STAYING CURRENT

Another look at the core concepts of physiology: revisions and resources

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Michael J, McFarland J. Another look at the core concepts of physiology: revisions and resources. Adv Physiol Educ 44; 752–762, 2020; doi:10.1152/advan.00114.2020.—In 2011, we published a description of 15 core concepts of physiology, and in 2017 we described how core concepts could be used to teach physiology. On the basis of publications and conference presentations, it is clear that the core concepts, conceptual frameworks, and the homeostasis concept inventory have been used by faculty in many ways to improve and assess student learning and align instruction and programs. A growing number of colleagues focus their teaching on physiology core concepts, and some core concepts have been used as explicit themes or organizing principles in physiology or anatomy and physiology textbooks. The core concepts published in 2011 were derived from inputs from a diverse group of physiology instructors and articulated what this group of instructors expressed a decade ago. On the basis of current feedback from the physiology teaching community as a consequence of the use of core concepts in teaching and learning, we have revisited these concepts and made revisions to address issues that have emerged. In this article, we offer revised definitions and explanations of the core concepts, propose an additional core concept (“physical properties of matter” which combines two previous concepts), and describe three broad categories for the revised core concepts. Finally, we catalog published resources for each of the core concepts that provide instructors tools to focus facilitation of student learning on goals (learning outcomes), activities and assessments to enable students to develop and apply their understanding of the core concepts of physiology.

INTRODUCTION

The core concepts of physiology were identified by a group of 73 physiology faculty members from a broad range of postsecondary colleges and universities in the United States, and seven other countries (46). The concepts described by these physiology instructors were intended to be used as tools to support instructors and departments and to help students master physiology (44). The goal was to focus physiology pedagogy on conceptual understanding and less on memorization of facts (52).

What do we mean by a core concept? It is a big idea that is essential to the understanding and practice of a discipline, the mastery of which results in enduring understanding and the ability to address novel problems across that discipline (35, 44, 68).

Our work with the physiology core concepts has included “unpacking” four of the original core concepts, thus creating conceptual frameworks that systematically organize a hierarchy of “smaller” ideas making up the concept (35). Dozens of physiology instructors have contributed to the development of conceptual frameworks for flow-down gradients (46), homeostasis (36), cell-cell communication (45), and cell membrane (42). This community continues to contribute to current work on unpacking two additional core concepts, mass balance and structure/function. (Note that in our earlier work, we have referred to this core concept as “structure/function”, and we will use this form to refer to our past work. We are offering a new, refocused revision of this concept, which we refer to as “structure → function”.)

Many physiology instructors now use the core concepts in their physiology courses, including those in the Physiology Majors Interest Group, or P-MIG (17, 27, 35, 55, 62). Some authors of physiology or anatomy and physiology textbooks (4, 56, 60) have organized their textbooks around one concept or a few core concepts, or they have used these concepts as recurring themes. Core concepts have also been the focus of presentations and workshops at national meetings and within individual departments (Experimental Biology, APS Institute of Teaching and Learning, University of Oregon, Michigan State University, physiologyconcepts.org). The core concepts that emerged from our survey a decade ago (46) have been increasingly used in classrooms, and as a result, we have received much feedback from instructors. We have received suggestions about adding core concepts to the list, as well as suggestions to make changes to the ones we have previously identified.

In this article, we present our current thinking about the core concepts of use to undergraduate physiology instructors. We present a revised list of core concepts and provide clear definitions and explanations of our current understanding. In addition, the lists and definitions are annotated with useful references to available learning resources. This should assist instructors in their courses as they help students learn to use the core concepts to understand physiology.

CORE CONCEPTS FOR UNDERGRADUATE PHYSIOLOGY, BIOLOGY, AND PREMEDICAL EDUCATION

In 2000, Modell (47) introduced the idea of teaching undergraduate physiology using general models. This informed our thoughts about and interest in core principles in the years that followed. We began our discussions about the big ideas, core concepts, or principles in physiology in the late 2000s. At the same time, other groups involved in undergraduate life science education were engaged in parallel conversations, projects, and meetings. The three Conceptual Assessment in Biology (CAB) meetings centered around the big ideas that should be assessed in undergraduate biology (40, 43). The identification of the core concepts of physiology was prompted by the CAB meetings and eventually led to our 2011 paper (46).
The meetings that resulted in descriptions of the Core Concepts and Core Competencies for undergraduate life science education in the first Vision and Change report (1) and the competencies for preparation for medical school outlined in Scientific Foundations for Future Physicians (SFFP - 6) also occurred at about this time. As can be seen in Table 1, there is considerable overlap among the core concepts that emerged from these three projects and the previous work on general models (47). There are also notable differences between these lists of concepts; for example, homeostasis is a core concept for physiologists, but not necessarily recognized as central to other biological subdisciplines, and although evolution is recognized as an important idea in biology, most physiology courses do not address it explicitly.

Articles and reports have used a variety of terms to describe the big ideas or “core concepts” of a discipline (see Table 1 below). So, there are many terms that refer to what we initially called “core principles” (46), and later called “core concepts” (44). For example, in biochemistry (64), the term “foundational concepts” is used to identify what we would call core concepts.

There are also instances in which a single term is used to mean somewhat different things in different reports. For example, “core competency” in the AAMC “Scientific Foundations for Future Physicians” report (6) was used to refer to what the AAAS Vision and Change report (1) called “core concepts” (e.g., big ideas like evolution) and “core competencies” (skills like quantitative reasoning).

CORE CONCEPTS, IMPLICIT KNOWLEDGE, AND KNOWLEDGE TRANSFER

As physiologists, we possess a great deal of knowledge that we routinely use without explicitly articulating (telling) to our students. For example, if a substance moves from A to B anywhere in the body, experts understand there is either an energy gradient present (the core concept of flow-down gradients) or that energy is being expended by the system (the core concept of energy). We help students master the phenomenon of synaptic transmission and later in the course, or series of courses, we introduce them to endocrine physiology, but we rarely call their attention to the fact that both of these topics share common features that are represented by the core concept of cell-cell communication. We may talk about the membrane sodium-pump and the role of ATP in the mechanism of muscle contraction without ever explicitly discussing the role of energy in all biological phenomena. We discuss cardiac function by first talking about the length-tension curve and then proceed to describe the molecular basis for this phenomenon without discussing the core concept of levels of organization. Finally, all too often we talk about the results of a particular experiment without articulating the process of scientific reasoning by which the experiment was designed.

Physiology instructors, as experts, have implicit knowledge about physiology core concepts that they use to make sense of physiological phenomena. Instructors often forget that their students need the scaffolding of a core concept and conceptual framework to make sense of the many “facts” that they believe students are expected to memorize. This situation is not unique to physiology. Loertscher et al. (32) observed that when expert biochemists examine a figure showing chemical reactions with multiple linked equilibria, “details [that] are not explicitly depicted in schematic images are ‘seen’ by experts who rely on tacit knowledge of cellular conditions and chemical principles.” Students are naïve learners, and, therefore, do not have the same implicit or tacit knowledge and rely on what is explicitly presented in the figures. Instructors or authors often fail to reveal or unpack implicit knowledge. Teaching that focuses on core concepts can make experts’ implicit knowledge explicit to students. Intentional, systematic use of core concepts in course design, formative

| The 2011 Core Concepts for Undergraduate Physiology (46) | Physiology General Models (47) | V and C Core Concepts and Core Competencies (1) | SFFP Undergraduate Competencies (6) |
|---------------------------------|-------------------------------|--------------------------------|---------------------------------|
| Causality [14] | Cell-cell communication | (Concept 4) Transformation of energy and matter | (E7) Sense and control |
| Cell membrane [1] | Cell-to-cell communication | (Concept 1) Evolution | (E5) Biomolecules |
| Cell theory [9] | Transport across membranes | (Concept 3) Info flow, exchange, and storage | (E8) Evolution |
| Energy [6] | Mass and heat flow | (Concept 3) Info flow and storage | (E5) Biomolecules |
| Evolution [15] | Control systems | (Competency 3) Modeling and simulation | (E7) Sense and control |
| Flow-down gradients [5] | Interdependence [4] | (Concept 5) Systems | (E6) Structure and function |
| Genes to proteins [11] | Levels of organization [12] | (Concept 5) Systems | (E3) Basic physical principles |
| Homeostasis [1] | Mass balance [13] | Conservation of mass | (E4) Basic principles of chemistry |
| Interdependence [4] | Physics/chemistry [10] | Molecular interaction | (E2) Scientific inquiry |
| Levels of organization [12] | Elastic properties of tissues | (E5) Biomolecules | (E6) Structure and function |
| Mass balance [13] | Scientific reasoning [8] | Process of science | |
| Physics/chemistry [10] | Structure/function [7] | (Concept 2) Structure and function | |
| Elastic properties of tissues | Scientific reasoning [8] | (Concept 1) Process of science | |
| Structural biology [7] | Structure/function [7] | (Competency 1) Process of science | |
| Structure/function [7] | Core concepts and competencies from Vision and Change (V and C) and Scientific Foundations for Future Physicians (SFFP) reports |

The concept labels for Vision and Change (V and C) and Scientific Foundations for Future Physicians (SFFP) have been edited for brevity. The numbers in brackets in the left column are the rank orders of importance from physiology faculty surveys (46). The SFFP report contained eight “competencies” (E1–E8) for entering medical school expectations.
assessment, and teaching can help remind instructors to make
the core concepts, and their subideas within conceptual frame-
works, explicit for students.
Use of core concepts will benefit students in another way. An
important goal for education in every discipline is the develop-
ment of the students’ ability to transfer what they learn in one
context to new contexts (8, 22).
For example, a widely accepted learning outcome in under-
graduate education is for “Students [to] transfer knowledge
and skills across disciplines” (16). Life science students can
both practice and demonstrate this by solving problems using
skills and applying concepts from multiple disciplines (7, 16,
31, 69). Successful physiology problem solving requires
learners to appropriately apply concepts from biology, chem-
istry, physics, mathematics, and other disciplines, including
the social sciences (6, 39). However, students are not often
given explicit instruction or practice with feedback about how
to draw on their knowledge outside of narrow or specialized
disciplinary contexts.
In addition to transfer of knowledge from one discipline to
another, mastery of physiology requires students to be able to
transfer conceptual understanding from one physiological sys-
tem to another (39, 47). “Big ideas [core concepts] are essential
because they provide the basis for . . . transfer.” (68). Emphasis
on development of physiology core concepts in learning out-
comes, and explicit targeted exercises that allow for practice
applying the core concepts with feedback, can help students
transfer what they know and are able to do from one context to
another.
The core concepts are a kind of knowledge that we, physiolo-
gists, have and that we use to understand physiological phenom-
ena. These core concepts are tools that students will benefit
from if they understand them and can learn to use them. In a
sense then, we are urging physiology instructors to make their
implicit knowledge as explicit as possible to help their students
master physiology.

HOW DO THE CORE CONCEPTS RELATE TO ONE ANOTHER?
The examples above illustrate another characteristic of the 14
core concepts; they refer to quite different kinds of ideas. We
have identified three broad categories or classes (Fig. 1). One
class of core concepts are universally applicable in the physical
world, whether the systems are inanimate or animate. They are,
therefore, general models (47). They unpack in a fundamentally
different way than do the core concepts applying to biological
systems only. Two of the core concepts in this group can, in
fact, be represented by simple equations (flow-down gradients
and mass balance).
In spite of the fact that these concepts are always used to
think about and discuss phenomena to which they apply, in-
structors (and textbook authors) rarely make explicit the fact
that each application is an example of a core concept with wide
applicability. One example of this problem is the multiple repre-
sentations of flow-down gradients found in a well-known medi-
cal physiology textbook (30); Fick’s 1st Law of Diffusion (p.
12), Poiseuille’s law describing blood flow (p. 331), and
Poiseuille’s law applied to the respiratory system (p. 436) all
express the same relationship. Furthermore, there is no explicit
recognition that these three seemingly different equations are
each applications of the same core concept. It is uncommon for
students to be able to generate this core concept from the
repeated examples that are presented.
However, for students, an understanding of these concepts
and their application would facilitate the acquisition of an
understanding of those physiological phenomena to which they
are applicable. Their widespread applicability everywhere in the
body and at every level of organization also means that what is

![Diagram of three general classes of core concepts of physiology.](http://advan.physiology.org)
learned about one phenomenon can transfer (8, 22) to learning the next applicable phenomenon that is encountered.

A second class of core concepts is applicable only in the biological (animate) realm. Most of the phenomena to which they apply are, in fact, the subject matter of physiology that students are expected to master. These concepts unpack into conceptual frameworks of varying degrees of complexity and depth (see below). They are generalizable, or applicable, to a very wide range of biological (physiological) systems. The conceptual frameworks that describe the component ideas making up a core concept provide students with a general structure for thinking about a wide range of mechanisms.

It is this property of generalizability that makes them useful tools in teaching and learning physiology. However, once again, it is rare for instructors to make explicit the commonality of the core concepts underlying related phenomena. One example of a core concept that is explicitly addressed across the entirety of a course is homeostasis. On the other hand, it is rare that cell-cell communication is invoked in discussing seemingly different phenomena such as neural stimulation of muscle contraction and the muscle responses to insulin. However, when students can be helped to recognize the generalizability of these concepts across seemingly dissimilar systems, the transfer of learning is facilitated. This makes learning both easier and deeper. However, students do not always spontaneously recognize the applicability of these concepts and instructors should build a learning environment that assists in this kind of transfer of learning.

Finally, there are a set of ideas that are best characterized as being ways of looking at the world. These “core concepts” are perhaps better thought of as overarching ideas that shape how physiologists, and perhaps all scientists, think about the problems they confront as they seek to understand the functioning of any system: animate (biological) or inanimate. These “concepts” are difficult to unpack in the same way that biological core concepts can be unpacked. Some of them may be explicitly referenced in a physiology course (scientific reasoning), while others are used without ever being rigorously defined; examples are structure ↔ function and levels of organization (again reflecting implicit knowledge that scientists employ). Nevertheless, these concepts provide a framework or scaffolding with which to organize information about a system. As such, they can be useful tools to help students build mental models and solve problems.

We suggest that physiology instructors think about the concepts that they routinely use and whether and how they attempt to help students recognize the generality, the wide applicability to seemingly different physiological phenomena, of the concept(s) they use. It is important for students to recognize that understanding a specific physiological phenomenon requires application of multiple core concepts of different kinds.

As an example of the use of multiple core concepts from the three classes of core concepts, consider the phenomenon of the length/tension relationship of skeletal muscle. Historically, explanation of this phenomenon started at the anatomic level (stimulation of muscle contraction at different lengths — scientific reasoning), moved to the level of the sarcomeres (levels of organization and structure ↔ function), and eventually uncovered the role of calcium and ATPase in generating the energy that produces sarcomere shortening (energy). To explain the length-tension phenomenon, to demonstrate meaningful learning (38), students must be able to negotiate all three classes of core concepts. Instructors must explicitly incorporate into their teaching these approaches to thinking about physiological phenomena, but all too often, these are tacitly used, but not explicitly discussed.

CORE CONCEPTS REVISED AND ANNOTATED

As we reviewed and revised our original list of core concepts (46) and considered the suggestions of our colleagues for changes and additions, we used six criteria in to determine which concepts to include in the revised list in Table 3. Each core concept on the list should have the following characteristics. A core concept should be 1) broadly applicable to understanding specific phenomenon in several disciplines and physiological systems, 2) conceptual, describing a big idea that we expect to result in an enduring understanding that enables students to address novel problems, 3) relevant to all (or most) undergraduate physiology courses, 4) clear and capable of being described by an unambiguous statement or model, 5) specific, i.e., should not be too broad, with too many underlying concepts, and 6) student understanding should be demonstrable, i.e., capable of being assessed. Using these criteria and feedback from colleagues, we revised the descriptions of some of the 2011 core concepts (46). In addition, we have combined some concepts and described a new one. These changes are noted in Table 3. (The list of core concepts in Table 3 is arranged alphabetically, and the “importance” of any individual core concept is not denoted by its place in the list.).

One particularly significant change made to the original list of core concepts was the combining of causality and physics/chemistry into a new concept that we call physical properties of matter. Both of the original concepts attempted to describe the idea that biological systems, like all systems in the physical world, obey the same set of laws and that, as such, they are mechanisms whose behavior can be described by a set of causal statements. In the explanation for this new concept, we have also mentioned several physical properties of biological entities that are often involved to explain important physiological phenomena (e.g., the role of the elastic properties of the aorta in creating the pressure pulse).

Another significant change was the relabeling of the concept that had originally been labeled interdependence. In analyzing the responses to our original survey (46), we realized that faculty interpreted and used this core concept in several different ways. On further examination of how colleagues teach physiology, we concluded that what was really being discussed was the idea of systems integration and the need to consider many physiological systems to understand a physiological problem.

Structure ↔ function has also been changed in a significant way, reflecting the fact that physiologists use this concept at both the macroscopic level of tissues and organs, as well as at the molecular level. The connecting symbol has also been changed from “,” which is vague, to “→.” This is intended to make explicit the fact the relationship between structure and function includes both the fact that structure determines function and the fact that physiological functions can alter structures.

Other changes were made to the wording of the definitions and explanations of eight core concepts: cell-cell communication, cell membrane, cell theory, energy, evolution, genes to proteins, levels of organization, and scientific reasoning. In all
cases, we were attempting to clarify our meaning to make the concepts more easily used in teaching. Two concepts, flow-down gradients and homeostasis, remain unchanged.

The description of each of the core concepts in Table 3 includes the following:

1. a definition of the core concept;
2. an explanation of that definition to clarify exactly what is meant;
3. references to available frameworks ("conceptual frameworks" or "unpackings") for the concept;
4. references to related assessment tools, including concept inventories;
5. references to instructional practices or activities to help students understand and apply a core concept; and
6. references to published learning outcomes related to the core concept.

The definition is a statement of our current understanding of how physiology instructors interpret and use this concept. The explanation is intended to inform the user (instructor or student) what the core concepts is about and how it is used. Both have been kept brief, and neither is meant to communicate the entire set of ideas that make up the core concept.

A fuller explanation of the scope of a core concept is provided by a framework or an unpacking of the concept. We have created and vetted a conceptual framework (CF; a hierarchically arranged unpacking of all the ideas that make up the core concept) (33) for four core concepts. As an example, 7 of the 51 items making up the conceptual framework for cell-cell communication (45) can be seen in Table 2. This sample illustrates the hierarchical (outline-like) character of a conceptual framework and the kind of generalizable explanation that more fully explain the substance of a core concept.

A framework provides the instructor and the learner with an organized or structured set of ideas that together provide the meaning of the concept. A CF can be used as the basis for writing a concept inventory (see below). It can also serve to help the instructor generate appropriate learning outcomes for their particular course.

Conceptual frameworks can help students identify questions to be asked of any phenomenon to be understood. These frameworks also facilitate students' transfer of learning from one phenomenon already mastered to other phenomena to be learned later.

Many core concepts have not yet been unpacked into a vetted hierarchical conceptual framework. There are, however, frameworks or 'unpackings' of some of these concepts in the literature or available from scientific societies. We expect that as more physiology instructors begin to use the core concepts in their teaching that conceptual frameworks for other concepts will be developed.

If an instructor believes that it is important that their students know and can use the core concepts, it is imperative that student achievement of these goals be assessed. Thus, the availability of assessment tools, including concept inventories (CIs), can provide means to assess student understanding. A concept inventory is a collection of multiple-choice questions designed to assess student conceptual understanding of the ideas making up a conceptual framework. An important characteristic of the questions making up a CI is that the distractors (wrong answers) are typically based on known student misconceptions (21). CIs are useful in assessing students’ understanding of a concept and diagnosing their inaccurate conceptions as they develop a more accurate mental model of a concept. CIs are not intended as summative or high-stakes assessments of disciplinary knowledge or mastery of the required learning objectives of the course.

Instructional practices refer to pedagogical tools and techniques that can be used to help students master a core concept or any topic in the discipline. Our focus is on activities and resources that have as their aim mastery of a core concept or the application of a core concept to physiological topics. Practices that only aim to help students master a particular physiological phenomenon are not included in Table 3.

Learning outcomes (or learning objectives) inform the student what he, she, or they should know and be able to do on any topic in the discipline to achieve mastery of the topic (41). They are a necessary part of the "learning environment" that every instructor must create. Learning outcomes are usually generated by the classroom instructor, but national organizations (scientific societies, educational reform groups) have also proposed learning outcomes for students in various disciplines (26). We have provided references to these outcomes when they are available for a particular core concept. Given the diversity of physiology courses and programs, it is likely that learning outcomes will vary a great deal.

Our intent, then, is to provide physiology instructors with references to as many of the available learning resources as possible; use of such resources in the classroom will help students learn physiology. The resources listed in Table 3 include publications, websites, and conference presentations aimed at undergraduate education. We recognize that this list is incomplete, and we are certain that there are other resources that are presently in development or unknown to us. There are many empty cells in Table 3, and we hope that helpful tools may yet be developed to fill these gaps. Again, the references to particular resources are not intended to be prescriptive. Each individual instructor will have to decide which, if any, of the cited resources will meet the needs of their students in their courses. Even if a particular tool is not exactly right for your students or your course, it can suggest how you might develop your own tools or adapt existing ones.
Table 3. Revised and annotated list of core concepts for undergraduate physiology arranged in alphabetical order

| Definition | Explanation | Framework | Assessment | Instructional Practice | Learning Outcome |
|------------|-------------|-----------|------------|------------------------|-----------------|
| **Cell-Cell Communication (Minor Changes in Wording)** | Cells communicate with one another using different mechanisms: generation and transport of endocrine signals, generation and transmission of neural (electrical) signals, and cell-cell contact. | (44) – P | (29) | | |
| **Cell Membrane (Minor Changes in Wording)** | Every cell has a membrane separating the constituents of the cell from the extracellular compartment, and in general, from other cells. Every physiological phenomenon (function) ultimately depends on the behavior of cells and their membranes. | (42) – P | (29) | (24) | |
| **Cell Theory (Minor Changes in Wording)** | Cell theory is one of the oldest concepts in modern biology. Although physiology students are introduced to this concept in other biology courses, it has physiological implications that may not be obvious to students. | | (28) | | |
| **Energy** | Ingestion of food, digestion, and the generation of ATP (the energy source for most biological processes) are steps in the process of providing every cell with the energy needed to function and survive. Students are introduced to this concept in other biology and science courses and should be able to apply it to physiological processes. | (3) | (29) | (59) – P | (3) |
| **Evolution (Minor Changes in Wording)** | Living organisms share a common ancestor, and the process of evolution has resulted in the present-day variety of species. The mechanisms of evolution act at many levels of organization and result in adaptive changes that have produced the extant relationships between biological structure and physiological function. This concept is often not addressed in physiology courses; however, students are introduced to the concept of evolution in other biology courses. | (3) | (5) | (2) | (3) |
| **Flow Down Gradients (Flux)** | Ions or other solutes crossing a cell membrane, blood flowing in blood vessels, gas flowing in airways, and chyme moving down the gastrointestinal tract are all processes that result from the interaction of an energy gradient and the resistance to flow that is present. It is likely that students have encountered this concept in previous science courses, but they need help to transfer that understanding to physiology. This core concept does not incorporate active transport mechanisms. | (44) – P | (13) – P | (34)-P | (35)-P |

Continued
| Definition | Explanation | Framework | Assessment | Instructional Practice | Learning Outcome |
|------------|-------------|-----------|------------|------------------------|-----------------|
| **Genes to Proteins (Minor Changes in Wording)** | This is the central dogma of molecular biology, and it explains both the development of the individual organism from a fertilized ovum, as well as changes that occur in the function and structure of organisms throughout life. Students are introduced to the central dogma in other biology courses. Although this concept may not be addressed explicitly in many physiology courses, students should be able to apply it in the context of physiology. | (3) | (29) | (25) | (3) |
| **Homeostasis** | The role of negative feedback in regulating the functions of the body is a particularly powerful core concept, in that it describes so much of organ system physiology. We have limited this core concept to a description of negative feedback systems, although we recognized that there are a number of other kinds of control mechanisms that contribute to determining system function. | (36) – P | (37) – P | (48) – P | (6) |
| **Levels of Organization (Minor Changes in Wording)** | To understand physiological phenomena and solve problems in physiology, it is necessary to determine at what organizational level(s) an answer is to be found. Students need frequent opportunities to apply this core concept in all physiological contexts. | (9) | (57) | | |
| **Mass Balance (Minor Changes in Wording)** | Mass (or matter) can be liquid (e.g., water, blood), gas (e.g., oxygen, carbon dioxide), solute within a liquid medium (e.g., ions, glucose, hormones), or solid (e.g., CaPO4 in bone). The region of interest may be considered to be a compartment with, potentially, multiple entry and exit paths. The quantity of mass within a compartment depends on the initial quantity of mass in the compartment, the rate of entry of mass into the compartment, and the rate of exit of mass from the compartment. | (19) – P | | |
| **Physical Properties of Matter** | In this core concept, we attempted to capture the idea that the functions of the body arise from the interaction of atoms, ions, and molecules, as described by the laws of chemistry and physics. A consideration of the physical properties of biological systems (elasticity, capacitance, viscosity etc.) is necessary to understand of physiological phenomena. Thus, an “explanation” for a physiological phenomenon or mechanism must include a set of statements outlining the cause-and-effect relationships (the causal relationships) between entities. | See American Chemical Society (acs.org) or American Physical Society (aps.org). | (9) | (54) | |
| **Scientific Reasoning (Minor Changes in Wording)** | Physics is a science. Our understanding of the functions | See American Chemical Society (acs.org) or American Physical Society (aps.org). | (3) | (18) | (66) | (6) |

Continued
Finally, the resources that are referenced here come from two different, but overlapping, sources. Some of them have been developed by physiologists for use in physiology classrooms. In Table 3, these have been labeled with a “P”. While not all of these will be usable in your classroom as written, most should be relatively easy to adapt for use in helping your students learn physiology. Other resources cited come from other science disciplines (e.g., biology, molecular biology, genetics, and physics), in which conceptual understanding is increasingly being emphasized. Because we are physiologists, not physicists or chemists, we have referred readers to resources for the core concept of physical properties of matter as stated by the American Physical Society (e.g., Forum on Education https://www.aps.org/units/fed/) and the American Chemical Society (https://www.acs.org/content/acs/en/education/). Finally, some core concepts have been defined in many biological sciences and overlap to a varying extent with the core concepts of physiology, i.e., “Vision and Change” (1). However, resources from these sources may be less adaptable for use in the physiology classroom, although they may well provide suggestions for resources for physiology that can be developed.

Table 3 provides a resource for instructors to assist them in the design, implementation, and alignment of critical elements of their courses, including learning outcomes, assessment, and instructional activities. As such, it contains our revised list of core concepts and the resources that can be used to assess student learning and support use of these concepts in the classroom. In can also be used by those engaged in more narrow tasks, for example it can serve as a starting point for those who might need to draft course or program learning outcomes.

| Definition | Explanation | Resources |
|------------|-------------|-----------|
| of the body arises from the application of the processes of science, including the scientific method; thus, our understanding is always tentative. It is scientific reasoning using inference, information literacy, observations, study design, data analysis and interpretation that has generated the information that fills our textbooks. To fully understand physiology, one must understand how the results were generated and how future results will be generated. | of a physiology course or curriculum, it is usually taught as a discrete topic to be mastered by the students. However, this concept should be explicitly addressed in all physiology courses. | (29) |
| Structure and function (from the molecular level to the organ system level) are intrinsically related to each other. The functions of molecules, cells, tissues, or organs are determined by their form (structure), and function can alter structure. (The change in the connecting symbol is intended to indicate the bidirectionality of the relationship between structure and function.) | This core concept is commonly used in two different ways: large-scale and molecular. Diffusion between body compartments is maximized when the surface area available is large and the diffusion distance is small; this structure → function relationship is an important feature of many physiological phenomena. There are other such macroscale phenomena where the structure of the system makes possible the function of that system. However, on a molecular scale, the structure of proteins like hemoglobin and enzymes determine their function, and changes in those structures alter their function in important ways. Thus, an understanding of a physiological mechanism requires some understanding of the structures that are involved. Understanding of structure requires understanding the function that those structures enable. | (3) |
| Organ systems work together; understanding the functions of the organism require a consideration of how multiple entities (cell, tissues, organs, and organ systems) interact with one another to sustain the life of the organism. | Physiology is typically studied and taught one organ system at a time. It is particularly important that students be given opportunities to address physiological phenomena and solve problems that require them to apply their knowledge of several systems at the same time. | (33) – P | (26) – P |

The “– P” label identifies resources that were developed specifically for physiology. *This is a new concept that combines “Physics/chemistry” and “Causality”.

**Structure → Function (Major Changes in Wording and a Change in the Symbol)**

| Framework | Assessment | Instructional Practice | Learning Outcome |
|------------|------------|------------------------|------------------|
| (3)        | (12) – P   | (3)                    |
| (11)       | (59)       |                        |

**Systems Integration (Formerly “Interdependence”)**

| Framework | Assessment | Instructional Practice | Learning Outcome |
|-----------|------------|------------------------|------------------|
| (33) – P  | (60) – P   | (63) – P               |

*This is a new concept that combines “Physics/chemistry” and “Causality”.*
SOME IMPORTANT CAVEATS ABOUT OUR LIST OF CORE CONCEPTS

Several features of the list of core concepts that we previously published (46), and the revised list published here, need clarification and emphasis.

1. Our lists of core concepts are not meant to encompass the breadth and depth of physiology knowledge. Rather, we and our survey respondents (46) viewed these as concepts that students in their particular courses ought to understand. These core concepts are focused on undergraduate physiology and, in particular, should be applicable to introductory physiology or “anatomy and physiology” courses. It is unlikely that any physiology instructor will ask their students to use all 14 of the core concepts on our current list in any particular course. It is possible, even likely, that some physiology instructors will want to add other core concepts to the list for their students to understand and use.

2. The list of core concepts in this paper is not meant to define the necessary contents of a physiology course or curriculum. It does present a set of tools that we believe will help students understand the specific physiology processes addressed by an instructor in a particular course. Our list is not intended to be prescriptive in any sense.

3. Finally, our list is not meant to be the final word about core concepts. We expect that these core concepts, their conceptual frameworks, and conceptual assessments will be modified by the instructors who use them to make them more useful tools for their students.

WHAT COMES NEXT?

These core concepts offer physiology faculty and students tools that can assist in the mastery of physiology (44). We are encouraged in this belief by the physiology instructors who have systematically incorporated core concepts into their courses (17, 33, 55, 62). We welcome the use of core concepts as explicit, recurring themes or organizing principles in physiology or anatomy and physiology textbooks (4, 56, 60). We hope to see more courses, curricula and textbooks focused on core concepts in the future.

However, for this to happen, it is imperative that the physiology teaching community begin producing additional learning resources that can make the use of core concepts more productive. What is needed is:

1. the identification of additional core concepts, if any, that might aid student learning of physiology.
2. the development and use of conceptual frameworks for additional core concepts and the editing or modifications of existing frameworks to better suit specific courses or students;
3. the development and validation, if possible, of concept inventories or classroom assessments for more of the core concepts;
4. the development of learning resources that specifically require students to use the core concepts and promote active learning; and
5. the development of learning outcomes that address student mastery of core concepts and the ability to apply core concepts to novel physiology problems.

Finally, we, as a community, need to continue to develop and nurture a culture of sharing learning resources and approaches to teaching in much the same way that we have always shared ideas about what we do in the research laboratory (41, 44).

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

J.M. and J.M. conceived and designed research; J.M. and J.M. prepared figures; J.M. and J.M. drafted manuscript; J.M. and J.M. edited and revised manuscript; J.M. and J.M. approved final version of manuscript.

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