Commentary

Mental Models and Meaningful Learning

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ABSTRACT

If you understand something, you can use the information you have acquired to solve problems to which that knowledge is relevant. Meaningful learning is learning with understanding. Achieving meaningful learning begins with the building of correct, appropriate mental models, or representations, of the knowledge being acquired. The next step is learning to use the available mental models to solve problems. In many of the biomedical sciences, this means being able to either calculate something, predict the responses of the system, or explain the responses of the system. Since only the learner can do the learning, the only possible role for the teacher is to help the learner to learn. This means creating an active learning environment in which the learner can acquire the needed information, continually test the mental models being built, and correct or refine those models as needed. In an active learning environment, students are given ample opportunities to learn to solve problems. If the goal of the course is the achievement of meaningful learning, it is essential that the students then be assessed to determined whether they have reached that goal.

INTRODUCTION

If you were asked, by a colleague, your chairman, or a student, "What do you expect your students to be able to do when they have completed your course?" it is likely that your reply would be something like "I want them to *understand* physiology (or anatomy, etc.)."

If you were then asked, "What does it mean to 'understand physiology'?" you would probably find it much harder to reply. Herb Simon, a Nobel laureate in economics who was really a renowned cognitive psychologist, has offered this succinct definition: "a person understands some information to the extent that he or she can use it in performing the tasks for which it is relevant."[1]

As teachers we are thus confronted by two key issues:

1. How do we help our students to achieve understanding of our discipline?
2. How do we know when our students have reached this goal?

This article will address both these issues and will do so by offering answers to four questions:

- What is meaningful learning, and how do we know when it has occurred?
- What is a mental model?
- What do mental models have to do with meaningful learning?
- What is the role of the teacher in bringing about meaningful learning?

Although the examples offered are drawn from physiology, the ideas being developed are clearly applicable to the teaching and learning of all the biomedical sciences.

WHAT IS MEANINGFUL LEARNING, AND HOW DO WE KNOW WHEN IT HAS OCCURRED?

Meaningful learning is learning with understanding.[2] When students achieve a level of meaningful learning, they are able to do things with the information they are acquiring; they can use their knowledge to accomplish appropriate tasks. Medical students, whether human or veterinary, are ultimately expected to be able to use the basic science they have learned in their medical practice. Initially, however, they are expected to use their basic science to solve problems relevant to the discipline(s) being studied.

What kinds of problems do we expect students to be able to solve? Students learning physiology are expected to be able to solve both quantitative problems (*calculate* renal clearance / alveolar PCO_2 / cardiac output from the available data) and problems involving qualitative changes in physiological parameters (*predict* the changes that will occur given the described pathology; *explain* the patient's symptoms).[3]

> Meaningful learning is learning with understanding.

For example, consider a case describing a patient with a stenosed aortic valve. Students might initially be asked to *predict* the consequences (increased, decreased, no change) of the stenosed valve on stroke volume, cardiac output, arterial resistance, and mean arterial pressure. They might then be asked to use data collected in a cardiac catheterization procedure to *calculate* the patient's cardiac output and stroke volume. The students can now assess whether their initial predictions were correct or not. Finally, they can be asked to *explain* why this patient tires on exertion.

To solve the problems described above, the student must not only have accumulated a set of facts (cardiac output = stroke volume × heart rate; the normal pressure gradient across the aortic valve is no more than 5 mmHg; mean arterial pressure is a regulated variable in the cardiovascular system; etc.) but also have related these facts to each other in some way (see "What Is a Mental Model?" below), and they must develop a procedure or process for using this organized knowledge to solve problems.

Finally, if a student *understands* physiology (that is, if she has not just accumulated or memorized a lot of facts) she will be able to solve novel problems, ones that she has not previously been asked to solve or has not read about in the textbook.

How do you know if your students *understand* your discipline? How do we determine whether or not meaningful learning has occurred? The simple answer is that you ask your students to demonstrate those behaviors that constitute *understanding*: calculating, predicting, and explaining. To the extent that they can successfully solve the problems you pose for them, they *understand* something. It must be reiterated here that *understanding* requires both the accumulation of facts *and* the ability to use the facts; you cannot solve problems if you do not possess the needed facts or data.

In practice, in the classroom, the process of assessing student understanding is not a trivial one, and there are many assessment tools from which to choose.[4] Furthermore, assessments of students' understanding should not be limited to setting novel problems for them on a summative examination. You can and should continually assess their level of understanding with questions and problems posed in the lecture hall, laboratory, or discussion section.

It cannot be stressed too strongly: if you claim that you are interested in helping your students *understand* your discipline, if your overarching educational objective is meaningful learning, but you merely test your students' ability to recall facts, your students will respond by memorizing everything possible and will not attempt to actually acquire an understanding of the discipline. They will do what you do, not what you say.

WHAT IS A MENTAL MODEL?

A mental model is a "representation" in memory of information that has been acquired.[5] It is made up of interconnected, related pieces of information (knowledge) with the same "structure" as that which is being modeled. Mental models serve many functions, including helping to make decisions or manipulate the system and helping to select, filter, and organize new knowledge as it is acquired.[6] Cognitive and learning scientists are currently debating exactly what the word "representation" might mean.[7] At issue is the nature or organization of such a "representation" and what properties these "representations" might have. Although several theories are being debated, none appears to be completely successful in explaining the full range of phenomena being investigated. At the same time, neuroscientists are actively seeking to understand the exact neural structure or mechanism by which information is stored in the brain as it is acquired.[8] But neither the organization of a mental model (its behavioral manifestation) nor its neural mechanism (its neural manifestation) is necessarily important to the teacher in the classroom.

> "Learning takes place inside the learner and only inside the learner."

What is important to the teacher is the understanding that as learners acquire new information, it is always organized into mental models. Norman has put it this way: "In interacting with the environment, with others, and with artifacts of technology, people form internal, mental models of themselves and of the things with which they are interacting."[6] This is certainly the case for students in an active learning environment (see "What Is the Role of the Teacher?" below) interacting with each other, a teacher, a textbook, and possibly a piece of teaching software. Lesh and Kelly put it even more succinctly: "Humans create models of situations."[9] Students in a laboratory, at the bedside, or in a clinical correlation conference create models of these "situations" and the subject matter encountered there.

In physiology, most important phenomena can be usefully represented as qualitative, causal models. Figure 1 contains an example of such a model, one that describes the relationships between the three determinants of alveolar ventilation. In such models a "+" sign indicates a direct relationship (if breathing frequency increases, then alveolar ventilation increases) while a "-" sign indicates an inverse relationship (if dead space increase, then alveolar ventilation decreases).

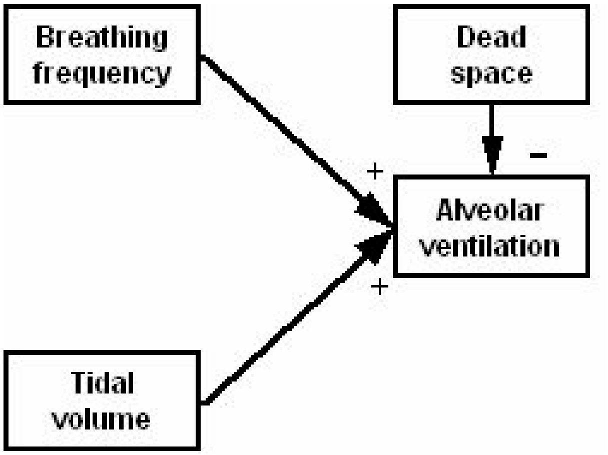

Figure 1: A qualitative, causal model representing alveolar ventilation

Such models, however, do more than simply visually represent the relationships between parameters. Each "box" representing a parameter can be thought of as "containing" all of the information about that parameter that the learner has acquired (definition, units of measure, functional relationship with other parameters, descriptions of the mechanisms involved, etc.). Thus, such models help the learner to organize all the new information he acquires and to relate that information to other things that he already knows.

Furthermore, such a model can be used to solve problems (make predictions, generate explanations). For example (see Figure 1), if asked to predict the consequences of breathing through a snorkel, one can "run" the model to predict that the increased dead space (the snorkel) must result in decreased alveolar ventilation.

Consider a more complex model, one that represents one of the key homeostatic mechanisms of the body, the baroreceptor reflex. With such a model, and an appropriate algorithm for running it, the student can *predict* the consequences of a myocardial infarct (IS is reduced, hence CO must decrease, leading to a decrease in MAP). The student can also *explain* why a patient in hypovolumic shock exhibits tachycardia, a weak pulse, and pale skin and mucous membranes (reduced CVP leads to decreased MAP and a reflex increase in HR and TPR, with reduced blood flow to the skin).

The model of an "expert" (the physiology teacher) and the model of the "novice" (the medical student learning physiology) will, of course, not be identical. Table 1 contrasts the properties of "expert" and "novice" models. One goal in the classroom must be to help the student evolve her model so that it has more of the properties of the instructor's model.

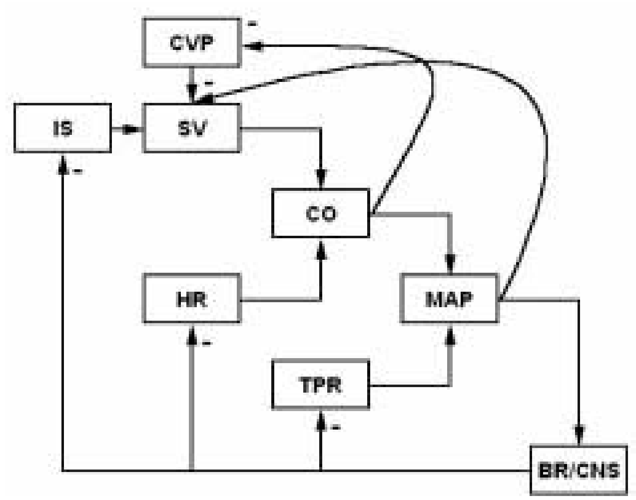

Figure 2: A qualitative, causal model representing the baroreceptor reflex

Table 1: Differences between "expert" and "novice" mental models

"Expert" Model	"Novice" Model
More or less complete (contains all elements and interconnections)	Incomplete (important elements are missing and important connections are absent)
Coherent and consistent (contains no contradictions and always yields the same answer)	Not completely coherent and often inconsistent
Richly interconnected (internally and externally) to other knowledge that is present)	Sparsely interconnected (both internally and externally)
Is used to solve problems efficiently and correctly	Potentially useable to solve problems, but errors in model lead to errors in solutions

However, one important function of the teacher is to decide exactly what constitutes an appropriate model to expect the learner to acquire. How complex should the model be? How many elements and relationships should it contain? Which ones? Should it be identical to the model of the "expert"? Sometimes, for some phenomena, the answer may be yes. If not, what simplified model is appropriate for the learner? In many cases, this is not a simple decision to make.

There is one other property of mental models that must be mentioned, which is that they are often seriously flawed in ways that significantly affect their utility. These flawed models may contain incorrect elements or relationships, or important elements and relationships may be missing. Such flawed models are often referred to as "misconceptions."[10-12] Misconceptions are known to be extremely resistant to change and can seriously compromise further learning about the phenomenon in question.[13] Furthermore, it is not uncommon for individuals to possesses multiple mental models, some more or less correct and others seriously flawed. In such cases, the choice of which model to use to solve problems is likely to be context dependent (e.g., in a classroom setting students use the model they acquired in the classroom, but in a non-school setting they will use a model acquired from their own personal experiences).

> The only possible role of the teacher is *helping the learner to learn!*

One example of a misconception in physiology is the common belief (held by close to 50% of nearly 2,000 students quizzed on this) that when individuals exercise, their breathing frequency increases but their tidal volume decreases.[10, 11] This is, of course, incorrect, since during exercise both breathing frequency and tidal volume are increased. When asked to explain their erroneous prediction, a great many students reply that with increased breathing frequency there is less time available for each breath and therefore less air (a smaller tidal volume) is moved with each breath. Based on such student explanations, it appears that this misconception represents the output of the faulty mental model seen in Figure 3 (the dashed arrow is an incorrect relationship under normal conditions).

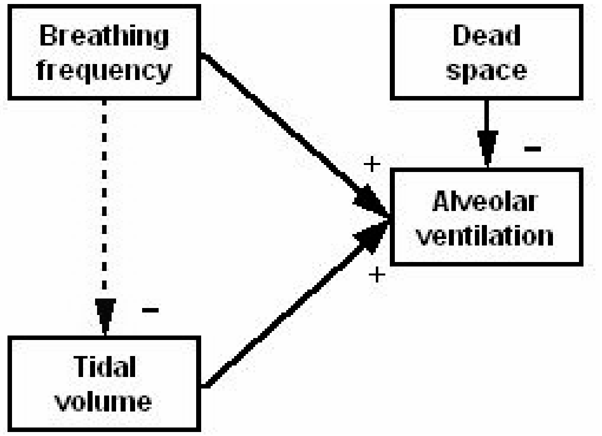

Figure 3: The likely faulty mental model that gives rise to the exercise/ventilation misconception

One thing to notice about this mental model is that it will generate correct predictions at least some of the time. If asked to predict what will happen to alveolar ventilation if either breathing frequency or tidal volume alone is changed, the model will generate a correct answer. It is only when the problem requires students to think about how both variables change in some situation that the model no longer yields a correct answer. This property of faulty mental models (misconceptions) is quite common; such models have some utility under some conditions, which makes it hard for students to change their models.

In summary, learning inherently involves building mental models of that which is being learned. Students need to learn how to do this most effectively (in a way most likely to lead to correct, appropriate models), and teachers need to learn how to help their students build correct models and refine incorrect models.

WHAT DO MENTAL MODELS HAVE TO DO WITH MEANINGFUL LEARNING?

The road to meaningful learning, to learning with *understanding,* starts with the learner acquiring new information. With this new knowledge, and any relevant old knowledge, the learner builds mental models. If the models being built are to be correct and appropriate, it is essential that the students have opportunities to test their models. When the model being built "fails," when it generates incorrect answers or predictions, the model must be refined (corrected). This cycle of building, testing , and refining mental models continues as long as knowledge acquisition continues.

However, to achieve meaningful learning, learning with *understanding,* the student must also acquire the skills needed to use his models to solve problems. This means that students must be given opportunities to practice solving problems. It also means that they must receive appropriate, timely feedback about how they are doing.

Clark and Linn,[14] in discussing students' understanding of phenomena such as heat and temperature, assert that it is "knowledge integration" (model building) that leads to "greater student understanding." Thus, it is appropriate to say that meaningful learning and the building of correct mental models are inevitably linked.

> *Understanding* requires both the accumulation of facts *and* the ability to use the facts.

WHAT IS THE ROLE OF THE TEACHER IN BRINGING ABOUT MEANINGFUL LEARNING?

"Learning takes place inside the learner and only inside the learner."[1] Only the learner does the learning. Only the learner builds the mental models that will be used in solving problems. That being the case, the only possible role of the teacher is *helping the learner to learn* ![4] As obvious as this may seem, all too many teachers behave as though the only thing that determines whether learning occurs is what they, the teachers, do in the classroom.

In order to help the learner to achieve meaningful learning, the teacher must create an active learning environment in which students can accomplish all of the needed steps to reach that goal. The students need to acquire information, whether from a lecture, a textbook, or a Web site. With this information they will build mental models. The learning environment in which all this is occurring should facilitate the students' testing, and refining, of these models as they are being built. Finally, students need opportunities to learn to solve problems using their knowledge and their mental models. This means that they need opportunities to practice solving problems and opportunities to receive timely feedback about their performance. Keep in mind that this means more than watching the instructor or a teaching assistant solve a problem at the black- (or white) board. What students need is an opportunity to watch the skill to be learned modeled (by the instructor or by a classmate), a chance to solve a related problem, and then the opportunity to receive feedback about their own performance.

It is important to recognize that an active learning environment is any place where a student is encouraged to engage in the learning activities described above. The lecture hall can be an active learning environment if the lecturer engages the students in active model building and testing by periodically asking questions or posing problems.[15] The student laboratory can be an active learning environment when the students are encouraged to make predictions using their models and then engage in a process of experimentation, followed by reflection on the results they have obtained and the original predictions they made.[16] The discussion section can be an active learning environment when students are given problems to solve, see appropriate problem solving being modeled, and get feedback on their problem solving.[17] If these conditions are not present, the students may look "active" to an outside observer, but they will not be engaged in active learning.

We can describe the key features of an active learning environment in another way. It is important that the learning environments that you build, whether in the lecture hall, the laboratory, or the discussion section, encourage students to work together, encourage them to "talk" the language of the discipline to one another and the teacher, and provide them with many opportunities to challenge (test) their mental models.

CONCLUSIONS

1. It is the job of the students to learn and to achieve the expectations defined by their teachers.
2. Learning involves building mental models of that which is being learned.
3. These mental models will be used to solve problems.
4. Meaningful learning has occurred when the students can solve appropriate problems with the models they have built.
5. It is the job of the teacher to help the learner to learn.
6. Thus, if meaningful learning is expected, the teacher must create learning environments in which such learning is most likely to occur.

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