TOWARD TECHNICAL UNDERSTANDING

Part 2. Elementary Levels

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

This is the second of three papers that stalk the question of what we mean by an understanding of technical material. In the first paper of the series, we noted that to understand has multiple meanings; our goal in these papers is to clarify the distinctions among those meanings and to organize them into a useful hierarchy. We also summarized what is now known about the structure and function of the human brain, and we used that knowledge to draw certain implications about the nature of learning.*

Any study involves many kinds of understandings and many ways to reach any of them. We propose that the ways of understanding technical material can be organized in a hierarchical fashion so that a progression through the hierarchy carries the student, in a systematic way, to a broader and deeper appreciation, perception, and comprehension of the material. The hierarchy consists of seven levels, shown in Figure 1.

In formal educational settings, much of a student's effort seems to be devoted to solidifying understanding at the current level, while much of the instructor's effort seems to be devoted to preparing students for the transition to the next level. Since the transitions carry the student to higher levels of understanding, the transitions between levels must be as important as the levels themselves.

A successful transition involves at least the two following characteristics. First, each transition must be motivated. In the early stages (levels 1 to 5), the transitions are motivated when we realize that mastery at the current level is not sufficient for our immediate needs. In the later stages (levels 5 to 7), the transitions are motivated when we realize that mastery at the current level enables us to move beyond our immediate needs. Second, each transition involves a reformulation of understanding at the current level. That is, understanding at the new level subsumes, but does not replace, understanding at previous levels. In each of the following sections, we first discuss a level and then provide the motivation and reformulation that constitute the transition to the next level.

LEVEL 1: MAKING CONVERSATION

Study begins when our attention is drawn to the objects, processes, and concepts that constitute a topic. At this most superficial level, understanding is just sufficient to enable students to participate in conversations about the topic. They at least know the names of some of the subject's primitive objects and concepts, so they can pose questions. With more exposure, they may even be able to converse fluently about the material. Yet at Level 1, they still lack any skill in using the objects and concepts.

For conversation to succeed as communication, participants must properly use the names of objects and concepts. It is a seductive misconception, however, to believe that the correct use of a name implies a correct understanding of the named object. For primitive humans, a name was thought to be an intrinsic part of an object, and that calling the name of an object exerted control over it. Thus, one of Adam's first acts in the Garden of Eden was to name the animals. Joseph Campbell has noted that in some ancient Indian cultures, pronouncing the Sanskrit name of a god was thought to call forth the god.[1] A similar tradition operated in ancient Judaism, so that correct pronunciation of the name of God (YHVH) was first held secret, then later avoided. In fact, in Judaism and other ancient cultures, names were considered to be so powerful that the entire universe was thought to have been created, not out of nothing, but from a calling of names.[2]

This ancient penchant for names was not intended to sig-

***J.M. Haile** is professor of chemical engineering at Clemson University, and is the author of* Molecular Simulation, *published by John Wiley & Sons in 1992.*

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nal understanding, but rather to compensate for *lack* of understanding. In modern times, we may still use names to deal productively with things we don't understand (an example is gravity). That is, sometimes we find it useful to substitute a name in place of the object named, even when the object itself is not understood.

In the classroom, however, manipulating names in place of objects can obscure rather than enlighten. Consider Feynman's example of *triboluminescence,* which can be described as the emission of a photon that may occur when certain crystals are subjected to sudden high pressure.[3] Such a statement may be precise, but it really only trades one name for other names (photon, crystal, emission, pressure); to attach meaning to such a statement, a student must explicitly connect these names to physical objects. Left to their own devices, many students fail to make such connections. They can be helped by translating formal descriptions into more familiar terms, such as this: when a few grains of sugar are taken into a dark room and squeezed with a pair of pliers, we might see a small flash of light—that's triboluminescence.[4] Names can help draw our attention to things,[5] but knowing names is only a first step toward understanding.

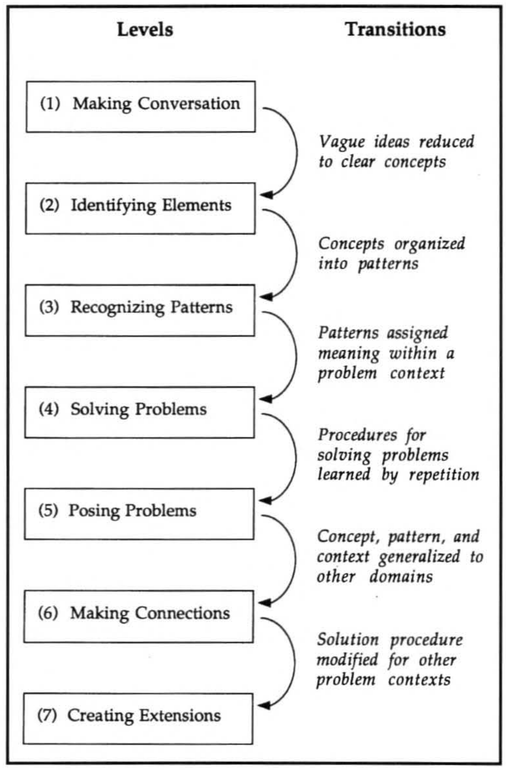

Figure 1. *The levels of understanding and the transitions between them.*

Transition:

Level 1 (Making Conversation)
to
Level 2 (Identifying Elements)

Motivation: Verbal fluency with a portion of a domain is not the same as having clear ideas about the objects comprising the domain, or knowing which objects are most important, or knowing how the objects can be used.

Reformulation: Vague and ambiguous ideas are reduced to concise and accurate statements about the structure and function of objects and concepts.

LEVEL 2: IDENTIFYING ELEMENTS

When we identify the elements—the objects and concepts—that constitute a topic, we define the elements and try to give a sense of how the element behaves in typical situations. Let's consider definitions first: a complete definition should encompass both structure and function. A *structural* definition should include two things: the identify of the class to which the object belongs and a list of those characteristics that distinguish it from other members of its class. A *functional* definition should also include two things: the typical or common use of the object, together with identification of situations where the object is not useful or in which it fails. The words used in these definitions *must* be words already known to the students; we are trying to build foundations in students' minds by reorganizing and expanding what they already know, and we can only build from the materials available.

Structural and functional definitions should be provided for concrete things, abstract things, and processes. We tend to define concrete things in terms of function (a valve is a pipe fitting used to control flow) and to define abstractions in terms of structure (entropy is the thermodynamic state function obtained by applying an integrating factor to the inexact differential formed by the reversible heat). To the extent that this observation is true, it is one source of students' discomfort with abstractions. To help us remember that both structure and function are important, here are five diagnostic questions that students and instructors can use to test understanding of elements:

1) *What is it?*
2) *How is it related to or how does it differ from other members of its class?*
3) *For what is it used?*
4) *How can it fail?*
5) *How can we learn about it?*

These diagnostics are illustrated in Table 1 for a concrete thing and for an abstraction. In addition to objects, these diagnostics can also be applied to processes; you might care to practice by applying them to flash distillation.

Note that questions (1) and (2) are *ontological* in that they address structure; questions (3) and (4) are *causative* in that they address function; and question (5) is *epistemic.*[6] For concrete things, a typical response to question (5) is to take the thing apart or to operate it. For mathematical abstractions, a typical response is to explore the object's behavior by doing calculations with simple models. Note also that question (5) is intended to move the student from pure definitions toward meaning. That is, definitions do not necessarily constitute meaning, because meanings generally involve cross connections among objects, concepts, and levels of understanding. Consider,

When an ideal gas is heated in a closed rigid vessel, its internal energy always increases.

The unfortunate—such as a politician or a royal personage—might well know the definition of each word in this sentence without grasping the meaning of the sentence. To move toward meaning, students must participate in some of the activities suggested by the answers to question (5).

Transition:

Level 2 (Identifying Elements)
to
Level 3 (Recognizing Patterns)

Motivation: Knowing the identities and uses of individual objects is not the same as knowing how the objects are related or how they can be combined to increase their effectiveness.

Reformulation: Individual objects and concepts are organized into meaningful patterns.

LEVEL 3: RECOGNIZING PATTERNS

Structural and functional definitions can be given to most objects, concepts, and processes, but such definitions carry little meaning until the defined things are related to other objects, concepts, and processes. We use the word *pattern* to refer to those relations that impart meaning to sets of objects, concepts, and processes. For example, structural and functional descriptions of fugacity are given in Table 1; but meanings for fugacity can only be extracted from its relation to processes (such as diffusion) and to other properties (such as temperature and composition). Thus, a fugacity gradient measures a driving force for diffusion: a substance diffuses from a region of high fugacity to one of low fugacity. Moreover, when a fugacity is balanced across an interface, we have an absence of diffusional driving forces, producing diffusional equilibrium. Thus, the fugacity fits into a general pattern that uses driving forces to explain changes.

Other meanings can be attached to the fugacity by considering other relations. In fact, a general observation is that one object may participate in several different patterns and, moreover, that more than one pattern can often be contrived from the same set of objects and concepts. This is illustrated schematically in Figure 2. From the same objects, different patterns provide flexibility in that one pattern may prove more useful in one situation while another serves better in another situation. This flexibility leads to a problem-solving strategy; when a particular pattern of known information does not seem to be leading to a solution, try reformulating the information into a different pattern. When we say a concept is rich in meaning, we imply that it contributes to multiple patterns.

One of the great mathematical physicists of the 19th century, Henri Poincaré, had an understanding of classical dynamics that anticipated modern studies of nonlinear dynamics, unstable systems, and chaos. He was also deeply curious about the nature of creativity and the workings of the mind. In addressing the question as to why most people cannot understand mathematics, Poincaré wrote[7]

> A mathematical demonstration is not a simple juxtaposition of syllogisms, it is syllogisms *placed in a certain order,* and the order in which these elements are placed is much more important than the elements themselves.

Such ordering of elements produces patterns, so we can

TABLE 1
Example of Level-2 Diagnostics Applied to a Concrete Object and an Abstract Object

Diagnostic	Object: Globe Valve	Object: Fugacity
(1) What is it?	Valve whose body houses a chair-shaped seat located roughly mid-way between body walls. At the lower end of the stem is a disk that fits into a seat when the stem is lowered.	In a mixture containing component i at mole fraction x_i, the fugacity f_i is the thermodynamic state function obtained from the following isothermal derivative of the chemical potential: $d\mu_i = RT\,d\ell n f_i$ with low-pressure boundary condition $\lim_{P \to 0} f_i = x_i P$.
(2) How is it related to or how does it differ from other members of its class?	Differs from other valves in structure of seat and disk. Distinguished from others by globular shape of body.	Differs from chemical potential μ_i and activity a_i in that absolute values can be obtained for fugacity f_i, but only relative values can be obtained for μ_i and a_i.
(3) For what is it used?	For fine control of flow, as opposed to gate and ball valves, which only provide on/off control.	To express criteria for phase and reaction equilibria; thus fugacity provides starting points for solving phase and reaction equilibrium problems.
(4) How can it fail?	Worn seat and disk; leaks in packing; jammed stem; stripped threads on stem; solid matter blocking seat.	Not useful unless a model (such as a PVTx equation of state) is is available that relates f_i to measurables, such as T, P, and x_i.
(5) How can we learn about it?	Study design drawings; study cut-away model; take one apart; operate one *in situ;* operate one in a process simulator	Explore its T, P, and x_i dependence by performing calculations using simple models.

interpret this statement by saying that people fail to understand meanings to the extent that they fail to recognize and interpret patterns.

The *pattern is the fundamental unit of understanding* not just in mathematics, science, and engineering, but in any intellectual activity. For example, in music a single note or chord has essentially no meaning; musical meaning arises only when notes are organized into patterns. In the piano music of Bach, for example, many patterns can be identified as mathematical transformations of some relatively simple theme. Experienced musicians do not study music at the level of notes but at the level of phrases—patterns of notes. Similarly, masters at chess study their game not in the positions of individual pieces, but in the patterns produced by the relations among the positions.[8] It is intimate familiarity with patterns that allows a master to play, and win, several games simultaneously.

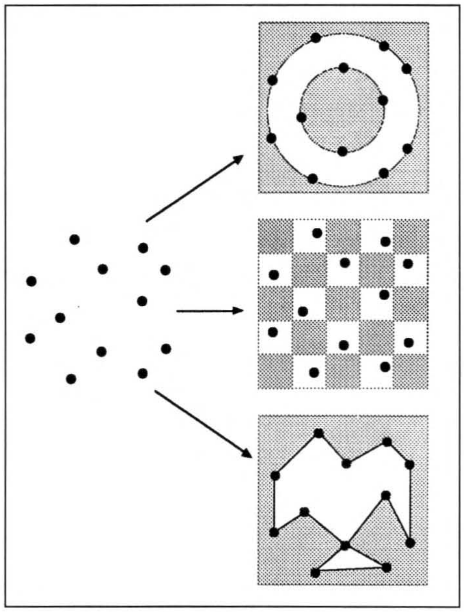

Figure 2. *Let each dot on the left represent an isolated fact or a single piece of information; any one such fact has essentially no meaning. But by establishing relations among facts, we create patterns in which the information takes on meaning. Three patterns are illustrated schematically on the right. Note that each of these patterns is formed from the one arrangement of dots shown on the left. That is, the same information can usually be organized into several distinct patterns, none necessarily "right" or "wrong," but some more useful than others in particular situations.*

Patterns are distinct from classifications. Classifying objects according to common characteristics helps us organize information, and it may help us identify relations and patterns, but a classification does not establish relations among objects. Note also that a meaningful pattern does not necessarily result when we simply organize information into a familiar structure. In the use of language, this observation motivates the distinction between syntax (proper structure) and semantics (meaning).[6] For example, consider this German sentence from Wiener:[9]

Der Geist will es, aber der Fleisch ist schwach.

A syntactically correct, word-for-word translation would be "The ghost want to, but the meat is rare." Although this translation preserves the syntax of the original, it fails to capture the meaning. In a syntactically correct structure, meaning is rarely embedded in individual elements; rather, it is usually gleaned from relations among the elements. A meaningful pattern is more than the sum of its parts.

Confusion as to the distinction between syntax and semantics seems pervasive and a cause for concern. We now have software that can check the spelling and grammar used in student themes, lab reports, and term papers; we have equation solvers by which students can readily implement all kinds of numerical methods; we have symbolic manipulators that students can use to take derivatives, evaluate integrals, and perform algebra; we have process simulators that students can use, not only to perform complex design calculations, but also to replace experience in laboratories. Over a period of just a few years, we have introduced an astonishing number of black boxes into our courses, with little concern about their impact on understanding gained or lost by students. The point here is that a syntactically correct manipulation of a black box does not necessarily evoke any semantically correct response from the student who operates the box.

In the hands of an expert, a black box can offer positive benefits—it can enable more work to be done in less time. Experts attach meaningful relations between input and output, and they are sensitive to any deviation from an expected outcome. If an outcome is unexpected, they have other independent means for checking. But a positively beneficial tool in the hands of an expert can be positively dangerous in the hands of a novice. Novices cannot make logical and meaningful relations that connect output to input, they have ill-formed expectations as to what the output should be, they are not aware of how a black box can be wrong, and they have few if any independent mechanisms for checking the output.

Given our present understanding of how minds work, it is difficult to see how a black box, which is intended to *hide* the relations between output and input (*i.e.,* hide patterns), can be used to establish meaningful relations in the brains of students. It may be, however, that some use of black boxes can reinforce or strengthen patterns that have been established through other learning activities. Thus, a black box should be introduced only after students have developed understanding about those relations hidden by the box.

Since the cerebral cortex learns by modifying existing structures, presenting new patterns should always proceed inductively, starting from particulars. For example, say the goal is to develop the pattern we call the stuff equation:

$$\begin{pmatrix}\text{Rate of}\\ \text{STUFF into}\\ \text{system by}\\ \text{interactions}\end{pmatrix} - \begin{pmatrix}\text{Rate of}\\ \text{STUFF out}\\ \text{of system by}\\ \text{interactions}\end{pmatrix} + \begin{pmatrix}\text{Rate of}\\ \text{generation}\\ \text{of STUFF}\\ \text{in system}\end{pmatrix} - \begin{pmatrix}\text{Rate of}\\ \text{consumption}\\ \text{of STUFF}\\ \text{in system}\end{pmatrix} = \begin{pmatrix}\text{Rate of}\\ \text{accumulation}\\ \text{of STUFF}\\ \text{in system}\end{pmatrix}$$

We should start with a particular application, preferably extracted from the student's experience—balancing a check book is a possibility, wherein the "system" is the bank account and "stuff" is money. Additional, very different, applications are usually needed to help students solidify interpretations of all terms. Only then should we present the generalization, using "stuff," in the above form.

Patterns are effective devices because minds seek patterns. Since minds try to find patterns in any case, we might as well try to develop patterns that are known to be effective and useful. Inversely, we should help students avoid patterns that are misleading or unproductive. That is, we should devote some effort to showing students ways *not* to think.

Patterns are also effective because they provide a means for attaining efficiency in education. With the quantity of technical information doubling every five years, how can we ever teach it all? The answer is not merely that we can't, but more importantly, that we shouldn't. Repeatedly presenting new applications without establishing any overriding pattern wastes resources because it provides no lasting benefit to students. The purpose of a university education is not to simply teach facts or to train operators of black boxes; rather, it is to develop a small core of important patterns in the brains of students. Important patterns are those that will help students grow by adding new information to their existing core. Likewise, new information is important to the extent that it connects to old information and established patterns; without such connections, new information is isolated and essentially meaningless. By extension, we should not teach any topic that lacks patterns that could serve as a basis for future growth of students.

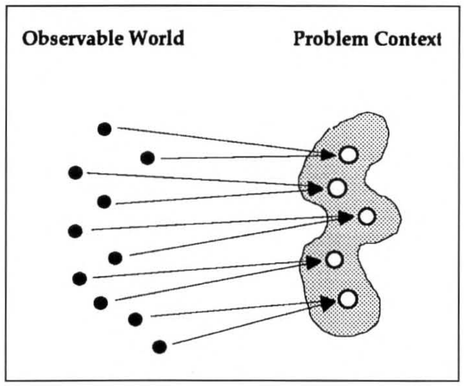

Figure 3. *Schematic of a homomorphic projection of information from the observable world onto a pattern. Such projections are many-to-one; that is, they preserve some facts but suppress others. The pattern created by such projections takes a particular meaning when it is superimposed onto a problem context.*

Transition:

Level 3 (Recognizing patterns)
to
Level 4 (Solving Problems)

Motivation: Recognizing a pattern is not the same as knowing how the pattern can be used or recognizing situations in which it can be used.

Reformulation: The pattern is connected to problem situations—contexts in which the pattern takes on particular meanings.

LEVEL 4: SOLVING PROBLEMS

At previous levels, our attention is focused on identifying, defining, and attaching meaning to objects, concepts, and patterns. Now we begin to use those objects, concepts, and patterns to answer questions; the formulation of answers is called *problem solving*. To solve problems, not only must we be aware that certain patterns exist, but we must also recognize when they are useful. That is, patterns themselves are useless until they are related to still other patterns, objects, and concepts. These other related things constitute a *context* in which a pattern acquires a particular meaning. The act of recognition amounts to a projection of relevant information onto an appropriate pattern in the problem context. In the language of group theory, such a projection is *homomorphic* in that only relevant information is projected; irrelevancies are suppressed. This is illustrated schematically in Figure 3. These projections are usually homomorphic because reality nearly always provides more information than we need. Recognition of the appropriate projection is a vital step in solving a problem.

To illustrate a homomorphic projection, say we are faced with a heat exchanger that is no longer operating to specifications. One diagnostic would be to check the energy balance. Thus, we determine the temperatures, pressures, compositions, flow rates, and phases of all streams and project them onto the pattern of the stuff equation; under this projection the stuff equation becomes an energy balance. This projection is homomorphic in that we need only information about streams into and out of the exchanger; information about the interior of the exchanger, such as heat transfer areas and heat transfer coefficients, is suppressed. The result of the energy-balance calculation may or may not help us solve the problem; if it does not, then we seek other patterns. The lessons here are that the problem context suggests patterns that may be useful and the context imparts meaning to the results obtained from the patterns. Thus, say we find that the energy balance is satisfied with ±3%; is this satisfactory or not? The answer depends on context. In some situations ±3% would be perfectly satisfactory, but in others it would be absolutely devastating. Students often have difficulty reconciling the meaning of a computed number to the context of the calculation.

The projection from the observable world onto a pattern in the problem context is a first step in developing a solution procedure. The development of a complete procedure is an important aspect of achieving understanding at Level 4; we do not address the detailed aspects of that development here, however, because a considerable body of literature already exists. The modern literature on solving problems begins with Polya,[10] and a continuing survey is available from Woods.[11] We do, however, emphasize three general points about solving problems.

First, we have two general strategies for solving problems: an offensive strategy, in which we try to move toward a stated goal, and a defensive one, in which we try to avoid undesirable penalties. In most situations, we use an offensive strategy, but if we can't find a successful offensive strategy, then we should consider a defensive one. The lesson here is to maintain flexibility; in some situations, penalty avoidance is sufficient to be successful. For example, an offensive strategy guides most investments in the stock market (the goal is to increase capital), but in some markets the winning strategy is a defensive one (to avoid losing capital).

Second, one mistake that commonly prevents our solving a problem is a failure to verify default assumptions. Default assumptions are those many aspects of experience that we take to be generally true. Such assumptions free us from having to repeatedly make the same judgment about a familiar situation. Without default assumptions, we could rarely find time to accomplish anything new. But sometimes we cannot solve a problem because a default assumption no longer applies. Polya lists several in a mathematical context,[12] such as

1) If we have N equations in N unknowns, then we can solve for the unknowns.

Here are some others:

2) If a simple algorithm provides a result, a complex algorithm will provide a more reliable result.
3) If a statement is true, then so too is its converse.
4) If any data fail to fit the expected pattern, we can ignore those data.
5) If two effects are similar, then their causes are similar. This assumption takes several forms, including: Large effects have large causes.
6) If the problem has boundaries, then its solution has the same boundaries.

Confining the search for a solution to the boundaries of the problem is a common source of difficulties; in some situations, simply extending the boundaries converts an intractable problem into a trivial one.

Third, in problem solving, memory plays multiple, conflicting roles. On one hand we need long-term memories to recall patterns that might be helpful in the current problem context. (These might be evoked from Polya's heuristics:[10] Have you ever solved this problem before? Have you ever solved a similar problem?) On the other hand, we need short-term memories to identify our current position in the solution procedure, to recall how results from previous steps affect the current step, and to recall how results at the current step are to be used in subsequent steps. The simultaneous use of these memories seems to interfere with creation of new memories; that is, in any challenging problem, so many neural networks are activated that few are available for forming new memories. When we solve a new problem for the first time, our attention is so preoccupied with finding the solution that we rarely learn *how* to solve it. This observation motivates the transition to Level 5.

SUMMARY

In this paper we have suggested that the multiple meanings for technical understanding can be organized into a hierarchy, and we have described understanding at the elementary levels. In our discussion of those levels, an important point has emerged: the fundamental unit of understanding is the pattern. Patterns impart meaning by providing structures that establish relations among chunks of information, so our understanding of a topic remains rudimentary until we can see patterns. Further, we advance to higher levels of understanding only to the extent that we can recognize, interpret, and apply patterns. The importance of this point can probably not be overemphasized. We conjecture that one of the most effective improvements we can make in education is to organize material so that students learn patterns, not sequences of individual facts.

As students progress through the first levels of understanding, they move from an initial encounter with a topic to some facility with solving problems. So, when they are able to solve problems at Level 4, they have made significant progress. Nevertheless, achieving skill at solving problems marks a rather elementary level of understanding; solving a problem is not the same as knowing *how* to solve it. This realization begins the transition from Level 4 to Level 5. This transition is often difficult to make and therefore it is the one we use to distinguish elementary understanding from more advanced levels. Those advanced levels will be described in the third paper in this series.

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