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Bridging the Gap

Bridging the Educational Research-Teaching Practice Gap

CONCEPTUAL UNDERSTANDING, PART 1: THE MULTIFACETED NATURE OF EXPERT KNOWLEDGE*

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The term "conceptual understanding" has been used rather loosely over the years in educational practice, with a tendency to focus on a few aspects of an extremely complex phenomenon. In this first article of a two-part miniseries on conceptual understanding, we describe the nature of expert (versus novice) knowledge and show how the conceptual understanding of experts is multifaceted in nature requiring competence in a wide range of cognitive skills. We then discuss five such facets of conceptual understanding that require competence in the cognitive skills of memorization, integration, transfer, analogical reasoning, and system thinking. We also argue for the importance of explicitly teaching and assessing such facets of understanding as part of all molecular life science curricula so as to better prepare our students to become experts in the field. Examples of the assessment tasks that can be used to promote the development of multifaceted conceptual understanding in students are presented in Part 2 of this series.

Keywords: Assessment, conceptual understanding, cognitive skills, expert versus novice knowledge, meaningful learning.

The past decade has seen a dramatic increase in biochemical knowledge, leading to extensive debate as to what we should be teaching in terms of the core knowledge and key concepts of our field. Yes, we have a wide range of educational resources and curriculum documents prepared by eminent biochemists and biologists (*e.g.*, see [1]), but, however, these are broad and detailed, and they often do not clearly identify the fundamental core conceptual knowledge of our discipline. In response to this concern, Hamilton *et al*. [2] have founded the IUBMB-driven Concept Inventory Project, which is currently being piloted by members of an Australian Carrick Grant award (see [3]). These and various other smaller projects, focusing on specific themes such as structure and function of biomolecules, properties of amino acids, reversible equilibrium [4], and metabolism (Degerman and Tibell, personal communication) could have an important influence on education in the molecular life sciences, leading to graduates with more focused and meaningful conceptual knowledge for tackling developments at the forefront of our field.

Content knowledge stored in long-term memory remains inert unless individuals possess the cognitive ability to put such knowledge to active use. This premise is supported by Mayer [5, p. 226] who suggests that successful learning includes not only acquiring knowledge but also having the cognitive skills to use such knowledge in a variety of new situations. Similar sentiments have been expressed by Chattopadhyay [6] who suggests that the objective of genetics learning should be to promote conceptual understanding and thinking (cognitive) skills that encourage students to apply their knowledge to real-life situations. This is supported by the goals of a U.S. Teagle Foundation sponsored project being conducted by Wolfson *et al*. [7], which, *inter alia*, addresses the need to teach more cognitive skills to undergraduates, so that they are better prepared for the workplace. In essence, the development of cognitive skills in students can be viewed as fostering "meaningful learning," which Mayer [5] defines as going beyond the mere learning of factual knowledge to include the development of conceptual understanding in students.

Over the years, numerous authors have attempted to describe what it means to "understand a concept" (*e.g.*, [8]). Unfortunately, "conceptual understanding" continues to be used rather vaguely, focusing only on parts of what is a very complex idea. In support of this, Orgill and Bodner [9] are of the opinion that most biochemical concepts are multifaceted in nature and that true understanding of

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a concept stems from students being able to integrate all facets of a concept into some intelligible whole.

The idea of conceptual understanding being multifaceted was first proposed by White and Gunstone [10], some 15 years ago, who expressed concern that if the definition of conceptual understanding is limited by instructors to only "low-order" cognitive skills, such as memorization, important facets of its meaning would be neglected. For example, a particular student might perform well in a question requiring a definition of the concept of chemical equilibrium (requiring memorization skills), but perform poorly if asked to apply such knowledge to an explanation of the direction of metabolic pathways (requiring application and transfer skills) or to the development of a computer or physical model that represents the equilibrium process (requiring analogical reasoning). For this reason, White and Gunstone [10] also suggested that it is extremely difficult to compare two students' understanding of a concept, because one might do better in a test of one facet of understanding and another student do better on another. As a solution to their concerns, they suggest instructors teach and assess several facets of conceptual understanding, with each facet of understanding of a concept requiring competence in a different cognitive skill, so that students can develop a more comprehensive understanding of a particular science concept, and faculty can better understand deficiencies in student knowledge.

In this article, we will not attempt to focus on *all* the facets of understanding of a concept and related cognitive skills ever documented in the literature, but rather on a selected few that we recommend to instructors should be formally taught and assessed as part of all biochemistry course curricula. Our two major arguments for this recommendation are first, such knowledge and skills are essential components of expert knowledge and skill competence and therefore, important to develop in our own students and, second, students have shown various documented difficulties pertaining to each facet, which, therefore, need to be formally addressed and remediated. Thus, this first article of a two-part miniseries on conceptual understanding will aim to address the following specific questions:

- What is the nature of expert (versus novice) knowledge?
- What types of cognitive skills are crucial for students' development of various facets of expert conceptual understanding?

THE NATURE OF EXPERT (VERSUS NOVICE) KNOWLEDGE

A major goal of education is to develop students from novices into experts. This raises the question of what we mean by an "expert" as opposed to a "novice." In our view, novice and expert knowledge is defined by a continuum, because there is no clear boundary between when a "novice" has sufficient knowledge to be called an "expert," and, in the same vein, there is no clear absolute ceiling to expert knowledge. Nevertheless, we can suggest some types of knowledge and skills that tend to characterize an expert when compared with a novice and then focus our teaching on developing such knowledge in our students, so that we "move" or "scaffold" [11] them along the continuum toward expert thinking and understanding.

The science education literature contains extensive research on the nature of expert as opposed to novice knowledge and, therefore, the type of knowledge and skills which would be desirable to develop in modern molecular life sciences curricula. For example, experts display a wide range of higher-order cognitive skills that include the ability to synthesize, critically analyze, and evaluate information [12] that has been gained in a situated context [11]; to be creative, to transfer and apply knowledge to other novel contexts [4], to reason analogically about concepts [13], to reason locally as well as globally (system thinking) [14], and to visualize abstract structures and processes at different levels of biological organization from molecular through to microscopic and macroscopic levels [15]. In addition, through their wider experiences, experts possess a far richer set of connections between ideas than novices do [16]. That is, experts construct more developed and interconnected mental models, explanatory frameworks, and schemata of concepts than novices, who often struggle to integrate their mental models into coherent and powerful conceptual frameworks [17]. In support of this, Khodor *et al*. [18] suggest that experts' knowledge is integrated around certain core and fundamental concepts, which provide them with a sophisticated knowledge structure for solving novel problems. In contrast, Stevens *et al*. [19] maintain that novices, by virtue of their more fragmented knowledge, have a "lower ability to frame the problem" to recognize the importance of problem elements and to prioritize solution strategies. These workers have also found that "novice strategies are often ineffective (they fail to reach the correct answer) and inefficient (they require more steps, more time, and more reference material), whereas experts are more efficient in the use of resources and in deriving the correct answer." For example, Nahum *et al*. [17] have pointed out that students often confuse intramolecular and intermolecular bonds, overgeneralize bonding concepts, and memorize terminology without understanding the underlying conceptual relevance of bonding phenomena. Chi *et al*. [20] also showed that when solving physics-related calculations, novices tended to play "hunt for the formula," whereas experts qualitatively analyzed the problem and performed order of magnitude estimates before trying to obtain a solution quantitatively. Indeed, many of our own biochemistry students favor using a formula, over first-order principles, to calculate thermodynamic parameters and seem unperturbed when answers reflect unphysiological values such as *molar* concentrations of cellular metabolites.

Because much of the cognitive processing used by experts to solve problems is "automatic" or part of their tacit knowledge, instructors need to make a directed effort to explicitly explain such crucial processes to novices [21]. In this regard, Novak and Cañas [22] have suggested that getting experts to construct concept maps can be a very useful tool for "exposing" their tacit knowledge, whereas Marbach-Ad *et al*. [23] used a curriculum development exercise involving faculty with expertise in host–pathogen interactions to access their tacit knowledge. The following is another approach, which can be a very useful "Bridging-the-Gap" [24] workshop exercise (Grayson, personal communication) for helping colleagues identify their own expert knowledge and skills for development in students:

1. Without going into specific details of content knowledge, address the following question in groups of three or four persons and summarize all the responses on one side of a large board.
    - What type of knowledge and skills do you think characterize your practice as an expert biochemist?
2. Repeat (1) above, but instead, address the following question and record the responses on the other side of the board.
    - What type of knowledge and skills do you explicitly teach in your biochemistry courses?
3. Discuss and compare the responses to the two questions.

In the first author's experience, colleagues usually find a profound difference between the responses to questions (1) and (2), particularly with respect to cognitive skills (*e.g.*, application and linking of knowledge for solving problems) and the requirements for deep conceptual understanding, which tend to predominate in response to question 1 but are mainly absent from responses to question 2. This helps colleagues realize the importance of adjusting their course curricula to be more focused on cognitive skills and the development of expert knowledge in their students. Crucially, what also typically emerges is the realization that being an expert is not about how much content can be "reeled off," but rather about having a basic conceptual "vocabulary" and the cognitive skills required to make sense of new or existing knowledge. Because of the nature of science [25, 26], it is also essential for novices to comprehend that scientific knowledge is dynamic and can be added to or replaced rather quickly, whereas the cognitive skills essential for expert practice develop slowly and remain relatively constant.

To help students develop expert-like knowledge and skills, it is important to promote what Entwistle and Ramsden [27] call a deep approach rather than a surface approach to learning. As discussed in a previous article of this column [28], a deep learning approach requires students to develop understanding through the use of various cognitive skills such as integration, critical analysis, and application of knowledge. This relates well to the ideas of Bloom *et al*. [29] who, some 50 years ago, published a taxonomy of educational objectives, which has made a significant impact on teaching, learning, and assessment. Allen and Tanner [30] have demonstrated how this taxonomy can be used effectively in cell biology for the design of questions that probe different aspects of students' knowledge and cognitive skills. More recently, Anderson *et al*. [12, 31] have revised the taxonomy to include both a *knowledge* and *cognitive process* dimension. Aspects of the cognitive process dimension were developed by educational psychologist, Richard Mayer, who, in a subsequent work [5], illustrates how the idea of deep learning is closely related to fostering a *meaningful learning approach* as a major educational goal. According to Ausubel [32], and in line with a constructivist view of learning [33], meaningful learning occurs when students have sufficient prior knowledge upon which to anchor new ideas. Fisher *et al*. [34] extend the definition by stating that "meaningful learning occurs when individuals actively incorporate new ideas into their mental structures, ask themselves what the implications of the idea are, and assess whether those implications make sense" (p. 80). Mayer [5] maintains that a key outcome of meaningful learning is that students should not only become competent in the cognitive process of remembering (recognizing and recalling) scientific knowledge but also develop other cognitive competencies that characterize experts such as understanding, applying, analyzing, evaluating, and creating. In this regard, Novak [35] views learning on a continuum, which can vary from "extreme rote" to "highly meaningful," with the latter involving higher-order cognitive skills. Most importantly, Mayer [5] recommends that such cognitive competencies should be explicitly taught as a primary educational objective. Meeting this objective is where assessment can show great power as a "Bridging the Gap" tool. Because of the well-established importance of aligning course objectives with teaching, learning, and assessment (see [28]), specifically designed assessment tasks can be extremely effective in directing and promoting the teaching, learning, and development of such cognitive skills in our students, so that they progress toward becoming experts [28].

THE MULTIFACETED NATURE OF CONCEPTUAL UNDERSTANDING

On the basis of the above argument, we pose the question, which facets of conceptual understanding compose expert understanding of a concept? Because it is neither feasible nor practical to teach and assess all facets of understanding of a concept, it is important to try and select the most important ones. There are facets of conceptual understanding that instructors should always focus on regardless of the nature of the concept and others that are of greater relevance to a particular concept or educational context. Table I lists a selection of what we consider to be important cognitive skills cen-

Table I

Selected cognitive skills that are central to various facets of expert conceptual understanding in biochemistry and molecular biology

Understanding a concept means the ability to:
Memorize knowledge of the concept in a mindful manner, as distinguished from rote learning
Integrate knowledge of the concept with that of other related concepts so as to develop sound explanatory frameworks
Transfer and apply knowledge of the concept to understand and solve (novel) problems
Reason analogically about the concept
Reason locally and globally about the concept (system thinking)

tral to various facets of expert conceptual understanding in biochemistry and molecular biology.

Bloom's revised taxonomy [12] advocates the following standard format for stating educational objectives, which we also use in Table I: "The student will be able to, or learn to, *verb noun*," where the verb indicates the *cognitive process* and the noun the *concept* or *knowledge* that is intended to be learnt. A key aspect of these objectives is that they should be teachable and assessable, and the type of assessment task used should be aligned with course objectives (see [28]). In this section, we briefly discuss the five cognitive skills that are central to various facets of expert conceptual understanding (Table I), while examples of assessment tasks that can be used to measure and promote development of such cognitive skills in our students are presented in Part 2 of this miniseries.

Mindful memorization (Table I) is *not* rote learning, but a crucial cognitive skill required for the understanding of all concepts. Fisher *et al*. [34] defines "mindfulness" as paying attention *with intention to understand or make sense of information*. Thus, mindful memorization can be defined as an essential cognitive process in which *information* is memorized with some specific *intention* or purpose in mind, namely to *understand*, use, or apply the information in problem-solving activities that require higher-order cognitive skills. Therefore, it is important that the memorization precedes any other higher-order cognitive processes, such as transfer and application, because all cognitive processes require "something to process"—in this case—memorized information. Memorization skills are a crucial component of all expert competence (Table I), and we need to teach and assess (see part 2 of this series) such basic skills in our students, so that they have meaningful underlying knowledge upon which to exercise their higher-order skills. Knowing facts or being able to regurgitate a concept should, however, not be confused with understanding the nature of the concept. One increasingly important facet to know in this era of instant electronic retrieval of information and open-book tests is to know that something is known (*e.g.*, the citric acid cycle) and where to find it and should you need it. This is not exactly memorization but is related to it and is an important facet of learning (anonymous reviewer, personal communication).

The memorization of isolated facts leads to knowledge that exists in the mind as "disconnected chunks" of information [36]. For memorized knowledge to become useful for understanding phenomena and for solving problems, the "chunks" need to be integrated into a meaningful network or schema of concepts that serve as a sound *explanatory framework* for a particular topic (Table I). Such explanatory frameworks and the *integration* skills necessary for developing them characterize an important facet of expert conceptual understanding and problem-solving knowledge, and, therefore, we need to explicitly teach and assess such skills in our students. Concept mapping [37, 38] is recommended to biochemists as an example of a useful tool for illustrating the nature and extent of an expert's versus a novice's integrated knowledge. Concept maps are composed of concepts (that form the "nodes" of the map) linked to each other by propositional statements (written along mono or bidirectional arrows) that describe relationships between concepts. They are thought to mimic the storage of knowledge in the mind [38] and to reflect the nature, elements, links, network, and structure of a person's explanatory framework about a particular topic and, therefore, their understanding of the relevant concepts. Thus, concept maps are also very useful for revealing evidence of poor integration skills, deficiencies in knowledge, or alternative conceptions [39] that require remediation [40]. More extensive visualization of large groups of concepts can be achieved by generating semantic networks [41]. Semantic networks allow for visualizing both 3D and bidirectional connections between concepts, allowing for the development of sophisticated concept descriptions. For example, Gorodetsky and Fisher [16] reported that biology experts typically demonstrate 20–30 bidirectional links to big ideas such as "DNA" or "protein," whereas students usually create far fewer links. In Part 2 of this series, we will discuss how concept maps and semantic networks may, with the aid of various software and map scoring methods, be used as tools for promoting and assessing students' conceptual understanding.

The facet of expert understanding requiring competence in the cognitive skills of *transfer and application* of knowledge (Table I) is considered by Mayer [5] to be a fundamental goal of education and is arguably the most important facet that biochemistry and molecular biology experts draw on in their practice. Transfer has been defined by Mayer and Wittrock [42] as the ability to use or apply knowledge of a concept to solve new problems, answer new questions, or facilitate learning of new subject matter. For transfer and application of knowledge about a concept to be successful, a person must first memorize and integrate the key concepts into an explanatory conceptual framework. That is, their prior conceptual knowledge must be adequate and soundly constructed and must have been initially learned and well understood in a meaningful and situated context before they abstract, transfer, and apply it to solving problems in another context [5, 11, 43, 44]. Science education research (*e.g.*, [45]) has shown that students have numerous difficulties regarding knowledge transfer. Therefore, it is essential to explicitly and formally teach and assess transfer and application skills as part of our biochemistry and molecular biology curricula, so that such difficulties can be corrected and so that our students develop the problem-solving skills that characterize experts.

According to Orgill and Bodner [9], the cognitive process of *analogical reasoning* (Table I) involves comparing a familiar domain (the analog) with a less familiar domain (the target). Analogies enable students to make connections between abstract concepts (the target) and more concrete concepts (the analog) with the intention of promoting understanding of the abstract concepts. Because learning in biochemistry depends very heavily on understanding the abstract world of molecular structures and processes, developing analogical reasoning skills is absolutely crucial for becoming an expert biochemist. In addition, modern biochemistry textbooks and accompanying computer and web-based resources make great use of analogies to explain and visualize biochemical phenomena while instructors make extensive use of them during teaching. Examples of analogies used in biochemistry (*e.g.*, [9, 46]) include the "lock-and-key" analogy representing enzyme-substrate binding; the "hand-and-glove" analogy for induced fit in enzyme-substrate binding; the term "chaperone" for proteins that direct the folding of other proteins; the term "fluid mosaic" for the dynamic structure of a cell membrane; DNA as a "recipe" for creating a human organism; ATP as the energy "currency" in cells; and, the mitochondrion as the "power plant" of the cell. Analogies play a variety of educational roles including clarifying thinking and inducing sound understanding of a concept or phenomenon [47], adjusting or changing an alternative conception (*e.g.*, [48, 49]), or addressing inappropriate reasoning difficulties [50]. It is important to note one caveat about the use of analogies. They can also sometimes be misleading, because students may perceive the analog literally and transfer the wrong features of the analog to the target. It is important that biochemistry instructors teach and assess analogical reasoning skills as part of all course curricula to minimize student conceptual difficulties and promote development of expert skills. In Part 2 of this series, we present examples of tasks that can be used to assess and promote such development in our students.

The ability to *reason locally and globally* (Table I) about a concept or phenomenon and to grasp the implications of local effects on a complete living system is a crucial, but often disregarded, facet of experts' biochemical knowledge. Local and global reasoning skills are essential for understanding concepts and phenomena in the molecular life sciences. For example, it is important to understand that any local changes, such as activation or inhibition of one reaction in a metabolic pathway might also have global effects on all the reactions in a pathway as well as on the system as a whole. In this regard, Anderson and Grayson [51] obtained empirical evidence of a localized reasoning difficulty in which several biochemistry students correctly thought that the irreversible inhibition of glyceraldehyde-phosphate dehydrogenase would stop this reaction (*i.e.*, would have a local effect) but failed to predict that this inhibition would have a global effect on the overall flux through glycolysis. Such difficulties have important implications for students' thinking when studying systems biology [14, 52] and for understanding metabolic control analysis where extensive kinetic and thermodynamic information from single reactions (local) are used in mathematical modeling to predict the behavior of a (global) system. *System thinking* requires students to no longer think linearly and in a reductionist manner about metabolic pathways and about dated phenomena such as single rate-limiting steps [53]. Instead, system thinking involves considering the dynamic nature of metabolism and signal transduction pathways and the role of all reactions in a pathway in determining metabolic flux. Empirical studies in science education suggest a strong link between the development of system thinking and conceptual understanding [54], whereas system thinking has also been shown to be fundamental to students' construction and holistic integration of mental models in the life sciences [52]. Indeed, Evagorou *et al*. [55] have recently reported on the use of interactive simulations for developing system thinking in fifth and sixth graders at elementary school. These workers cite the following six abilities of expert system thinkers (p. 2), which we suggest could also be applied to higher education contexts of the molecular life sciences:

- Analyze interrelationships between different objects and explore emergent properties;
- Analyze phenomena and problems in wider contexts;
- Consider multiple cause-and-effect relationships;
- Discover and represent dynamic processes (delays, feedback loops, and oscillations) that underlie patterns of the system's behavior;
- Anticipate the long-term consequences and possible effects of present actions;
- Understand changes in a system over time [55].

In view of the importance of system thinking as an expert skill, we recommend that it be taught and assessed as part of formal biochemistry curricula, so that our students can develop this facet of understanding of biochemical concepts. To promote the development of system thinking in our students, we will need to develop assessment tasks that address each of the above abilities. Examples of such tasks are presented in Part 2 of this miniseries on conceptual understanding.

CONCLUSION

The aim of this article was to expose readers to literature regarding the nature of conceptual understanding. We are of the view that "conceptual understanding" is a term that is used rather loosely both in science and education, because it is multifaceted, complex, and most instructors tend to focus only on selected aspects of the phenomenon. To optimize students' understanding of a concept, so that it becomes comparable to that of experts, instructors need to teach and assess as many of the facets of the concept as feasible. However, clearly neither students' nor experts' understanding of a concept will ever be absolute as there will always be other facets of understanding that require competence in other cognitive skills. This fits well with a life-long learning philosophy and the idea of "moving" along the novice-expert continuum. In this regard, White and Gunstone [10] state that "understanding of a concept is not a 'dichotomous state' but rather a continuum in which one can only say that someone might have a level of understanding above or below some arbitrarily set level" (p. 6).

In conclusion, we consider the cognitive skills discussed in this work (Table I) to be important for biochemists, which, if taught in conjunction with content knowledge, can play an essential role in scaffolding our students' educational development. We propose that biochemistry and molecular biology educators adopt the following, as part of their instruction, to improve the cognitive skill competencies and, therefore, the conceptual understanding of their students:

- Consider conceptual understanding as a multifaceted phenomenon that requires competence in specific higher-order cognitive skills;
- Identify what facets of understanding and skill competence constitute expert knowledge of the topic you are teaching and aim to develop as many of these as possible in your students;
- Explicitly, teach and assess these facets of understanding and cognitive skills as a formal part of every course in the biochemistry and molecular biology curriculum.

In Part 2 of this miniseries on conceptual understanding, we will use specific examples of assessment tasks to illustrate how one might use assessment as a powerful "Bridging the Gap" tool for promoting the teaching, learning, and development of multifaceted knowledge in our students.

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