken a decisive step away from episodic learning and into abstract thought. Thus, the touching and manipulating of objects, which is characteristic of tactile learning, seem to aid the human mind in learning to create abstract images. We conjecture that mastery at the somatic level is a prerequisite for later facility with highly abstract thought. Thus, Newton was an accomplished experimentalist before he wrote the largely theoretical *Principia,*[8] Gibbs designed gears and brakes for railway cars before he developed the abstract thermodynamics of phase equilibria,[9] and (to stretch the point only slightly) Einstein worked with concrete inventions submitted for patent before he developed the theory of relativity.[10] The close interdependence of manual dexterity and abstract mental processing has been emphasized in a book by Frank Wilson;[11] similarly, the connections between manual skills and engineering talents have been emphasized in an article by Petroski.[12]

Toolmaking, which reverses tactile learning, is the attempt to convert abstract images into concrete objects. Toolmaking is taught in master-apprentice relations with little verbal communication; the instruction relies heavily on gestures, physically realized procedures, and concrete trial-and-error strategies. An enhanced remnant of this somatic mode of instruction serves as the basis for today's graduate education.

Somatic modes of communication rely on manual gestures and body motions—obvious abstractions employed to convey ideas and relations among concrete objects and situations. There is a growing body of evidence to support Donald's position that human language evolved from manual gestures.[13] Further, somatic forms of communcation are still employed in the performing arts, in sign languages for the handicapped, and in signals used by referees and umpires in sporting events.

An instructive example of somatic learning has been documented in a recent article published in this journal;[14] as a student, S. Godiwalla found herself frustrated by instructors who consistently presented engineering subjects at high levels of abstraction. She needed to see the pumps, valves, and fittings that were being represented symbolically in lectures; to understand, she needed to handle the objects, look inside them, take them apart. Her response was to find a technician who could help her convert abstract symbols into concrete reality. It is germane to note that Ms. Godiwalla was a double major in chemical engineering and dance; thus, we have strong evidence for a student functioning at the somatic level.

MYTHIC UNDERSTANDING

In evolutionary terms, mastery of somatic skills serves as a foundation for creating abstract names for concrete things, then language, and then names for abstract things such as virtue, patience, and deceit. Understandings at this level are characterized by oral traditions, such as myths and epic poetry, and so they can be called *mythic* understandings. In an earlier paper in this series,[2] I discussed the power that primitive people attributed to names. That power becomes extended and generalized when myths are used to explain

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how the world works. At the mythic level, understandings are developed and conveyed through stories: oral structures composed of an introduction that establishes a conflict, an internally consistent narrative line, and a conclusion that resolves the conflict. Egan reminds us that Carl Sagan and Richard Feynman were both masters at presenting technical material in narrative forms.[6]

To establish such narratives, storytellers usually create conflicts based on binary opposites: good vs. bad, strong vs. weak, industrious vs. lazy. For us as sophisticated instructors, this is a simple-minded way to view the world; further, it leads to two-valued logic systems that are not merely wrong, but dangerous.[15] (For example, "Never trust anyone over 30." "All Democrats are liberals." "People who can't do, teach.") Nevertheless, binary opposites are effective for introducing new ideas, and they allow us to develop narrative lines that conclude with discussions of engineering judgment. In technical material, binary opposites rarely occur, but the same advantages can be obtained by appealing to binary alternatives; for example, we might introduce chemical processes as either batch or continuous, instruments as either digital or analog, and pumps as either centrifugal or positive displacement. The degree to which such a pair fails to cover all possibilities would be left for later discussions at higher levels of understanding.

ROMANTIC UNDERSTANDING

Once a culture has established an oral tradition, it may proceed to further levels of abstraction by creating graphic images for objects, situations, and events. Such pictures, hieroglyphs, and other graphic devices may be followed by creation of symbols for numbers, an alphabet, and writing. Note that graphic devices and writing involve abstractions identified at the mythic level combined with manual dexterity developed at the somatic level. This particular combination of manual and mental abilities may have prevented some cultures from converting their oral traditions into written language. Thus, some cultures remained at the mythic level, while others developed graphic expression without adding a written language. Graphics, numbers, and writing bring a richness and flexibility that is missing from the somatic and mythic levels; however, these advantages come at the price of greater difficulty in attaining mastery at this level.

It is a command of graphic symbols and writing that characterizes *romantic* understanding, so called because the explanatory stories of mythic understanding are converted into stories driven by human needs and aspirations. One aspect of romantic understanding is an emphasis on bounds—on the limits of human performance. Thus, at the romantic level, we focus on the highest building, the longest bridge, the fastest car, the most powerful rocket engine, and the smallest (nanoscale) motor. The seven wonders of the ancient world were all made by man.

To illustrate the human context of a technical topic, let us consider using the romantic mode for introducing the second law of thermodynamics. In so doing, we would not merely introduce such abstractions as entropy, irreversible processes, and heat engines, we would place those abstractions within the context in which they were invented: the needs driven by the industrial revolution occurring in Europe in the early 1800s. To humanize the discussion, we could discuss the personal histories of such figures as Sadi Carnot in France, Rudolf Clausius in Germany, and William Thomson (later Lord Kelvin) in Britain, whose efforts culminated in a formal statement of the second law.

A second aspect of romantic instruction is that material is not presented in a linear sequence; rather, the presentation emphasizes salient points and ignores details. To illustrate, Egan uses the metaphor of map-making. If we were to take a romantic approach to mapping a country, we would not proceed systematically from one coordinate to the next; instead, we would locate the prominent features—the mountains, lakes, rivers, canyons, gorges, and cities. Adding details involves understandings beyond the romantic. We find it convenient to extend this metaphor by referring to the "object" defined by this romantic activity as the conceptual *landscape* for a topic.

A third aspect of the romantic mode is the uncovering of interesting and unexpected connections. For example, Sadi Carnot's work on heat engines was influenced by the interests of his father, Lazare Carnot, who was minister of war under Napoleon in 1800 and minister of the interior during Napoleon's Hundred Days in 1814. When war erupted between France and Britain in 1792, France faced a possible shortage of pencils. It was Lazare Carnot who commissioned Nicolas-Jacques Conté to develop a process for making high-quality pencil lead from low-quality graphite.[16] By about 1794, Conté had succeeded in inventing the *crayons*

Conté, which are essentially our "lead" pencils. Thus, the second law of thermodynamics is circuitously connected to an instrument that contributed to writing and, hence, to the spread of romantic understandings.

Connections are often interesting because they are counterintuitive or amusing. For example, modern textbooks routinely use the second law to prove that there can be no perpetual motion machine. But it is amusing to note that Sadi Carnot reversed the logic: he deduced the second law from the assumption that perpetual motion machines cannot exist.[17] Such connections serve as themes for popular essays written by James Burke and now regularly published in *Scientific American.*

Besides bounds, connections, and human interest, the romantic level invokes pictorial symbols: diagrams, flowsheets, plots, and other figures that are characteristic of engineering. At first blush, there may seem to be little to say about these devices—they are taken for granted in both engineering education and practice—but for this very reason, they may be easily misused in teaching. First note that although plots are romantic devices, they may invoke interpretations at other levels of understanding. For example, some plots can be interpreted in terms of the performance of equipment; this appeals to somatic understanding. On other plots, a curve might be interpreted in narrative terms as illustrating a response to conflicts or competition between variables; this appeals to mythic understandings. Still other plots may be interpreted as expressing relations among terms and quantities in equations; this appeals to philosophic understandings, as discussed in the next section. Thus on entering the romantic mode of learning, a student may readily understand some plots, but have difficulty with others.

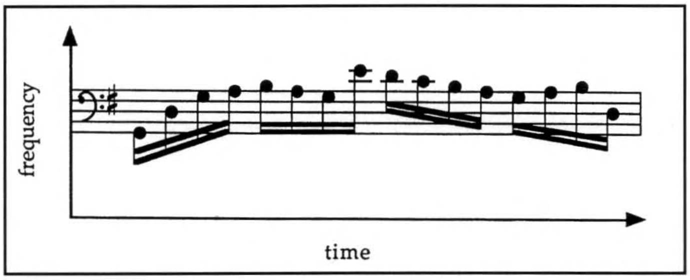

Figure 1. *The x-y plot is a graphic device characteristic of those deployed at the level of romantic understanding. Nevertheless, such plots are late inventions in human history, coming long after romantic, philosophic, and ironic understandings were fully developed. The first x-y plot was apparently the musical staff, created by a Benedictine choirmaster during the Middle Ages.*[18]

Second, note that *interpreting* an existing plot usually involves lower levels of understanding than those used in *creating* the plot. For example, the first x-y plot was, apparently, the musical staff created by Benedictine monks during the Middle Ages;[18] on the staff, pitch (frequency) of each note is plotted on the ordinate, while time runs along the abscissa, as shown in Figure 1. The musical staff is a graphic—a romantic—device created by philosophic thinking for use by mythic performers. Nevertheless, creation of a plot can involve somatic elements that are beneficial to some students; they gain understandings by manually transforming a table of data onto graph paper. This benefit is lost when we force all students to construct plots on computers, for somatic contact with the data is replaced by representations and manipulations at higher levels of abstraction.

PHILOSOPHIC UNDERSTANDING

To our knowledge, all human cultures developed somatic knowledge and mythic traditions and some developed romantic learning, but few developed *philosophic* understandings; in fact, we know of only one such culture—the ancient Greek. At the philosophic level, the graphic tools and written language mastered at the romantic level *may* enable development of higher-order thinking skills: inductive and deductive logic, inferential reasoning, analysis and synthesis, critical thinking, creation of theoretical constructs, and generalizations. These abstractions relate, simplify, and extend knowledge gained at lower levels in the hierarchy.

Our experience implies that the transition from romantic to philosophic understandings is a difficult one; in fact, individuals do not seem able to make the complete transition by themselves.[6] That is, to progress beyond a superficial level of philosophic understanding, an individual must reside in a community of philosophic and ironic thinkers and learn from them. This is *the* principal role of higher education in our society,[1,6] although the role is poorly understood by most students, many administrators, and some faculty.

To achieve technical understandings at the philosophic level, we rely heavily on mathematical logic using equations. An equation is a romantic construct: a collection of graphic symbols arranged to show relations among quantities and ideas. But even at this romantic level, many students have difficulty distinguishing equations from formulae: formulae are means for converting numbers into other numbers (such is the use of the quadratic formula), while equations are means for expressing relations. Of course, most equations can also be used as formulae, but their real import lies in relating ideas, not numbers.

The *use* of equations in developing mathematical chains of logic, however, is not a romantic activity, but rather a philosophic one; examples include proofs, derivations, and the deductions routinely employed in problem solving. Such activities are highly abstract and require substantial sophistication on the part of the student. As instructors, our tendency is to underestimate the somatic, mythic, and romantic skills that students must have mastered before they can manipulate equations productively at the philosophic level. As Marvin Minsky has noted, "it takes years to become proficient at the language of mathematics."[19]

In addition to mathematics, we have a host of other devices for developing and conveying philosophic understandings; examples include problem-solving strategies, operating procedures, technical reports, computer programs, generalized patterns (such as the unit operations), and generalized theories (such as occur in transport phenomena). Such philosophic devices are routinely explored and exploited in our teaching and in this journal, so there is no need to belabor them here.

Philosophic understandings develop from systematic explorations of a subject's conceptual landscape. In such explorations, we seek justification for the prominent features identified at the romantic level; further, we seek to expose the logical connections—the details— that relate the prominent features. But such an exploration soon overwhelms us with the innumerable details that establish the often-complex web of connections among important points. To maintain control over the material, we seek simplifications via overriding patterns, theories, schema, and generalizations that organize our knowledge into structures that are useful; in the words of Mach, we seek *economy of thought.*[20]

The reorganization of knowledge into abstract and economical structures is the characteristic activity of learning at the philosophic level. Following Vygotsky, we can divide this activity into four steps:[21]

1. *Conceptualization,* which is the creation or recognition of a concept that arises from observing concrete situations. For example, placing a pan of water on a hot stove might lead us to the concept of heat as an explanation for the observed temperature rise. Conceptualization may take place at mythic, romantic, or philosophic levels; often, it incorporates features from all three.
2. *Transference,* which is the use of the concept to solve problems in concrete situations other than the one that inspired conceptualization. Thus, continuing with our example, when we place the pan of water in a refrigerator, we might again use the concept of heat, now to explain the fall in temperature.
3. *Generalization,* which is creation of an abstract interpretation of the concept, independent of any concrete object or situation. Thus we might eventually generalize the concept of heat to the more abstract notion of energy: heat is a form of energy that "crosses" system boundaries. Exploration of the generalized abstraction might lead us to generalized rules; for example, whenever the net effect of a process is to add energy to a system, we expect temperature to rise.
4. *Extension,* which occurs whenever we recognize concrete situations, unlike those in conceptualization and transference, to which the abstract form of the concept can be applied. For example, we place ethanol in an insulated vessel and then do work on it. We understand that the temperature will rise because we have added energy, even though no heat crossed the boundaries.

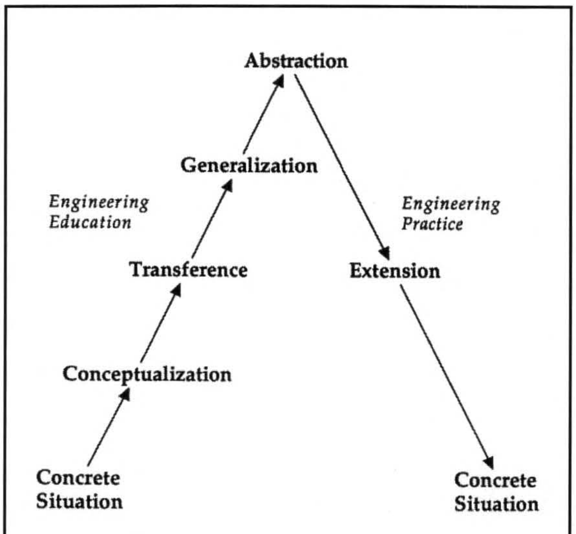

Figure 2. *Psychological studies of learning[21] and neurological studies of brain function[2-4] confirm that student understandings of abstractions develop in a bottom-up learning strategy from concrete situations to abstract concepts. Thus, it is counterproductive to attempt to teach conservation of energy by confronting students first with the generalized energy balance. However, we apply abstractions in a top-down fashion, from abstract notion to concrete situation. Thus in problem solving, students should be taught to start with the generalized energy balance and then proceed deductively.*

The articulation of these steps helps us recognize a possible pitfall when using standardized tests to assess student progress. It is relatively "easy" to drill students in conceptualization and transference, so they can perform well on standardized tests, but without the ability to generalize and extend what they know, such students remain confined to a rather superficial level of philosophic understanding.

Note that, as illustrated in Figure 2, we *develop* understandings of abstractions by instructing in a bottom-up mode: concrete situation to abstraction. But, we *apply* abstractions in a top-down mode: abstraction to concrete situation. These two strategies, bottom-up for engineering education and top-down for engineering practice, were deduced from Vygotsky's psychological studies of language acquisition in children;[21] but we emphasize that they are consistent with our earlier deductions about proper learning strategies based on the current understanding of brain function.[1-3] Note also that as students develop and practice these skills, they often find extension, the transition from abstract to concrete, to be just as difficult as generalization, the transition from concrete to abstract.[21]

Finally, we must emphasize the dangers that are inherent in the power of philosophic understandings: the command of knowledge and economy of thought provided by patterns and generalizations can easily seduce any of us into self-deception.

We are particularly susceptible to self-deception at two levels of philosophic development. One occurs at the novice level, where the student's knowledge base is small, so nearly *any* theory or generalization can organize and explain situations and events.[6] The mild form of this disease leads to overconfidence: the student considers his understanding complete, so filling in details is considered to be an unnecessary waste of effort. More severe cases lead to mental stagnation, prejudice, and antisocial behavior.

The second window of susceptibility comes with mastery of philosophic understanding of a particular, well-defined and usually narrow, portion of a discipline. Though the domain of knowledge may be small, it still requires years of effort to master, so that although success is a true accomplishment, it may induce self-deception manifested as hubris. A common symptom is the expectation that the patterns, generalizations, and organizing principles found in the restricted domain must apply to other domains; if they do not, then those other domains are deemed unimportant and can be ignored. Thus, we have scientists who treat humanists with disdain, and humanists who treat scientists with contempt. Such narrowly trained experts can pose considerable dangers to a society, as was emphasized long ago by Ortega y Gasset.[22]

IRONIC UNDERSTANDING

If we are able to avoid or overcome self-deception, and if we gain sufficient facility and experience with manipulating knowledge at the philosophic level, then we may come to realize that even the power of philosophic understanding is limited. Any real situation is so complex that it is, at best, only incompletely described by our abstractions, theories, and generalizations; in fact, many real situations are not described by *any* of our hard-won theoretical constructs. Such realizations may drive us to a level of understanding that Egan calls *ironic*.[6]

One aspect of ironic understanding is a proper perspective on models; all our attempts to describe and explain reality are merely models. At the somatic level, we use the human body in our first crude attempts to model. At the mythic level, the myths themselves serve as modeling devices.[5] At the romantic level, graphics and writing allow us to revise the simple models of myths into more elaborate structures. At the philosophic level, technical thinking is dominated by mathematical models; at this level, we think we know much. The transition to the ironic level starts when we realize we still know very little.

As engineering instructors we are probably more comfortable than most with the roles that models assume in contributing to and limiting our understandings. As engineers we routinely justify the use of a particular model in a given situation by the *a posteriori* observation that it solved the problem. "Whatever works" is laden with ironic overtones. Nevertheless, engineering students have considerable difficulty in recognizing models, in accepting their limitations, and in selecting the appropriate model for a given situation. For many students, "whatever works" is a cop-out rather than a signal of subtle sophistication.

Another aspect of a properly developed ironic understanding is an underlying sense of humor. To have successfully completed the transition from the romantic to the philosophic level, to have spent years in mastering a discipline at the philosophic level, and then to realize that one still knows little—such progression must drive an individual to either despair or to humor. To react with humor is to recognize and accept the irony of our lot.

More generally, the ironic thinker is sensitive to anomalous situations that fail to adhere to the usual philosophic patterns and theories. Such thinkers display considerable insight in attaching abstract interpretations to concrete phenomena, flexibility in manipulating concepts, and judgment in combining models with formal theories. Ironic thinkers are comfortable with multiple solutions, the lack of solutions, ambiguity, uncertainty, and doubt.

It is probably too much to expect that in four years we can bring many engineering undergraduates to even an operational understanding at the ironic level; nevertheless, we can sow seeds for future growth. In our instruction, we can continually emphasize the roles and limitations of models, and we can give students exercises that force them to select the model most appropriate for a given situation—such exercises develop engineering judgment. To illustrate that many situations have no single "right" answer, we can confront students with open-ended problems; further, any problems having multiple solutions allow us to illustrate the consequences of manipulating a situation to achieve different objectives.

Finally, we can exploit humor as an instructional device. Elsewhere I have speculated about the probable relations between humor and creativity.[3] Here it is appropriate to twist an observation of Minsky's:[19] at the philosophic level, engineering instruction is essentially the humorless activity of using mathematical logic to establish connections, but ironic instruction contains a humorous element that relaxes constraints and allows the mind to seek unconventional connections. Both modes of instruction are needed to start students toward understandings at the ironic level.

CORRESPONDENCE BETWEEN THE SPECIAL AND GENERAL HIERARCHIES

In this section we point out that the hierarchy of technical understandings, introduced previously,[2-4] corresponds to the general hierarchy,[6] which is described in the previous sections. In fact, the technical hierarchy is a subset of the more general one; this is illustrated in Figure 3.

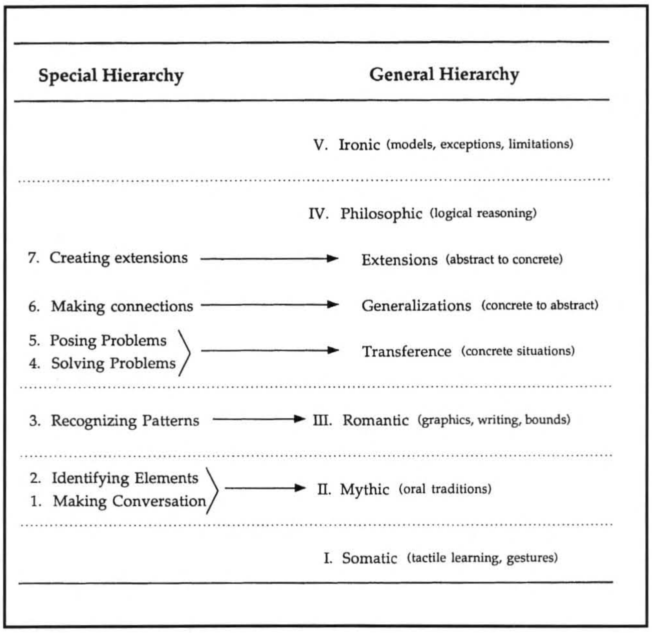

Figure 3. *The hierarchy of technical understandings (left) introduced previously[2-4] is a special case of the more general hierarchy (right) developed by Egan.[6]*

The technical hierarchy begins, at its most elementary level, with *making conversation,* and it continues with articulation of definitions that *identify conceptual elements.* These activities are fundamental to the oral traditions characteristic of mythic understanding, for conversation leads to storytelling, and both conversation and storytelling reveal the need for a language composed of words having commonly accepted definitions.

The third level in the technical hierarchy is *pattern recognition;* at this level we attach meanings, rather than mere definitions, to a concept by relating it to other concepts. The pattern formed in this way defines the conceptual landscape, which is a product of romantic understanding.

The fourth and fifth levels of the technical hierarchy involve *problem solving* and *problem posing.* These are the principal activities that constitute transference of concepts among concrete situations in philosophic understanding. *Making connections,* at the sixth level of technical understanding, is the same as the philosophic exercise of generalizing concepts from concrete situations to abstract ones.

Finally, at the seventh level of technical understanding, *creating extensions* is the philosophic activity of applying abstractions to different concrete situations. Thus, we have a close and satisfying correspondence between the technical hierarchy and the more general one.

In the next paper in this series we will discuss how the general hierarchy can be applied to engineering education.

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