

ASSESSING CONCEPTUAL UNDERSTANDING OF PHYSIOLOGY AS A DISCIPLINE: A “BIG IDEAS” APPROACH

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This is very much a work in progress. It has been publicly posted with the hope that it will generate comments, corrections, arguments, and debates. Any and all contributions to the discussions about the issues raised here are welcomed. You can, of course, contact any or all of the authors with your comments.

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DRAFT - Do not cite

I. INTRODUCTION

Every science teacher will claim that their goal is that their students gain an “understanding” of their discipline. When asked what “understanding” means, or how one would know when “understanding” was present, most teachers are hard pressed to provide coherent, operational definitions of what they mean.

Simon (2001) has proposed that “understanding” something means being able to use the information acquired to perform tasks to which that information applies. Michael (2001) discussed “meaningful learning” and how to help students achieve it, and his definition (the ability to apply what one knows) is very similar to Simon’s definition of understanding. Michael and Rovick (1999) pointed out that in physiology, instructors typically present students with problems that require them to explain and/or predict responses of perturbed physiological systems. van Lehn and his colleagues (2007) have discussed what they call “robust learning” (it generalizes predictably, it enables far transfer, is retained over a long time span, and it prepares the student for future learning) and it is in many ways similar to learning with understanding or meaningful learning.

However important this focus on learning with understanding may be, it does beg the question of what it is that students should be learning and understanding. The research agenda to be described here represents an attempt to begin answering this particular question.

Another relevant observation . . . It has been known for many years that students come into our classrooms with mental models of scientific phenomena that differ in significant ways from the accepted scientific models (Wandersee, Mintzes, and Novak, 1994). These student models have been variously referred to as alternative conceptions, naïve conceptions, or more generally, misconceptions. It is of great significance that we also know that even our successful students leave our courses with most of their misconceptions intact, and in some cases with additional misconceptions. This seems to be the case whatever we try to teach and however we try to teach it.

Conceptual assessment in physics

These observations contributed to the development in the early 90’s of the Force Concept Inventory (FCI) by Hestenes and his colleagues (Hestenes, Wells, and Swackhamer, 1992; Hestenes and Halloun, 1995). This assessment instrument is made up of a number of multiple choice questions that each pose a qualitative problem for the student to solve. The distracters were designed to represent common misconceptions about motion that students are known to exhibit (Halloun and Hestenes, 1985; Hestenes, Wells, and Swackhamer, 1992). Thus, the FCI represents both a test of conceptual understanding ***and*** a diagnostic tool for the detection of misconceptions.

While many aspects of the FCI and its use are still surrounded by considerable controversy, its use has provided objective evidence for what many physics teachers have always known. Students may be quite skilled at selecting the correct equations to be used to solve a problem, well able to manipulate the equations in an appropriate way to calculate a correct answer, and still not understand the concepts underlying the problem used solved.

The use of the FCI has also provided the physics education community with an instrument with which to assess the effectiveness of various approaches to teaching and learning physics. Hake (1998) has compared learning outcomes of traditionally taught physics courses with the learning outcomes of “active engagement” courses and demonstrated clear differences in the learning gains as measured by the FCI; “active engagement” clearly results in more learning. There are many other such studies, some large and some small.

The problems in biology education

The state of teaching and learning in the biological sciences is no different than is present in physics. Students have misconceptions about biological phenomena of all sorts. Students who successfully complete a biology course may have little or no understanding of the concepts of biology. Active learning paradigms seem to lead to better learning outcomes, but we lack the assessment tools to demonstrate this rigorously and unequivocally.

However, the biological sciences are somewhat different than physics. At the very least, studies of biological phenomena are highly integrative in that they are largely based on applications of physics (and chemistry). In addition, biology is in many different ways a much broader and more diverse discipline than physics. Biology is, in fact, many different disciplines. There is no agreed upon curriculum for the study of biology, no well defined starting point and no obvious trajectory that students should follow. It is not even clear what the concepts or big ideas are that students should be learning. This poses a particular problem for teachers of biology because of the knowledge explosion that is occurring in the field; there is clearly more that could be taught than there is time for students to learn and teachers must make decisions about what is most important to learn.

Conceptual assessment in biology

On March 2-4, 2007 the National Science Foundation sponsored a workshop on “Conceptual Assessment in the Biological Sciences.” The meeting was held in Boulder, CO and was organized by Dr. Michael Klymkowsky of the Department of Molecular, Cellular, and Developmental Biology, University of Colorado.

This workshop brought together a group of 21 biology teachers, educators, and educational researchers with a common interest in student learning with understanding (not just memorizing) in biology, and an interest in student misconceptions and/or the conceptual bases of their disciplines.

The overall objectives for the meeting were: (1) to start building a community of life science educators interested in conceptual assessment by sharing information about who is doing what and what has already been accomplished, (2) determine what biological sciences or major topics are not being worked on, and (3) discuss ways of disseminating our ideas to a broader audience of our colleagues.

After a day and half of intense discussion it was clear that we need to start by defining the concepts, or big ideas, in biology that we wanted our students to understand. “Big ideas” have been defined by Duschl, Schweingruber and Shouse (2007) as follows: “Each [‘big idea’] is well tested, validated, and absolutely central to the discipline. Each

integrates many different findings and has exceptionally broad explanatory scope. Each is the source of coherence for many key concepts, principles and even other theories in the discipline.”

The obvious example of a “big idea” in biology is “evolution.” For physiologists, the obvious “big idea” is “homeostasis.” Each biological discipline can undoubtedly identify at least one obvious “big idea.”

No consensus was achieved at the meeting about what belongs on the list of big ideas in biology, but the conversation led to a list of big ideas that will represent at least the starting point for a further discussion of this issue. The next section contains a list of big ideas (and some discussion of each of them) extracted from discussions at the Boulder meeting.

There was some discussion of the problems of creating valid and reliable assessment instruments. It was recognized that development of conceptual items requires the use of a two-tiered approach, with each answer to each question requiring an explanation. Explanations can be generated as short written statements or articulated in a structured interview. Given a corpus of student explanations it is then possible to write multiple choice items representing student explanations for the answers they select. While there was general agreement about this approach, no attempt was made to develop a protocol to be used by each group that attempts to create a conceptual inventory. Diane Ebert-May and her colleagues at Michigan State are developing an Assessment Database that may be a valuable tool for collecting (in a searchable format) the conceptual assessments we develop and the student responses we collect as this work proceeds.

A brief report of this meeting will appear in *Advances in Physiology Education* (Michael, in press).

An agenda for developing and using conceptual inventories in biology

It was agreed that the immediate item on our agenda was to seek funding for a follow up meeting of the CAB group to be held by the end of the year. The expected outcomes of this meeting are: (1) identification of big ideas in biology and an initial attempt to “unpack” these big ideas in the context of different biology disciplines, (2) development of a protocol for the writing of conceptual assessment items and a methodology for determining their reliability and validity, (3) continued community building with a focus on developing collaborative groups to pursue CAB in different disciplinary areas, and (4) a document describing and discussing conceptual assessment in biology for widespread dissemination.

In the interim the various groups that might be pursuing concept inventories in specific areas (genetics, ecology, physiology) will be carrying on with applying these very general ideas to their particular disciplines.

Thus, a research agenda made up of a number of inter-related pieces is being assembled.

❑ What are the big ideas in biology and specifically physiology?

The first issue on the agenda is to determine what set of big ideas is needed to “cover” all of the various biological sciences (see SECTION II). This list reflects a consideration of how experts (scientists in the field) think about biological phenomena and the kinds of mis-conceptions that students reveal as they attempt to learn to understand the phenomena of interest to the field.

We need to determine if there is some structure to the set of big ideas or whether it is most usefully viewed simply as a list. The figure on page 10 is a very preliminary, still incomplete “map” of the big ideas and their relationships to one another. What seems evident is that there are relationships between big ideas that necessitate them “cross-referencing” one another. (Cell function depends on information and information flow occurs between cells. When each of these big ideas is unpacked it is likely that there will be common themes that can provide vehicles for enhancing student learning.)

We then need to “unpack” each of these big ideas within the context of our particular disciplines; big ideas are made up of smaller (but still pretty big) ideas and so on (see SECTION III).

The structure or framework of big ideas (whatever its shape) that results will be useful for several reasons. It should inform teachers about what the important ideas their courses ought to emphasize. When typical introductory biology textbooks are more than 1000 pages in length, it is essential that we direct students to the most important ideas in the field, not all the details. Secondly, the structure of big ideas must be the starting point for construction of conceptual assessment instruments; if we know what the “concepts” are we can write test items that will tell us whether students understand them. We can also hope that development of the list of big items and the conceptual inventories will encourage textbook writers to produce more appropriate learning resources for our students.

❑ How do we determine whether students understand the big ideas?

In physics there is a fairly obvious difference between typical exam questions that require quantitative answers and questions that address the student’s understanding of the concepts underlying a problem scenario. In much of biology it is not obvious that there is a similar distinction. That is to say, it is not obvious what a conceptual question in biology would look like and how it would differ from the usual exam questions that we write.

That said, there is a fairly well defined protocol for the development of test items that are valid and reliable. A two tiered approach to item development will be used in which the student answers a question and then must explain the basis for that answer. Explanations may be written or may be generated in the course of a structured interview. There are now available a variety of software tools for processing such data. The explanation generated then serve to guide the development of distracters for use in a purely multiple choice exam.

In order to develop a useful conceptual inventory in any discipline we will need to use it with a large, diverse population of students. The Michigan State Assessment

Database will provide a useful tool for the collection and analysis of the large amounts of data that will be needed.

- ❑ How do we use our ability to assess conceptual understanding in biology to reform biology teaching?

The existence of valid and reliable conceptual assessment instruments for biology and individual biological sciences will provide educational researchers a measurement tool with which to ask questions about the kind or size of the learning outcomes that result from the many different approaches to teaching science that are currently being pursued (problem-based learning, case-based learning, discovery or inquiry learning etc.).

Whatever the results of such research, there will remain the problem of convincing our colleagues that there is a problem with current paradigms of teaching biology and that there is a new research-based paradigm available to inform their teaching practices.

Thus, we face two related problems: (1) disseminating our results as widely as possible, and (2) facilitating the faculty development efforts that will be required to produce real change in the ways that biology is taught and learned.

This research agenda needs to be pursued by educators and educational researchers in each of the biological disciplines. It also needs to be pursued in a much broader way by the community of biology educators (from all disciplines) with an interest in reforming biology education.

II. “BIG IDEAS” IN PHYSIOLOGY

The eight “BIG IDEAS” listed here would seem to serve as the foundation for *mammalian physiology*. They are thinking tools that are used by physiologists to understand the mechanisms which they are interested in. They can also be used as thinking tools by students seeking to understand physiology. This list is not definitive and does not represent any consensus among the participants at the Boulder meeting. It is, however, the product of reflection by the four authors on the issues raised at the Boulder meeting.

This list of “BIG IDEAS” has been ordered in some loose sense (see comments with the descriptions of each “BIG IDEA” below). The last two “BIG IDEAS” on the list while of undeniable importance in biology as a whole are less applicable in physiology teaching.

Feder (2005) has proposed a set of “central core ideas or concepts that an undergraduate education might strive to communicate,” an agenda not unlike our agenda. There is considerable overlap between his list and our list of “BIG IDEAS.”

This list of “BIG IDEAS” (see below) is a product of reflections by experts (physiologists) on how they think about physiological phenomena and a knowledge of the misconceptions that students studying physiology reveal. **It is not a prescription or description for the content of a physiology course.**

(A) Living organisms are **causal mechanisms** whose functions are to be understood by applications of the laws of physics and chemistry.

The label employed here is probably not the best at communicating what is being referred to here. In some sense this BIG IDEA is a refutation of the notion of vitalism that has never completely disappeared from our culture. If this is all that it describes it would be better to think of it as a description of the nature of the research enterprise in the biological sciences.

However, it is essential to recognize that understanding physiological systems (being able to explain the mechanisms producing a response or predicting the occurrence of responses) requires the ability to think causally. Physiology teachers believe that this requirement is one of the major sources of the difficulties that students having in learning physiology (Michael, 2007).

There are other implications that must also be considered. The properties (states) and functions of the organism are measurable, and changes in the measured values are meaningful. Physiology is thus at least partially a quantitative discipline, and the learner must pay attention to units of measurement and to orders of magnitudes of measured variables.

Another idea of increasing relevance is that of emergent properties that arise for the interactions of complex systems (like living organisms or whole environments).

Finally, this BIG IDEA is an antidote to the kinds of teleological thinking that are so prevalent among students and others.

(B) **The cell is the basic unit of life.** The organism is made up of tissues comprised of different cells with specialized structures and functions. Cells in the organism must cooperate with one other (exchange information, exchange matter) because no individual cell can “do it all” to ensure the survival of the organism.

This BIG IDEA is one of the oldest in the “modern” era of biology. It is so elemental that it is usually assumed, but without appropriately recognizing the important consequences that follow from it.

(C) Life requires **processing of information** in and between cells and between the environment and the organism. The transmission of genetic information is a major determinant of the structure and function of each cell. Information transmission between cells (cell-to-cell communications) is essential to coordinate the activity of the myriad of cells making up the organism. Information flow from the environment is required so that the organism can react appropriately to things happening in the external world.

Information is one of those terms that is frequently used in everyday discourse, although its meaning in that context may not always correspond to its technical meaning. Information flow is present at multiple levels in every organism and is, in fact, one of the hallmarks of living systems.

In physiology, the defining BIG IDEA of homeostasis is, in some sense, a consequence of information flow.

(D) Living organisms must obtain matter and energy from the external world to continue to exist. That **matter and energy must be transferred and transformed** in a varied of ways in order to build the organism and to perform work (from the cellular to the organismal levels).

This BIG IDEA encompasses the conservation of mass and energy, but also many other ideas. All functions of living organisms are energy dependent and all organisms must have access to energy in order to survive (plants from sunlight and animals from plants or other animals).

Regulation and control (components of the BIG IDEA of homeostasis) involves altering the function of cells by altering their uses of matter and energy.

(E) **Homeostasis** (and “stability” in a more general sense) maintains the internal environment of living systems in a more or less constant state. Important system parameters are measured and the measured value is compared to a pre-determined set-point (desired) value. The difference is used to generate signals that alter the functions of the organism to return the regulated variable towards its pre-set determined value. Stability is also a property of ecosystems (although the mechanisms are probably quite different).

This is perhaps the defining BIG IDEA in physiology. But the general notion of stability of function is applicable in thinking about a wide variety of biological systems, although the mechanisms by which that stability is achieved may differ.

It is also true that the mechanisms by which stability is achieved can be used in describing the behavior of inanimate objects as well as things like social systems.

(F) To understand the behavior of the organism requires understanding the relationship between the **structure and the function** of the organism, since function is dependent on structure and structure must match the functional needs of the organism.

This BIG IDEA is, on one level, a fairly abstract statement of the obvious interaction between the way in which the pieces of a mechanism are assembled into a system and the functions that the system can carry out. However, it also describes several very specific examples of commonalities that extent across many different physiological systems.

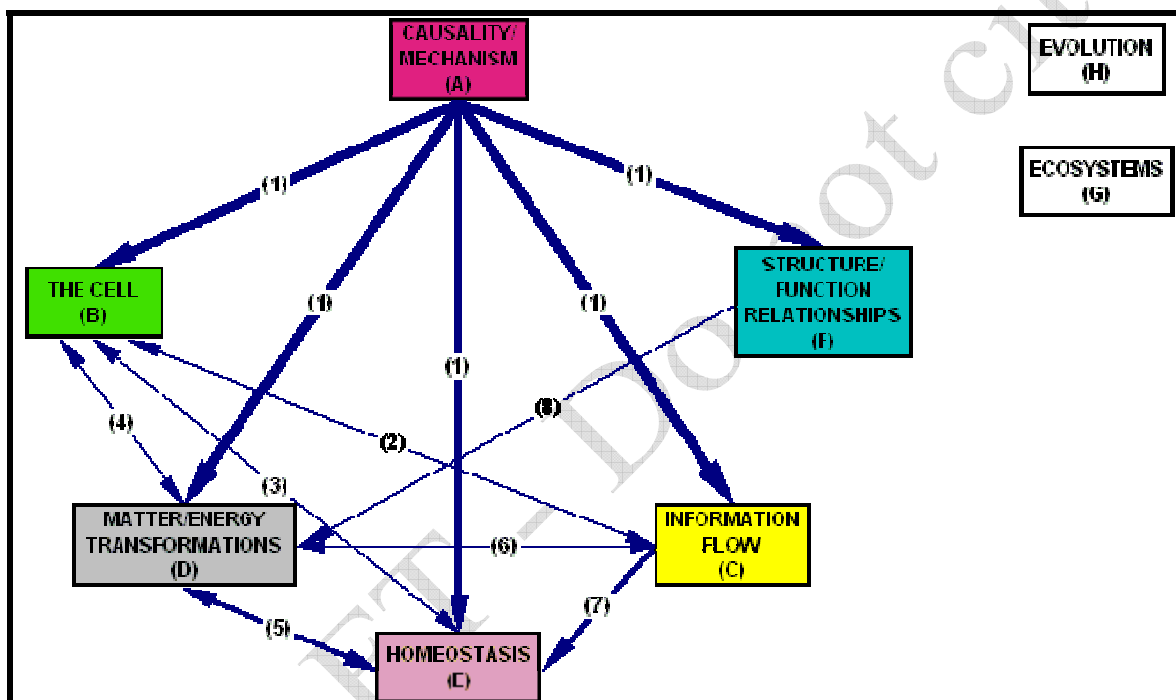
(G) All life exists within an **ecosystem** comprised of the physicochemical world and the total biological world.

Physiology is not typically taught from an ecological or even environmental standpoint, with the possible exception of comparative physiology. Nevertheless, it is clear that the individual organism exists, and survives to reproduce or not, in as part of an ecological system. More attention to this is undoubtedly warranted in the physiology education community.

(H) ***Evolution*** provides a scientific explanation for the history of life on Earth and the mechanisms (at the molecular level and at the level of species etc) by which changes have occurred to the life.

Over the past 100 or so years, this BIG IDEA has become the major organizing idea for essentially all aspects of biology. Its implications inform all biological sciences, although the teaching of these sciences draws upon the explanatory power of the BIG IDEA of evolution to variable degrees.

Although the list of “BIG IDEAS” above has been presented as a sequence, it appears that there is a much more complex relationship between the “BIG IDEAS.” A very preliminary representation of these4 relationships can be seen in the figure below.



It is important to emphasize that this list of BIG IDEAS in biology is not to be read as defining the content of a course or a curriculum. It is a description of the ideas that biologists use in attempting to make sense of biological phenomena. It is a list of ideas that that should be present in a “biology” course in varying proportions depending on the specific subject matter of the course. The relationship between the list of BIG IDEAS and the content of courses or curricula will vary amongst the different biology disciplines.

The explanatory power of each of these “BIG IDEAS” for understanding physiology varies considerably. There can be no question that homeostasis is THE central idea in physiology, while for most (non-comparative) physiologist ecosystems play little role in helping to organize their thinking. Finally, we need to distinguish between the uses of these “BIG IDEAS” in doing physiology research and their use in teaching physiology.

Your comments on any aspect of this list of “BIG IDEAS” would be welcomed. In particular, if you think we have left out an important “BIG IDEA” please let us know.

III. UNPACKING THE “BIG IDEAS” OF PHYSIOLOGY

Like atoms which can be unpacked into a great many smaller particles, each “BIG IDEA” is made up of a collection of other ideas that may be “smaller” in scope, but are nevertheless, have deep and wide explanatory power. When we unpack a “BIG IDEAS” the results are “big ideas.” Furthermore, it is not clear what it would mean to say that a student “understands” the BIG IDEA of homeostasis in the absence of evidence that the student can apply the component ideas to solve a specific problem.

What follows is an attempt to unpack each of the “BIG IDEAS” important in physiology. There is still much to be done to complete this process and input from interested physiologists will be most helpful.

This list does not define the content of a physiology course, in either a prescriptive or a descriptive sense.

BIG IDEA: (A) CAUSAL MECHANISM

- big idea: (1) The laws of physics and chemistry describe the functioning of the organism
- big idea: (2) The organism is a “mechanism” in which changes in function arise from the behavior of the mechanism and in which changes “propagate” to affect other functions (the “needs” of the organism do not, in general, determine function)
- big idea: (3) States and functions of the organism are measurable and units of measurement and orders of magnitude matter
- big idea: (4) Interactions between the component parts of complex system give rise to emergent properties.

BIG IDEA: (B) THE CELL

- big idea: (1) The cell membrane contains the contents of the cell and determines what can enter and leave the cell
- big idea: (2) The internal constituents and state of the cell are different than the extracellular environment big idea:
- big idea (3) Although all cells have the same DNA not all genes are expressed in every cell
- big idea: (4) As a consequence, cells have many common functions, but also many specialized functions
- big idea: (5) The organism is a collection of cooperating cells, each cell type contributing its special functions to the “economy” of the organism

BIG IDEA: (C) HOMEOSTASIS

- big idea: (1) The organism attempts to maintain a more or less constant internal environment that is different than the external environment
- big idea: (2) Stability of the internal environment occurs via information flow in the form of negative feedback
- big idea: (3) Some limited set of internal system parameters are regulated (held more or less constant) by the manipulation of other parameters whose values are controlled
- big idea: (4) The “desired” value of a regulated parameter behaves like a “set-point”
- Big idea: (5) The value of the set-point can change as the situation of the organism changes
- big idea: (6) The actual value of a regulated variable must be measured by the body (a parameter can only be regulated if it can be measured)
- big idea: (7) The determinants of a regulated variable must be controlled by the body by altering matter/energy transformations

BIG IDEA: (D) INFORMATION FLOW

- big idea: (1) Transmission of genetic information (if anyone has any suggestions for deeper unpacking they would be most welcomed)
- (2) Cell-to-cell signaling
- (a) Cells secrete chemicals which reach near or distant cells and alter their behavior (hormones, neurotransmitters)
- (b) Cell membranes contain signaling molecules that affect the behavior of cells in physical contact
- (c) Gap junctions between neighboring cells allow ions and other molecules to pass back and forth, affecting function in all cells
- (3) Intracellular signaling mechanism link and integrate cell membrane events and cell functions

BIG IDEA: (E) MATTER/ENERGY TRANSFER AND TRANSFORMATIONS

- big idea: (1) Matter and energy are conserved in a closed system. Living systems must obtain matter and/or energy from the external environment.
- big idea: (2) Solutes move across a membrane either passively (down an electrochemical gradient) or actively (using metabolic energy to power a pump)
- big idea: (3) Bulk flow of a substance occurs down a pressure gradient
- big idea: (4) Energy is stored in high energy bonds in the constituent molecules of biological systems
- big idea: (5) This energy is used in biosynthesis, moving solutes, and powering muscles

- BIG IDEA: (F) STRUCTURE/FUNCTION RELATIONSHIPS**
- big idea: (1) The 3-D structure of cells and tissues is a determinant of the functions of the cell and tissue
- big idea: (2) Surface area is a determinant of the movement of all substances and hence surface area (and the surface to volume ratio) is a determinant of function
- big idea: (3) All physical objects (cells, tissues, organs) have elastic properties that are determinants of function
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- BIG IDEA: (G) ECOSYSTEMS**
- big idea: (1) Multicellularity represents an internal ecology in which every cell interacts with every other cell.
- big idea: (2) Man interacts with all aspects of the physical and chemical environment (abiotic) and is affected by natural and man-made aspects of this world.
- big idea: (3) Man interacts with all members of the biological community in the environment.
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- BID IDEA: (H) EVOLUTION (of particular relevance to physiology)**
- big idea: (1) Physiological investigations make use of animal models to understand function and these organisms have a different evolutionary history than Man.
- big idea: (2) Evolution is “conservative” and the human organism contains many structures and mechanism that reflect evolutionary development (not optimal design).

Unpacking the BIG IDEAS in/for other disciplines (perhaps even for different courses in the same discipline) will likely yield a different list of “big ideas” than one we have presented here.

The “big ideas” also can be unpacked in a way that makes sense for each particular discipline. Going down to this third level would bring us to a set of ideas that begin to define the content of a physiology, or any other, course.

What is not clear at this time is what level is appropriate for the conceptual assessment items we want to write.

IV. APPROACHES TO WRITING CONCEPTUAL ASSESSMENT ITEMS IN PHYSIOLOGY

Conceptual assessment in physics

The Force Concept Inventory (FCI; Hestenes, Wells, and Swackhamer, 1992) is a set of multiple choice questions each of which describes a scenario and then requires the student to apply their understanding of the underlying concepts to select an answer. Such questions are clearly different in style and content from typical physics course exam questions which require the identification of appropriate equations, their manipulation, and the calculation of a numerical value. The questions making up the FCI are unquestionably testing something different from what is tested by the usual course exams.

One important feature of the FCI is that the questions that make it up are appropriate for physics students at any post-secondary educational level. This is, in part, the consequence of physics being a discipline with an essentially universally agreed upon curriculum. It is also a consequence of the focus on qualitative prediction based on an understanding of Newton's Laws.

Conceptual assessment in physiology

In physiology it is not obvious what would distinguish typical exam questions from conceptual questions testing a student's understanding of the BIG IDEAS of physiology.

It seems reasonable to assert that physiology conceptual questions ought to require only an understanding of the BIG IDEAS (and their unpacked "big ideas") independently of any knowledge of the details of a physiological system. If we want to know if a student understands the BIG IDEA of homeostasis we do not want the student's ability to correctly answer the question to be determined by his/her remembering the difference between the carotid baroreceptor and the aortic baroreceptor, or their remembering that the central chemoreceptors make a greater contribution to respiratory drive than do the peripheral chemoreceptors.

Similarly, we do not want the students' ability to answer these questions to be dependent on their having mastered the often esoteric terminology, jargon, or acronyms that abound in physiology (although it is appropriate to expect some facility with the fundamental "language" of physiology). Unlike the situation in physics, there is no common curriculum and physiology courses, particularly at the introductory level, can differ significantly in their content.

How do we want to use our assessment items?

We must begin by asking what uses will be made of the assessment items that are written. There are at least three ways in which they might be used:

- (1) to assess student learning of a particular topic in physiology ("do my students understand the "big ideas" of cardiovascular physiology?),
- (2) to assess whether students understand the "big ideas" of physiology by the end of my physiology course,
- (3) as an assessment tool to evaluate the effectiveness of some educational intervention ("does the use of computer-simulations result in more conceptual understanding than the use of "wet" labs?).

Assessment items written for purpose (1) would thus be based within the specific knowledge domain of interest (ie, CV physiology). Similar questions would also be written based in other domains (respiratory, renal, or endocrine).

Assessment items written for purpose (2) could either be a mix of questions from different domains or they might be (relatively) domain independent questions.

Assessment items written for purpose (3) could be either domain dependent or domain independent.

What is the target audience for our assessment items?

There is another issue to be confronted. Physiology is taken by students at very different educational levels, ranging from freshman undergraduates to graduate and medical students. Naturally, our expectations for each of these student populations differ; the depth and breath of understand that can be expected will vary. It is an open question whether one assessment instrument can appropriately be applied to all student populations.

This observation suggests that we need to consider building both a general purpose assessment instrument as well as assessment instruments for many different for many different audiences.

A methodology for writing concept inventories

Libarkin and Anderson (unpublished; 2006) have described the process by which they developed the Geoscience Concept Inventory. While their approach is certainly not unique and clearly builds on the processes used to generate other concept inventories, their explicit description of the steps involved provides a valuable guide for those seeking to write new inventories.

A brief description of the steps they followed as they might be applied to developing a physiology concept inventory is presented here.

1. Review of concept goals

Agreement has to be reached on the concepts (or BIG IDEAS) to be tested AND the uses to which the inventory will be put.

2. Qualitative data collection

Collect responses to open-ended questionnaires (presumably to questions reflecting the decisions made about content and goals in step 1) were collected from large numbers of students attending a wide variety of institutions. Focused interviews can also be used to collect qualitative data about what students understand.

3. Generate test items

Based on a qualitative understanding of what concepts students understand and don't understand generate multiple choice questions. It is critical that the wording of these items be as non-technical as possible (we don't want to test whether students have mastered the technical jargon of physiology). We must also make sure that students' ability to correctly answer a question does not depend on their remembering a piece of physiological "trivia."

There appear to be five possible approaches to writing appropriate questions, although they are not equally easy to implement.

- ☐ Write questions that are based on scenarios referring to physiological responses that can be directly perceived by the subject (see Michael, 1998) and ask questions that assess whether students can apply their understanding of the BIG IDEAS to thinking about these situations.
- ☐ Write questions that are based on scenarios referring to common everyday situations and then ask students to apply their understanding to thinking about these situations (homeostasis with reference to a situation involving a home heating/cooling system).
- ☐ Write questions referring to imaginary animals with specifically selected features and ask questions requiring students to use their understanding of the BIG IDEAS to think about these creatures and their responses.
- ☐ Write questions that are based on non-mammalian species (with which the students are presumably not familiar) and their physiological responses.
- ☐ Write questions in which essentially all of the needed “facts” are provided and ask questions that require the students to utilize their understanding of BIG IDEAS to answer.

Whichever approach we take, or some mix of approaches, it is essential to remember that not every assessment item we write will be appropriate for use with every student. As was pointed out by Michael et al. (2002), if students in a course are not expected to understand something it makes no sense to ask them a question about that topic.

4. Review of test items

It is important that the widest population of content experts and experts in teaching the discipline (any one individual might well be both) be involved in vetting the questions that are written.

5. Pilot and pre-testing

We will want to pilot test the assessment items with as large and diverse a population of students as possible. This is particularly important if we expect to be able to use our inventories with the heterogeneity of the students we all teach.

6. External review by participating faculty

Physiology faculty teaching at each of the educational levels of interest should answer the questions developed and provide feedback on each question (wording, logic, ambiguity etc.).

7. Revision of test items

All assessment items need to be revised on the basis of faculty feedback and the responses generated by the students in the pilot study.

8. Post-testing of pilot courses

The revised questions must be administered to as large and diverse a population as possible.

9. Think-aloud interviews

To more fully understand how students understand the questions and how they reason to an answer it is useful to conduct in-depth structured interviews with as many selected students as possible. The amount of work involved in conducting and analyzing these interviews necessarily will keep the number of students small.

10. Reduction of choices to five or fewer

Psychometricians claim that multiple choice questions should have no fewer than 3 choices and no more than 5 choices. There may be questions in the pool that don't meet these criteria and they will need to be identified, and either modified or dropped.

11. Apply Item Response Theory analysis to results

There are a number of approaches to determining the statistical properties of multiple choice items, and the IRT (Rasch) approach proved to be particularly useful in constructing the geoscience inventory.

Conceptual assessment in biology

Garvin-Doxas, Doxas, and Klymkowsky (in press) have described a process for generating valid and reliable assessment items in biology, and a set of computer-based tools for accomplishing the process. In brief, they propose asking students open-ended questions, and analyzing the students' responses, their words, to obtain samples of student thinking about the issue being explored. From the students' own words one can then construct multiple choice questions in which the distracters are built from prevalent student explanations (and words).

The PERC group (Michael et al., 1999; Michael et al., 2002) followed a similar protocol in which simple prediction questions were followed by open-ended requests for explanations of each student answer. From these student explanations we were able to construct distracters that reflect common student thinking about the problem. For example, when asked to predict whether depth or breathing will increase, decrease or stay the same during exercise, students commonly predicted that depth of breathing (tidal volume) would decrease. The most common explanation for this was (in students' words) that if frequency is up then there isn't enough time to take in as much air with each breath. These words then provided the basis for a multiple choice distracter.

Writing open-ended questions in physiology

What follows are some very preliminary attempts to generate open-ended questions to be used as described above. Such questions need to sufficiently non-directive to encourage students to respond in a very open fashion, but also sufficiently

directive so that students stay, more or less, on task. These are intended to be answered by no more than a short paragraph.

Muscle cells and nerve cells perform different functions in the body, yet both require the availability of oxygen in order to maintain their normal functions. Explain. **{Testing the students' understanding of the need for energy to power all the functions of the cell. "big ideas" E4 and E5.}**

Muscle and nerve cells clearly have different functions in the body although they have exactly the same DNA in their nucleus. How do different functions arise in cells with the same DNA? **{Although the genes are the same, different sets of genes are expressed (ie., some are NOT expressed) leading to the development of different structure and different function. – "big idea" D1}).**

Investigators observe that in spite of changes in activity and in the external environment, Tribbles maintain a nearly constant concentration of X in their blood. What does this tell you about Tribbles' physiological mechanisms and substance X? **{That its concentration is measured by some system in the body, and that alterations in body function can bring about changes in the concentration of X. "big idea" C.}**

The structure of the lungs supports its function in gas exchange between the atmosphere and the blood. What structural properties would you predict are present in the lungs to enable this function? **{Big surface area and short distance for diffusion to maximize exchange. "big idea" F2}**

V. ORGANIZING A DATABASE OF QUESTIONS FOR A PHYSIOLOGY CONCEPT INVENTORY

It may be very difficult to write a physiology concept inventory that will be appropriate for students at ALL academic levels (students in introductory physiology course to students in upper division or medical level courses), although an attempt to do so ought to be made.

If, in fact, it does prove to be impossible, what are the possible responses to this problem? Three answers suggest themselves:

- (1) select a single academic level to target and then write an assessment instrument aimed solely at that student population,
- (2) write a number of different assessment instruments each addressing a different population (each assessment instrument could be limited in scope; ie, only some "big ideas" and/or only some physiology topics), or
- (3) create a database of assessment items useable at different academic levels and make it possible for individual users to build their own assessment instrument.

The table below is a representation of such a database. Note that such a database could be used in implementing any of the suggested approaches.

(A) CAUSAL MECHANISM		CV	Resp	Renal
(1)				
(2)				
(3)				
(4)				
(B) THE CELL				
(1)				
(2)				
(3)				
(4)				
(5)				
(6)				
(7)				
(C) INFORMATION FLOW				
(1)				
(2)				
(2a)				
(2b)				
(2c)				
(3)				
(3a)				
(3b)				
(3c)				
(3d)				

The left hand column contains the unpacked list of “BIG IDEAS” (to be found on pages 3 and 4).

The other columns represent the broad topic areas normally taught in physiology at any educational level.

Each of the hi-lighted cells would then contain ***one or more*** questions testing the “big idea” described in the first column in the context of the physiology topic defined by the column. The cell could contain multiple examples of questions testing that “big idea” for a defined student population (ie, students in an introductory physiology course) or it could contain questions aimed at students at a variety of educational levels, or the cell could contain both.

An instructor or educational researcher could then assemble an assessment instrument for a particular course of purpose in several different ways:

- (1) select questions to test ALL the “big ideas” (left most column) as they apply to an understanding of the respiratory system only,

- (2) select questions to test all the “big ideas” subsumed under “INFORMATION FLOW” across one or more of the organ system topic areas (CV and respiratory or CV and renal), or
- (3) select questions that sample the students’ understanding of some set of “big ideas” across some set of physiology topics.

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