THE "BIG IDEAS" OF PHYSIOLOGY
PART I: WHAT SHOULD STUDENTS UNDERSTAND?

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ABSTRACT

The explosion of knowledge in the biological sciences has created a growing problem for biology educators. There is more to know than students can possibly learn. Thus, difficult choices have to be made about we expect students to master. One approach to making the needed decisions is to consider those BIG IDEAS that provide the thinking tools for understanding all biological phenomena. We have identified nine BIG IDEAS which appear to cover all of ***physiology*** and we have begun the process of unpacking them into their constituent component ideas. While such a list does not define the content for a physiology course, it does provide a guideline for selecting the topics on which to focus student attention. This list of BIG IDEAS also offers a starting point for developing an assessment instrument to be used in determining whether students have mastered the important ideas of physiology.

I. INTRODUCTION

The knowledge explosion is alive and well in biology. One of its more visible signs is the length of the textbooks that we recommend to students (see Table 1). The assigned textbook in a typical introductory biology course may be more than 1000 pages long and contain a very large number of ideas, concepts, principles and facts. The situation in physiology is no different, whether we look at human anatomy and physiology books, physiology texts aimed at undergraduates, or medical and graduate level physiology textbooks.

However well the course is taught, students can only learn a fraction of what is in such a book. Furthermore it is clear that they will retain an even smaller fraction over time. Equally important, the focus on learning ever more "content" does not help students understand physiological principles. This is a long-recognized and persistent problem in all of biology (Nelson, 1989; Wright and Klymkowsky, 2005).

TABLE 1
The size of popular, current textbooks of biology and physiology

	Pages of text
INTRODUCTORY BIOLOGY	
Freeman, 2005	1392
Campbell et al., 2004	1312
HUMAN ANATOMY & PHYSIOLOGY	
Saladin, 2007	1248
Marieb, 2007	1296
Martini, 2007	1110
UNDERGRDUATE PHYSIOLOGY	
Sherwood, 2004	801
Widmaier, Raff, Strang, 2004	738
MEDICAL PHYSIOLOGY	
Boron and Boulpaep, 2003	1267
Berne, Levy, Koeppen, Stanton, 2004	978
Guyton and Hall, 2006	1066

What should a student know after having taken a physiology course? Obviously, not everything found in the textbook! What do we want students to retain long after they have completed the physiology course? There is no generally agreed upon answer to these questions.

As we think about these questions, it is useful to reflect on the fact that this is not the case in all disciplines. In physics, for example, there is near universal agreement on what the content of a first level physics course ought to be. In fact, the physics curriculum is remarkably similar across all colleges and universities that offer a degree in physics. It is this nearly universal agreement on what physics students should know that has made it possible for the physics education community to generate assessment instruments with which to determine what students do, in fact, know. The Force Concept Inventory (FCI) developed by Hestenes, Wells, and Swackhamer (1992) was only the first of such concept inventories to be written and widely used.

Can the physiology education community define what students should understand and develop instruments to allow us determine what students do know?

II. CONCEPTUAL ASSESSMENT IN BIOLOGY: AN NSF SPONSORED MEETING

In March, 2007 NSF sponsored a meeting at the University of Colorado in Boulder, CO to consider the issue of conceptual assessment in biology. Twenty-one biology educators from a variety of disciplines came together to discuss the possibility of developing an assessment instrument to determine student understanding of concepts in biology. It is fair to say that the assumed goal was an instrument that would do for biology what the Force Concept Inventory (Hestenes, Wells, and Swackhamer, 1992) has done for physics.

The bulk of this meeting was devoted to attempts to decide what it is that students should be expected to know. We need to know what should be assessed before deciding how to generate an assessment instrument.

However, it is difficult to decide what is meant by a "concept." An informal survey (Michael, unpublished results) of at least a dozen physics educators presenting papers at an American Association of Physics Teachers meeting resulted in no operationally useful definition of what they meant by the term "concept" when referring to the Force Concept Inventory. Furthermore, it seems likely that the term means something different to biologists than it does to physicists.

Participants did find the notion of "BIG IDEAS" to be a useful construct with which to attack the problem of defining what to assess. Duschl, Schweingruber and Shouse (2007) offer the following definition of this term:

> 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.

There was considerable discussion of what BIG IDEAS might best represent the bases for the biological sciences, and a tentative list was eventually generated. But it is not clear that this list will serve all of the various biological disciplines equally well, and continued consultation among biology educators will be needed to arrive at a definitive set of BIG IDEAS.

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

Other conversations about disciplinary big ideas have been occurring at many levels in the past several years. The Washington State Board of Community and Technical Colleges has convened two workshops (in 2003 and 2007) to discuss disciplinary big ideas. The central question they addressed was "Assuming for the moment that [an] introductory course is the LAST course the students will ever take in the area, what core discipline-specific ideas/concepts do you want ALL students taking the course to understand deeply; i.e., be able to apply and even transfer to other settings five years later?" Biologists participating in these meetings generated lists of big ideas that closely mirror the list developed at the CAB meeting.

III. BIG IDEAS IN PHYSIOLOGY: WHAT STUDENTS SHOULD KNOW

As physiology educators we were interested in generating a set of BIG IDEAS in ***physiology*** that could inform our teaching and that of our colleagues. The nine BIG IDEAS described here appear to be able to serve as the foundation for physiology. This list is not definitive and input from the entire physiology education community is needed if we are to reach a broad consensus about what ideas students should learn.

Each of the BIG IDEAS is defined and its context within physiology is described. An example of important physiological phenomena, commonly taught in physiology courses at all levels, is provided for each BIG IDEA.

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.

We believe that course objectives in our physiology courses should reflect and support the learning of these disciplinary BIG IDEAS but these are not course objectives. ***This list is NOT a prescription for the content of a physiology course***, but reflects concepts that are at the core of our discipline.

BIG IDEA I

Living organisms are machines whose ***causal mechanisms*** can be understood by applications of the laws of physics and chemistry.

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.

It is, however, something more than this. It is essential that students 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). In particular, students have difficulty distinguishing between cause and effect (does lung volume change cause pressure change or visa versa).

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.

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

EXAMPLE: Blood flow to exercising muscle is increased. This is a consequence of the muscle's increased metabolism generating local stimuli that relax arteriolar vascular smooth muscle and reducing resistance to flow. (Students commonly argue that blood flow increases because the exercising muscle "needs" more oxygen, without recognizing that "need" is not a mechanism.)

BIG IDEA II

The cell is the smallest, self-replicating unit of integrated function . The organism is made up of tissues comprised of different cells with specialized structures and functions.

This BIG IDEA is one of the oldest in the "modern" era of biology. It is so elemental that it is usually implicitly assumed, not explicitly stated. As a result the important consequences that follow from it are often unappreciated.

The cell membrane that separates the interior of the cell from the external environment has specific properties, and these contribute to the specialized functions of every cell. In a complex, multicellular organism cells have specialized functions, with no one cell able to perform all of the tasks required to maintain the organism.

EXAMPLE: The islet of Langerhans in the pancreas is comprised of three different types of cells, each of which releases a different hormone involved in the regulation of glucose metabolism.

BIG IDEA III

Life requires ***<u>information flow</u>*** in and between cells and between the environment and the organism.

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.

Genetic information determines, in complex ways, the structure and function of the organism as it develops from a fertilized egg. Information about the state of the external world must be available to allow appropriate responses to the many conditions that pose a danger to the organism. Information must be passed from cell to cell in order to make possible the coordinated responses of the organism to changes in both the internal and the external environment.

EXAMPLE: The strength of contraction of a skeletal muscle, which must be matched to the task to be performed, is determined by information delivered to the muscle by the number of active neurons and the frequency of firing action potentials in the nerve innervating the muscle.

BIG IDEA IV

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

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). Energy in the form of compounds with high-energy bonds is used to synthesize biological molecule, to power solute pumps, and to produce contraction of muscles.

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

EXAMPLE: The distribution of solutes across the cell membrane is created and maintained by pumps in the cell membrane that move solutes against their electrochemical gradient. The work to accomplish this comes from the release of energy stored in ATP molecules.

BIG IDEA V

Homeostasis is a process that maintains the internal environment of living systems in a more or less constant state.

This is perhaps the defining BIG IDEA in physiology.

Important system parameters are measured and the measured values are compared to a pre-determined set-point, or desired, values (although we do not know the mechanisms generating all of these set-points). The difference is used to generate signals (information) that alter the functions of the organism to return the regulated variable towards its pre-set determined value.

EXAMPLE: In mammals body temperature is maintained more or less constant in the face of changes to environmental temperature by manipulating heat production and heat loss through various mechanisms.

BIG IDEA VI

To understand the behavior of the organism requires understanding the relationship between the ***structure and 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 extend across many different physiological systems. For example, when two systems carry out similar functions certain features of their structure can be expected to be similar.

EXAMPLE: Gas exchange in the lungs and absorption of the products of digestion in the small intestine occur, in the latter case in part, by the process of diffusion. In both cases, the area across which diffusion occurs is very large and the distance to be traversed is short as a consequence of the structure of the respective systems.

BIG IDEA VII

Living organisms carry out functions at many different ***levels of organization*** simultaneously.

Research in physiology currently extends across levels of organization that include: molecules, cell components, whole cells, tissues, organs, organ systems, and the whole organism.

At each level we encounter emergent properties that can not simply be accounted for by any simple "summation" of properties at lower levels.

EXAMPLE: Knowing the properties of each isolated component involved in blood pressure regulation does not allow one to predict the behavior of the negative feedback system that is the baroreceptor reflex.

BIG IDEA IIX

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, as part of an ecological system. Comparative physiology clearly applies this BIG IDEA in significant ways, and more attention to this is undoubtedly warranted in the general physiology education community.

EXAMPLE: A number of industrial chemicals (DDT, PCB) and plant products have estrogen-like properties that can disrupt the body's reproductive functions.

BIG IDEA IX

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 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 varying degrees. Explanations of physiological phenomena do not commonly invoke the processes of evolution, although this is more common in studies of comparative physiology.

EXAMPLE: The hemoglobin mutation that results in HbS confers some protection against malaria (a useful evolutionary adaptation), although it also results in serious illness resulting for impaired tissue perfusion.

Table 2 contains a list of these BIG IDEAS in summary form.

TABLE 2
Big Ideas In physiology

I. Living organisms are ***causal mechanisms*** whose functions are to be understood by applications of the laws of physics and chemistry.
II. ***The cell*** is the basic unit of life.
III. Life requires ***information flow*** within and between cells and between the environment and the organism.
IV. Living organisms must obtain matter and energy from the external world. This ***matter and energy must be transformed and transferred*** in varied ways to build the organism and to perform work.
V. ***Homeostasis*** (and "stability" in a more general sense) maintains the internal environment in a more or less constant state compatible with life.
VI. Understanding the behavior of the organism requires understanding the relationship between ***structure and function*** (at each and every level of organization).
VII. Living organisms carry out functions at many different ***levels of organization*** simultaneously.
IIX. ***Evolution*** provides a scientific explanation for the history of life on Earth and the mechanisms by which changes to life have occurred.
IX. All life exists within an ***ecosystem*** made up of the physicochemical and biological worlds.

It is important to emphasize that t***his list of BIG IDEAS in phyiology 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 list a list of ideas that that should be present in a physiology 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 also 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.

IV. 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 nevertheless, have deep and wide explanatory power. We are calling these "component ideas."

What follows is an attempt to unpack the BIG IDEAS most important in <u>physiology into their component ideas</u>. There is still much to be done to complete this process and input from interested physiologists will be most helpful.

BIG IDEA: I. CAUSAL MECHANISM

component: (1) The laws of physics and chemistry describe the functioning of the organism

component: (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

component: (3) States and functions of the organism are quantifiable and the absolute magnitudes and changes in magnitude are important to understanding the system

BIG IDEA: II. THE CELL

component: (1) The cell membrane contains the contents of the cell and determines what can enter and leave the cell

component: (2) The internal constituents and state of the cell are different than the extracellular environment

component (3) Although all cells have the same DNA not all genes are expressed in every cell

component: (4) As a consequence, cells have many common functions, but also many specialized functions

component: (5) The organism is a collection of cooperating cells, each cell type contributing its special functions to the "economy" of the organism

BIG IDEA: III. HOMEOSTASIS

component: (1) The organism attempts to maintain a more or less constant internal environment that is different than the external environment

component: (2) Stability of the internal environment occurs via information flow in the form of negative feedback

component: (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 component: (4) The “desired” value of a regulated parameter behaves like a “set-point”

component: (5) The value of the set-point can change as the situation of the organism changes

component: (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)

component: (7) The determinants of a regulated variable must be controlled by the body by altering matter/energy transformations

BIG IDEA: IV. INFORMATION FLOW

component: (1) Transmission of genetic information
- (a) Genetic information is coded in DNA making up genes
- (b) Expression of a gene (reading of the code) results in the cell producing a protein (enzyme)
- (c) Expression of genetic information can be turned on and off leading to cell differentiation
- (d) Expression of genetic information determines intracellular function

component: (2) Neural information processing
- (a) Information is encoded and transmitted by all-or-non action potentials generated in neurons and sensory receptors
- (b) Information is passed from neuron to neuron by chemical transmission at synapses, some of which are excitatory and some of which are inhibitory
- (c) The probability of a neuron firing is determined by the balance between the excitatory and inhibitory inputs

component: (3) Chemical information processing
- (a) Cells produce and release signaling molecules which affect their own function and the function of neighboring cells
- (b) Endocrine cells produce and release hormones which are carried to all cells in the body by the circulation
- (c) In order to respond to a signaling molecule a cell must have a specific receptor for that molecule
- (d) When signal molecules bind to a receptor they alter target cell function by altering intracellular enzyme activity

BIG IDEA: V. MATTER/ENERGY TRANSFER AND TRANSFORMATIONS

component: (1) Many physiological processes affect and are affected by changes in the equilibrium state of intra- and extracellular chemical reactions

component: (2) Solutes move across a membrane either passively (down an electrochemical gradient) or actively (using metabolic energy to power a pump)

component: (3) Flow (bulk flow, diffusion) of a substance occurs as the result of an energy gradient

component: (4) Energy is stored in high energy bonds in the constituent molecules of biological systems

component: (5) This energy is used in biosynthesis, moving solutes, and powering muscles

BIG IDEA: VI. STRUCTURE/FUNCTION RELATIONSHIPS

component: (1) The 3-D structure of cells and tissues is a determinant of the functions of the cell and tissue

component: (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

component: (3) All physical objects (cells, tissues, organs) have elastic properties that are determinants of function

BIG IDEA: VII. LEVELS OF ORGANIZATION

component: (1) Biological organisms function at many levels of organization (atoms to the whole organism) that exist on different physical scales.

(2) Processes occurring on one levels can often be explained by mechanisms occurring at lower levels (reductionism)

(3) Some phenomena at a particular level of organization can not be fully explained by mechanisms occurring at lower levels; such emergent properties represent more than the "sum" of mechanisms at lower levels

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

V. WHAT DO WE DO WITH A LIST OF BIG IDEAS?

The first thing that can be done with a list of BIG IDEAS and their component ideas is to make decisions about what we want students to be able to do and understand, and about which BIG IDEAS contribute to students reaching those goals. To say that all students should understand the BIG IDEAS is not to say that is ALL they need to understand. But in the finite time we have for student learning in any course, we must start to make decisions about what is more important than something else. Although these BID IDEAS should not be taken as a list of topics to be covered in any physiology course, they should be taken into consideration in determining course objectives at every educational level.

For example, what do we want students to understand about the respiratory system? The importance of the BIG IDEA of homeostasis suggests that students need some understanding of the regulation of arterial PO_2 and PCO_2 by the system. That means they need to understand that there are neural receptors measuring both variables and that both variables can be changed by altering alveolar ventilation. Do students need to understand the differences in the properties of the central PCO_2 receptors and the peripheral receptors that measure both PO_2 and PCO_2? That will depend on the overall goals of the particular course we are talking about. Do students need to understand the consequences of a ventilation/perfusion imbalance in determining the values for arterial PO_2 and PCO_2? Again, that depends on the students and course.

With more known about the physiological mechanisms of the body than can possibly be learned, a principled approach to deciding what to include in the course is of some considerable benefit. Students also need to know that what we expect from them is understanding of the BIG IDEAS and the application of them, and that this is more valuable than knowing a hundred isolated facts.

The other thing that we can do with a list of BIG IDEAS is to generate an assessment tool with we can determine whether students do, in fact, understand what we expect them to understand. Assessing student understanding of BIG IDEAS can be done independently of their knowledge of and understanding of the details of particular physiological systems. Such an assessment instrument would then allow us to: (1) measure individual student learning, (2) determine the success of our course in helping students learn, and (3) determine the efficacy of new, experimental interventions to promote learning with understanding. Another positive consequence of the use of such an assessment instrument is that students will begin to believe that these BIG IDEAS are important. Students pay attention to, and take seriously, that which is assessed.

In the following paper we will discuss what such an assessment might look like and how we can proceed to develop it.

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