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The "core principles" of physiology: what should students understand?

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Michael J, Modell H, McFarland J, Cliff W. The "core principles" of physiology: what should students understand? *Adv Physiol Educ* 33: 10–16, 2009; doi:10.1152/advan.90139.2008.—The explosion of knowledge in all of the biological sciences, and specifically in physiology, has created a growing problem for educators. There is more to know than students can possibly learn. Thus, difficult choices have to be made about what we expect students to master. One approach to making the needed decisions is to consider those "core principles" that provide the thinking tools for understanding all biological phenomena. We identified a list of "core principles" that appear to apply to all aspects of physiology and unpacked 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 "core principles" also offers a starting point for developing an assessment instrument to be used in determining if students have mastered the important unifying ideas of physiology.

general models; assessment

THE KNOWLEDGE EXPLOSION is alive and well in physiology. One of its more visible signs is the length of the textbooks that we recommend to students (see Table 1). Popular, recent editions of physiology textbooks (a set within easy reach on the bookshelf of the first author) have become 1,000+-page encyclopedias, whether we look at human anatomy and physiology books, physiology texts aimed at undergraduates, or medical- and graduate-level physiology textbooks.

However well a course is taught, students can only learn a fraction of what is in such books. Furthermore, it is clear that students will retain an even smaller fraction over time. Equally important, the focus on learning more "content" does not help students understand physiological principles. By "understand," we mean being able to use the information acquired to perform those tasks, such as problem solving, for which it is relevant (27). The problem of "content overload" and its negative impact on understanding is a long-recognized and persistent problem in all of biology (1, 24, 31).

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 are no generally agreed upon answers to these questions.

As we think about these questions, it is useful to reflect on the fact that they are not a major issue in all science 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 in 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 more or less agree on assessment instruments with which to determine what students do, in fact, understand. The Force Concept Inventory (FCI) developed by Hestenes et al. (14) was only the first of such concept inventories to be written and widely used. It is widely acknowledged that the FCI has had a profound impact on reforming physics education (15, 28, 30).

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

Conceptual Assessment in Biology: NSF-Sponsored Workshops

The National Science Foundation sponsored two workshops, Conceptual Assessment in Biology (CAB) I and II, during which a group of biology educators conducted a conversation aimed at developing assessment instruments with which to measure student understanding of biology (15). The first workshop (CAB I) was held in March 2007 at the University of Colorado (21) and the second (CAB II) was organized by California Polytechnic State University in January 2008 (22).

Two fundamental issues were addressed at these two meetings: *1*) what should we ask students to learn (understand) and *2*) how can we determine whether they have learned it.

The first question has proven difficult to answer. This is due, in part, to the fact that "biology" is a very broad science that is taught at a great many academic levels. Consequently, there probably is no single answer to this question.

An additional difficulty arises when one tries to determine what is meant by a "concept." Five years ago, an informal e-mail survey was conducted (J. Michael, unpublished obser-

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Table 1. *Number of pages of current popular textbooks of physiology*

	Reference	Number of Pages of Text
Human anatomy and physiology		
Saladin	26	1,248
Marieb and Hoehn	18	1,296
Martinin	19	1,110
Undergraduate physiology		
Sherwood	26a	801
Widmaier et al.	28a	738
Medical Physiology		
Berne et al.	3	978
Boron and Boulpaep	4	1,267
Guyton and Hall	11	1,066

vations) of ~20 physics educators presenting papers at an American Association of Physics Teachers meeting on topics related to physics "concepts." Twelve of the surveyed individuals replied, but none of these physics educators were able to offer an operationally useful definition of what they meant by the term "concept" when referring to the FCI. Furthermore, it seems likely that the term "concept" means something different to biologists than it does to physicists.

Participants at the CAB I meeting did find the notion of "big ideas" to be a useful construct with which to attack the problem of defining what to assess. Duschl et all. (7) 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 (see Table 1 in Ref. 21 and Table 2 here). However, 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".

At the CAB II workshop, the use of the term "big ideas" was called into question as many participants thought that this term was likely to be misunderstood or misinterpreted by others in the biology education community. A review of the recent papers written by workshop participants revealed that there is no single term in common usage.

We decided to use the term "core principles" to label those ideas that we believe fit the definition offered by Duschl et al. (7). Thus, we would say that the "core principles" are what we want every student to understand (be able to use) long after the course is completed. The "core principles" discussed in this article are derived from the authors' common experience in teaching physiology, previous work (23), and formal and informal discussions at workshops with other physiology and biology educators (21, 22). Many of these "core principles" are emphasized to different degrees in a variety of biology (5, 10) and physiology textbooks (Table 1).

In this article, we describe a set of "core principles" and their unpacked component ideas that we believe represent the foundation for the understanding all of physiology. The unpacked "core principles" provide the starting point for any attempt to develop conceptual assessment instruments for physiology.

"Core Principles" in Physiology: What Should Students Understand?

As physiology educators, we were interested in having a set of "core principles" in *physiology* that could inform our teaching and that of our colleagues. We believe that the "core principles" described here can serve as the foundation for understanding physiology. They provide students with thinking tools to aid their learning of physiology in their current courses and in the future.

Each of the following "core principles" 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 core principle.

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

Table 2. *"Core principles" in physiology (with applications in other biosciences)*

Core principle 1: evolution
Evolution provides a scientific explanation for the history of life on Earth and the mechanisms by which changes to life have occurred.
Core principle 2: ecosystems and environments
All life exists within an ecosystem made up of the physicochemical (abiotic) environment and other biological organisms.
Core principle 3: causal mechanisms
Living organisms are causal mechanisms whose functions can be understood by applications of the laws of physics and chemistry.
Core principle 4: the cell
The cell is the basic unit of life.
Core principle 5: structure/function relationships
Understanding the behavior of an organism requires understanding the relationship between structure and function (at each and every level of organization).
Core principle 6: levels of organization
Living organisms carry out functions at many different levels of organization simultaneously.
Core principle 7: information flow
Life requires information flow within and between cells and between the environment and the organism.
Core principle 8: matter/energy transfer and transformations
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.
Core principle 9: homeostatis
Homeostatis (and stability in a more general sense) maintains the internal environment in a more or less constant state compatible with life.

but reflects ideas that are at the core of our discipline. These ideas can provide students with powerful tools to aid them in their learning of physiology.

"Core Orinciples" in Physiology (With Applications in Other Biosciences)

Core principle 1: evolution. Evolution by means of natural selection provides a scientific explanation for the history of life on Earth and the mechanisms (at the molecular level, at the level of the species, etc.) by which changes have occurred to life. In physiology, evolution explains the origin of the relationships between structure and function that are at the core of our discipline and the variations in protein structure that underlie physiological functions at the molecular level.

CONTEXT WITHIN PHYSIOLOGY. Over the past 100 or so years, this "core principle" has become *the* major organizing idea for essentially all aspects of biology. Its implications inform all of the biological sciences, although the teaching of these sciences draws on the explanatory power of the "core principle" of evolution to varying degrees.

EXAMPLE. Mammalian species living in very arid environments have adapted to this condition and have been observed to have much longer loops of Henle than species living in less arid conditions. This makes it possible for them to concentrate their urine to a much greater extent, resulting in less water loss as urine.

Core principle 2: ecosystems and environments. All life exists within an ecosystem composed of the physicochemical environment and biological organisms.

CONTEXT WITHIN PHYSIOLOGY. 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 "core principle" in significant ways, and more attention to this is undoubtedly warranted in the general physiology education community.

EXAMPLE. A number of industrial chemicals [such as dichloro-diphenyl-trichloroethane (DDT) or polychlorinated biphenyl (PCB)] that are now widespread in the water supply are known to have estrogen-like properties that can disrupt the body's reproductive functions. These findings have obvious implications for the management of the environment and for understanding reproductive disorders in animals or humans.

Core principle 3: causal mechanisms. Living organisms are machines whose causal mechanisms can be understood by applications of the laws of physics and chemistry.

CONTEXT WITHIN PHYSIOLOGY. In some sense, this "core principle" 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 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 (in terms of chains of cause-and-effect relationships). Physiology teachers believe that this characteristic is one of the major sources of the difficulties that students have in learning physiology (20). In particular, students have difficulty distinguishing between cause and effect (does a pressure change cause a change in lung volume, or visa versa?).

There are other implications that must also be considered. The properties (physical or chemical states) and functions of the organism are measurable, and changes in the measured values are meaningful. Reasoning about physiology is thus both qualitative and quantitative, and the learner must pay attention to both the direction in which parameters change and the units of measurement and to orders of magnitudes of measured variables.

Finally, this "core principle" 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 reduce resistance to flow. (Students commonly argue that blood flow increases because the exercising muscle "needs" more oxygen, without recognizing that "need" does not describe a mechanism.)

Core principle 4: the cell. The cell is the smallest, self-replicating unit of integrated function. A multicellular organism is an organized structure made up of different cells, with each cell having some properties in common with other cells in the organism and each cell having some specialized structures and functions.

CONTEXT WITHIN PHYSIOLOGY. This "core principle" is one of the oldest in 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, each cell has specialized functions, with no one cell able to perform all of the tasks required to maintain the organism. Thus, the integration of the organism is the result of interactions between specialized cells.

EXAMPLE. The islet of Langerhans in the pancreas is composed of three different types of cells, each of which has the common feature of a membrane across which glucose can be transported. However, each of these different cells releases a different hormone involved, in one way or another, in the integrated regulation of glucose metabolism.

Core principle 5: structure/function relationships. To understand the behavior of the organism requires understanding the relationship between the structure and function of the organism. The structure of the organism both enables particular functions (makes them possible and determines the magnitude of what happens) and constrains functions (limits what can happen and the magnitude of what happens).

CONTEXT WITHIN PHYSIOLOGY. This "core principle" 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, only in part) by the process of passive diffusion. To maximize the flux of material across a membrane, there must be a large surface area available, and the thickness of the barrier to diffusion must be minimized. In both examples cited, these conditions are present as a result of the structure of the respective systems.

Core principle 6: levels of organization. Living organisms carry out functions at many different levels of organization simultaneously, and emergent properties exist at higher levels of organization.

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

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

EXAMPLE. Knowing the properties of individual neurons in the visual cortex, and even the properties of cortical columns of neurons, does not make it possible to predict the ability of primates to recognize faces. This is an emergent property of the primate central nervous system.

Core principle 7: information flow. Life requires information flow in and between cells as well as between the environment and the organism.

CONTEXT WITHIN PHYSIOLOGY. Information is one of those terms that is frequently used in everyday discourse, although its many meanings 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 to make possible the coordinated responses of the organism to changes in both the internal and 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 motor neurons and the frequency of firing action potentials in the motor neurons of the muscle. This motor signal is in part determined by signals generated in the motor cortex and in part by afferent feedback from sensors such as muscle spindles.

Core principle 8: matter/energy transfer and transformations. 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 to build the organism and to perform work (from the cellular to organismal levels).

CONTEXT WITHIN PHYSIOLOGY. All functions of living organisms are energy dependent, and all organisms must have access to energy 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 molecules, to power solute pumps, and to produce contraction of muscles.

Regulation and control (components of the "core principle" of homeostasis) involve 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 the form of ATP.

Core principle 9: homeostatis. Homeostasis is a process that maintains the internal environment of living systems in a more or less constant state.

CONTEXT WITHIN PHYSIOLOGY. This is perhaps the defining "core principle" of physiology.

Important system parameters are measured, and the measured values are compared with a predetermined "set point," or desired values (whatever the mechanisms of these set points). The difference is used to generate signals (information) that alter the functions of the organism to return the regulated variable toward its preset determined value.

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

These "core principles" are not completely distinct from one another (Table 2). For example, the "core principle" of information flow is an integral part of the "core principle" of homeostasis. Similarly, the "core principle" of homeostasis is related to the "core principle" of causal mechanism. The utility of these "core principles" as thinking tools is not diminished by any possible overlaps between them.

It is important to emphasize that this list of "core principles" in physiology is not to be read as defining the content of a course or a curriculum. Rather, 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 is present in many sections of a physiology course in varying proportions depending on the specific subject matter of the course. The relationship between the list of "core principles" and the content of courses or curricula will also vary among the different biological disciplines.

The explanatory power of each of these "core principles" for understanding physiology varies considerably. There can be no question that homeostasis is *the* central idea in physiology, whereas for most (noncomparative) physiologists, ecosystems and environments play a lesser role in helping to organize their thinking. Finally, we need to distinguish between the uses of these "core principles" in doing physiology research and their use in teaching physiology.

Unpacking the "Core Principles" of Physiology

Like atoms, which can be unpacked into many smaller particles, each "core principle" is made up of a collection of other component ideas that may be "smaller" in scope but nevertheless have deep and wide explanatory power. This process of disassembling a "core principle" into the set of ideas that it encompasses is what we mean by "unpacking." While we believe the set of "core principles" we have defined applies to all of biology, it seems clear that different biology disciplines will unpack the "core principles" in different ways. It is also likely that physiologists teaching at different educational levels will want to unpack the "core principles" differently. The way in which unpacking is done is, at least in part, a pragmatic decision based on the uses to be made of the results (see *Discussion*). There is certainly no one unique or correct way to unpack them.

What follows is one attempt to unpack the "core principles" into their component ideas. Other physiologists teaching other courses might unpack these "core principles" in different ways to emphasize what they expect their students to understand.

I. Evolution
- *A*. Evolution by means of natural selection provides an explanation for the origins of organisms and their physiological functions.
- *B*. Evolution explains the origin of the relationships between structure and function that are at the core of physiology.
- *C*. Variations in protein structure that underlie physiological function at the molecular level are driven by evolutionary mechanisms.

II. Ecosystems and environments
- *A*. Organisms exist within an ecosystem composed of the physicochemical (abiotic) environment and other biological organisms (biotic environment).
- *B*. Variations in both the abiotic environment (oxygen, temperature, DDT, etc.) and biotic factors (e.g., pathogens) can affect normal physiology and pathophysiology.
- *C*. Physiology arises from the action and interactions of cells and their interstitial "environment" [see *core principle IV* (the cell), *component idea B*].

III. Causal mechanisms
- *A*. The laws of physics and chemistry describe the functioning of the organism, and there are knowable physical causes for physiological phenomena.
- *B*. 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.
- *C*. States and functions of the organism are quantifiable, and the absolute magnitudes and changes in magnitude are important to understanding the system.

IV. The cell
- *A*. The cell membrane contains the contents of the cell and determines what can enter and leave the cell.
- *B*. The internal constituents and state of the cell are different than the extracellular environment [see *core principle II* (ecosystems and environments), *component idea C*].
- *C*. Although all cells have the same DNA, not all genes are expressed in every cell.
- *D*. As a consequence, cells have many common functions but also many specialized functions.
- *E*. The organism is a collection of cooperating cells, with each cell type contributing its special functions to the "economy" of the organism.

V. Structure/function relationships
- *A*. The three-dimensional structure of cells and tissues is a determinant of the functions of the cell and tissue [see *core principle I* (evolution), *component idea C*; *core principle II* (ecosystems and environments), *component idea C*; and *core principle IV* (the cell), *component ideas A–E*].
- *B*. Surface area is a determinant of the movement of all substances; hence, the surface area (and the surface-to-volume ratio) is a determinant of function.
- *C*. All physical objects (cells, tissues, and organs) exhibit elastic recoil, which contributes to determining function.

VI. Levels of organization
- *A*. Biological organisms function at many levels of organization (from atoms to the whole organism) that exist on different physical scales.
- *B*. Processes occurring on one level can often be explained by mechanisms occurring at lower levels (reductionism).
- *C*. Some phenomena at a particular level of organization cannot be fully explained by mechanisms occurring at lower levels; such emergent properties represent more than the "sum" of mechanisms at lower levels.

VII. Information flow
- *A*. Transmission of genetic information
  - *1*. Genetic information is coded in DNA, which make up the genes.
  - *2*. Expression of a gene (reading of the code) results in the cell producing a protein (enzyme).
  - *3*. Expression of genetic information can be turned on and off, leading to cell differentiation [see *core principle IV* (the cell), *component idea C*].
  - *4*. Expression of genetic information determines intracellular function [see *core principle IV* (the cell), *component idea E*].
- *B*. Information processing
  - *1*. Neural information processing
    - *a*. Information is encoded and transmitted by all-or-none 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 excitatory and inhibitory inputs.
    - *d*. Information is also passed from cell to cell via ion flow through the gap junctions that connect them [see *core principle VII* (information flow), *component idea A1*].
  - *2*. Chemical information processing
    - *a*. Cells produce and release signaling molecules, which affect their own function and the function of other cells, some nearby and others quite distant.
    - *b*. Endocrine cells produce and release hormones, which are carried to all cells in the body by the circulation.
    - *c*. 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 opening membrane channels or altering intracellular enzymes.

VIII. Matter/energy transfer and transformations
- *A*. Many physiological processes affect and are affected by changes in the equilibrium state of intra- and

extracellular chemical reactions [see *core principle III* (causal mechanisms), *component idea A*].

B. Solutes move across a membrane either passively (down an electrochemical gradient) or actively (using metabolic energy to power a pump) [see *core principle IV* (the cell), *component idea A*].

C. The flow (bulk flow, diffusion, and osmosis) of a substance occurs as the result of an energy gradient.

D. Energy is stored in high-energy bonds in the constituent molecules of biological systems.

E. This energy is used in biosynthesis, moving solutes, and powering muscles.

IX. Homeostatis

A. The organism normally maintains a more or less constant internal environment that is different than the external environment [see *core principle IV* (the cell), *component idea B*].

B. The stability of the internal environment occurs via information flow in the form of negative feedback.

C. Some limited sets of internal system parameters are regulated (held more or less constant) by the manipulation of other parameters whose values are controlled.

D. The "desired" value of a regulated parameter behaves like a "set point," and set points are often the products of natural selection [see *core principle I* (evolution), *component idea A*].

E. The value of the set point can change as the situation of the organism changes.

F. The actual value of a regulated variable must be measured by the body (a parameter can only be regulated if it can be measured) [see *core principle VII* (information flow), *component idea B*].

G. The determinants of a regulated variable must be controlled by the body by altering matter/energy transformations [see *core principle VIII* (matter/energy transfer and transformations)].

Discussion

The nature of the "core principles" that we have described here does not differ from the nature of the "big ideas" described by Duschl et al. (7) or Wiggins and McTighe (29). They are identical in character to Feder's "central core concepts" (9). The Committee on Undergraduate Biology Education of the National Research Council (6) defined a set of "general themes" that point to the same kinds of ideas. In all of these cases, the goal was to identify those ideas that every student ought to take away from a course in biology or physiology.

Furthermore, it is particularly noteworthy that the content of Feder's list of "central core concepts" (9) has considerable overlap with our list of "core principles." Furthermore, the list of "general themes" recommended by the Committee on Undergraduate Biology Education (6) contains many of the same ideas that we have proposed here as well as some additional ones.

Modell (23) described a set of "general models" or common themes, ideas, and relationships that can be used as a basis for understanding many seemingly different physiological phenomena. On examination, it appears that each of these general models is a component idea of one of our proposed "core principles" (see Table 3).

So, what can we do with a list of "core principles" and their unpacked component ideas?

First, "core principles", and their component ideas, can guide decisions about what we want students to be able to do and understand. Which "core principles" contribute to students reaching whatever learning goals we have established? To say that all students should understand the "core principles" is not to say that is *all* they need to understand. However, in the finite time we have for student learning in any course, we must make decisions about what is more important than something else. Although these "core principles" should not be taken as the list of topics to be covered in any physiology course, they should be recognized as a tool for building an overarching framework for specific course objectives at every educational level. They are also an important learning resource for students.

For example, what do we want students to understand about the respiratory system? The importance of the core principle of homeostasis suggests that students need some understanding of the regulation of arterial P_{CO_2} and P_{O_2} by the respiratory 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 receptors and peripheral receptors? 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 P_{CO_2} and P_{O_2}? Again, that depends on the students and the course under discussion.

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

Second, "core principles" can be used to develop an assessment tool with which we can determine whether students do, in fact, understand what we expect them to understand. Conceptual assessment of student understanding of "core principles" can be done independently of their knowledge and understanding of the fine-grained *details* of particular physiological systems. It is obvious that not all students will be expected to

Table 3. *The relationship between Modell's "general models" and the "core principles"*

General Models	Core Principles
Control system	Homeostatis and information flow
Conservation of mass	Causal mechanisms
Mass and heat flow	Causal mechanisms, structure/function relationships, and matter/energy transfer and transformations
Elastic properties of tissues	Structure/function relationships
Transport across membranes	Causal mechanisms, structure/function relationships, and matter/energy transfer and transformations
Cell-to-cell communication	Information flow
Molecular interactions	Causal mechanisms

Modell's "general models" were taken from Ref. 20.

understand all of the "core principles" or understand them to the same depth. Students in an introductory physiology course might be expected to apply their understanding of a component idea of a particular core principle to a simple scenario or problem (i.e., recognizing that negative feedback results in the maintenance of blood pressure), whereas students in a more advanced course could be asked to demonstrate their understanding by solving a more complex problem [i.e., a demonstration of understanding of the roles of different variables (blood volume, cardiac output, and peripheral resistance) in the negative feedback control of blood pressure].

The process of writing conceptual assessment instruments has been described in a number of other disciplines: Newtonian motion (12–14), electricity and magnetism (17), chemistry (25), and geoscience (16). Biology concept inventories have also been developed for natural selection, genetics, and other topics in biology (2, 8, 15). Typically, the process begins with generating open-ended questions with which to capture students' thinking about phenomena in their own words. This is then used a basis for writing multiple-choice questions in which the distracters (wrong answers) represent common student misconceptions. A two-tiered approach is commonly used in which the first question asks for a prediction or explanation about a system and the second questions asks the student to indicate the reason for their answer to the first question.

Such an assessment instrument would 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 "core principles" are important. Students pay attention to, and take seriously, that which is assessed.

The next step is to determine whether we can define a broadly based consensus about the important "core principles" for physiology. We are in the process of doing this using an online survey system to obtain the thoughts of physiology teachers. We will be reporting the results of this study when they are available.

REFERENCES

1. **American Association for the Advancement of Science.** *Benchmarks for Science Literacy*. New York: Oxford Univ. Press, 1993.
2. **Anderson DL, Fisher KM, Norman GJ.** Development and evaluation of the conceptual inventory of natural selection. *J Res Sci Teach* 39: 952–978, 2002.
3. **Berne RM, Levy MN, Koeppen BM, Stanton BA.** (editors). *Physiology* (5th ed.). St. Louis, MO: Mosby, 2004.
4. **Boron WF, Boulpaep EL.** (editors). *Medical Physiology*. Philadelphia, PA: Saunders, 2003.
5. **Campbell NA, Reece JB, Urry LA, Cain ML, Wasserman SA, Minorsky PV, Jackson RB.** *Biology* (8th ed.). San Francisco, CA: Cummings, 2008.
6. **Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century, National Research Council.** *BIO2010: Transforming Undergraduate Education for Future Research Biologists*. Washington, DC: National Academies, 2003.
7. **Duschl RA, Schweingruber HA, Shouse AW.** (editors). *Taking Science to School: Learning and Teaching Science in Grades K–8*. Washington, DC: National Academies, 2007.
8. **Elrod S.** *Genetics Concept Inventory (GenCI) Development* (online). http://bioliteracy.net/manuscripts08.pdf [17 November 2008].
9. **Feder ME.** Aims of undergraduate physiology education: a view from the University of Chicago. *Adv Physiol Educ* 29: 3–10, 2005.
10. **Freeman S.** *Biological Science* (2nd ed.). San Francisco, CA: Cummings, 2008.
11. **Guyton AC, Hall JE.** *Textbook of Medical Physiology* (11th ed.). Philadelphia, PA: Elsevier Saunders, 2006.
12. **Halloun IA, Hestenes D.** The initial knowledge state of college physics students. *Am J Phys* 53: 1043–1048, 1985.
13. **Halloun IA, Hestenes D.** Common sense concepts about motion. *Am J Phys* 53: 1056–1065, 1985.
14. **Hestenes D, Wells M, Swackhamer G.** Force concept inventory. *Phys Teach* 30: 141–158, 1992.
15. **Klymkowsky MW, Garvin-Doxas K, Zeilik M.** Bioliteracy and teaching efficacy: what biologists can learn from physicists. *Cell Biol Educ* 2: 151–161, 2003.
16. **Libarkin JC, Anderson SW.** The geoscience concept inventory: application of Rasch analysis to concept inventory development in higher education. In: *Applications of Rasch Measurement in Science Education*, edited by Liu X, Boone WJ. Maple Grove, MN: JAM, 2006, p. 45–73.
17. **Maloney DP, O'Kuma TL, Hieggelke CJ, Van Heuvelen A.** Surveying students' conceptual understanding of electricity and magnetism. *Am J Phys Suppl* 69: S12–S23, 2001.
18. **Marieb EN, Hoehn K.** *Human Anatomy and Physiology* (7th ed.). San Francisco, CA: Cummings, 2007.
19. **Martini FH.** *Fundamentals of Anatomy and Physiology* (7th ed.). San Francisco, CA: Cummings, 2007.
20. **Michael J.** What makes physiology hard for students to learn? Results of a faculty survey. *Adv Physiol Educ* 31: 34–40, 2007.
21. **Michael J.** Conceptual assessment in the biological sciences: a National Science Foundation-sponsored workshop. *Adv Physiol Educ* 31: 389–391, 2007.
22. **Michael J, McFarland J, Wright A.** The second Conceptual Assessment in the Biological Sciences Workshop. *Adv Physiol Educ* 32: 248–251, 2008.
23. **Modell HI.** How to help students understand physiology? Emphasize general models. *Adv Physiol Educ* 23: 101–107, 2000.
24. **Nelson C.** Skewered on the unicorn's horn: the illusion of tragic tradeoff between content and critical thinking in the teaching of science. In: *Enhancing Critical Thinking in the Sciences*, edited by Crow L. Washington, DC: Society for College Science Teaching, 1989, p. 17–27.
25. **Pavelich M, Jenkins B, Birk J, Bauer R, Krause C.** Development of a chemistry concept inventory for use in chemistry, materials and other engieeering courses. In: *Proceedings of the 2004 American Society for Engineering Annual Conference and Exposition*. Paper no. 2004-1907.
26. **Saladin K.** *Anatomy and Physiology: the Unity of Form and Function* (4th ed.). New York: McGraw-Hill, 2007.

26a. **Sherwood L.** *Human Physiology: From Cells to Systems* (5th ed.). Belmont, CA: Brooks/Cole-Thomson Learning, 2004.

27. **Simon HA.** Learning to research about learning. In: *Cognition and Instruction: Twenty-five Years of Progress*, edited by Carver SM, Klahr D. Mahwah, NJ: Erlbaum, 2001, p. 205–226.
28. **Stokstad E.** Reintroducing the intro course. *Science* 293: 1608–1610, 2001.

28a. **Widmaier EP, Raff H, Strang KT.** *Vander, Sherman and Luciano's Human Physiology: the Mechanisms of Body Function* (9th ed.). Boston, MA: McGraw-Hill Higher Education, 2004.

29. **Wiggins G, McTighe J.** *Understanding by Design* (expanded 2nd ed.). Alexandria, VA: Association for Supervision and Curriculum Development, 2005.
30. **Wood WB, Gentile JM.** Teaching in a research context. *Science* 302: 1510, 2003.
31. **Wright RL, Klymkowsky MW.** Content versus process: is this a fair choice? *Cell Biol Educ* 4: 189–198, 2005.