A PERSONAL VIEW | P-MIG Special Collection

Reflections on core concepts for undergraduate physiology programs

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McFarland JL, Michael JA. Reflections on core concepts for undergraduate physiology programs. Adv Physiol Educ 44: 626–631, 2020; doi:10.1152/advan.00188.2019.—Undergraduate education should help students build a deep, conceptual understanding of their discipline, not merely compel them to acquire factual knowledge. The core concepts for physiology (described in 2011), conceptual frameworks, and conceptual assessments are available to focus undergraduate physiology education on helping students understand and apply principles that govern and describe physiological processes. We review the context in which physiology core concepts were identified by a community of physiology educators. We explain the structure of conceptual frameworks and concept inventories and their benefit. We describe how core concepts have been used in physiology courses and departments, as communicated in publications, through presentations at physiology and biology education meetings, and within the Physiology Majors Interest Group (P-MIG). Finally, we share our recommendations and hopes for the next decade.

INTRODUCTION

The core of physiology expertise is the ability to use a finite set of principles, concepts, or models that are central to our discipline to make predictions and solve problems (27). When physiology educators are asked, “What do you want your students to know and be able to do?” the answer is rarely, “Have them name structures and their functions from memory.” Yet examination of introductory life science, physiology, and anatomy and physiology textbooks contains thousands of bits of information that implicitly signal to instructors and students that the latter is what is expected (5). There is broad consensus that undergraduate education should not merely be acquiring factual knowledge, but should allow students to build deep, conceptual understanding that allows them to apply their knowledge to analyze, synthesize, solve problems, and make decisions; they should develop and use higher level cognitive skills (2). Like Poincaré (30), physiologists understand that “a collection of facts is no more a science than a heap of stones is a house.” Physiology core concepts and conceptual frameworks can give students a scaffold to support and make sense of their accumulated facts as they build their understanding. These tools allow physiology faculty and departments to apply backward design (40) to courses and curricula and use the core concepts and elements of conceptual frameworks as explicit student learning outcomes. Many physiology faculty members engaged in the Physiology Majors Interest Group (P-MIG) have structured their teaching around core concepts and have used these to frame instruction and assessment within departments as well.

We were invited to reflect on the history and promise of the physiology core concepts as others in the Physiology Majors Interest Group share their data from collective P-MIG efforts to improve undergraduate physiology education (39). In this paper, we first review the work of different groups to identify and describe core concepts in physiology and related disciplines (biology and medicine) and to develop conceptual frameworks for these concepts. Second, we briefly describe the ongoing process that led to the development of the physiology core concepts and conceptual frameworks. Third, we discuss the need for assessment of core concepts that can be used for both formative and summative assessments (10) in courses, departments, and programs and the development and validation of a few assessment instruments for physiology, including the Homeostasis Concept Inventory (HCI) (18), the assessment for Measuring Achievement and Progress in Science for Physiology (Phys-MAPS) (33), and the Electrochemical Gradients Assessment Device (EGAD) (7). Finally, we consider how the existing tools—core concepts, conceptual frameworks and concept assessments (including concept inventories, a specific type of assessment instrument)—can and are being used in physiology courses and departments.

Core Concepts (a.k.a., Core Principles, General Models, Core Competencies, Big Ideas)

A core concept or “big idea” is an idea that is “well tested, validated, and absolutely central to the discipline” (12) (Table 1). Each core concept reflects many specific phenomena and has exceptionally broad explanatory scope (12). Wiggins and McTighe (40) described big ideas as “enduring understandings” that students would be able to use long after a particular course. We use the term “core concepts” to refer to those ideas, principles, and processes that (1) reflect expert reasoning; (2) are abstract and transferable, that is, they can be used to explain phenomena across a discipline or several disciplines; and (3) once understood will be applicable longer than most specific facts (20, 22, 26).

In the first decade of the 21st century, hundreds of life science instructors at undergraduate, graduate, and professional schools were engaged in discussions to identify and describe core concepts for life science higher education (2, 4, 19, 23). Vision and Change (2) outlined a consensus reached by hundreds of life science faculty that “five organizing themes [core concepts] describe lines of inquiry in modern biology”: evo-
Seven core competencies, that is, the skills and practices distinguished between five core concepts (a.k.a., big ideas) and principles that can provide an “organization model for biology storage, pathways and transformations of energy and matter, evolution, structure and function, information flow, exchange and storage, pathways and transformations of energy and matter, and systems. These are described as overarching biological principles that can provide an “organization model for biology education” (2). The Vision and Change report also distinguished between five core concepts (a.k.a., big ideas) and seven core competencies, that is, the skills and practices necessary to address complex biological issues. Scientific Foundations for Future Physicians (4) described the most important scientific competencies for entering and graduating medical students. These included skills as well as core scientific understandings. The American Society for Biochemistry and Molecular Biology identified a list of five foundational concepts central to biochemistry and molecular biology: evolution, matter and energy transformation, homeostasis, biological information, and macromolecular structure and function (36). For physiology education, the identification of core concepts began with Modell’s general models (27) that are physical, mechanical, or control principles common to physiology, physics, and/or engineering. For many physiology educators, this paper set the stage for teaching physiology from core concepts. The description of 15 core concepts for undergraduate physiology was done in this broader context (22).

Core concepts have been used successfully in program and curriculum design and assessment and in individual courses and activities. However, none of these efforts to identify core concepts were meant to encompass the entire breadth and depth of disciplinary knowledge. Nor were they meant to define the components of a course or a curriculum. They were meant to serve as a guide to help students build their understanding of critical, recurrent core concepts throughout their undergraduate studies. Unlike the Vision and Change and Scientific Foundations for Future Physicians reports, we did not determine nor recommend a concise set of core concepts for undergraduate physiology; rather we described 15 concepts physiology faculty considered critical to understand. This list of core concepts was not meant to be static or prescriptive. As we clarified in our published work on the core concepts for undergraduate physiology education, we expected that this list, along with the conceptual frameworks for some concepts (17, 20, 21), would be modified and changed by faculty to adapt and improve them to make them better tools for their students. Indeed, elsewhere we have considered and encouraged changes to the concepts we described in 2011.

Table 1. Definitions, terms, and examples for undergraduate physiology education

| Term                  | Definition                                                                                                                                                                                                 | Physiology Examples                                                                 |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Core concept          | A core concept is a big idea that is essential to the understanding and practice of a discipline, the mastery of which results in enduring understanding and ability to address novel problems across that discipline (21). | ● Cell-cell communication<br>● Cell membrane<br>● Flow down gradients (a.k.a. flux)<br>● Homeostasis<br>● Mass balance<br>● and 10 others (22) |
| Conceptual framework  | A conceptual framework is a hierarchical “unpacking” of a core concept into its constituent ideas, appropriate for a particular degree of mastery within a discipline. Conceptual frameworks for undergraduate physiology can be used in teaching and learning to develop and organize explanations using core concepts (17, 21). | ● Homeostasis conceptual framework (HCF) (17)<br>● Cell-cell communication conceptual framework (CCC CF) (20)<br>● Cell membrane conceptual framework (CM CF) (25) |
| Concept inventory     | A concept inventory is an assessment instrument (often multiple choice or multiple true/false) to gauge understanding and application of major concepts within a discipline, which is reliable and has been validated by experts in the discipline (10). | ● Homeostasis concept inventory (HCI) (18)<br>● Measuring achievement and progress in science in physiology (Phys-MAPS) (33) |
| Backward design       | Backward design is an outcome-oriented, learner-centered approach to teaching and learning that begins with a clear statement of learning outcomes followed by development or selection of assessments of those outcomes, and finally design of learning activities to facilitate student learning that is aligned with outcomes and assessments (10, 40). | Start with core concept (e.g., homeostasis). Identify a particular constituent idea for students to understand and apply (e.g., regulated variables require an active sensor, from the HCF). Choose assessment item(s) to probe student understanding and reveal common misconceptions (using the HCF). Design learning activities that allow students to demonstrate that variables without sensors are not homeostatically regulated, e.g., heart rate (28). |

A decade ago, we set out to identify and describe the concepts that a broad range of physiology instructors at community colleges, 4-yr colleges and universities, and professional schools considered to be important for undergraduate physiology. We referred to “core principles” in our earlier papers, but we now use the more widely used term, “core concepts.”

Our work to define core concepts of physiology began with an interested, engaged small group of six physiology faculty (Michael, Modell, McFarland, Cliff, Wenderoth, and Wright) who taught at diverse types of institutions. We shared a common goal to help students learn and develop more expertlike understanding and approach to solving problems in physiology. We all agreed that helping students build and refine mental models of the physiological process was a key step in helping students learn physiology (24). We believed that students should learn to apply mechanistic reasoning to describe physiological phenomena and predict outcomes from perturbations caused by behavior, injury, or disease (27). We also shared a dedication to student-centered active learning aligned to formative and summative assessments that could reveal students’ conceptual understanding.
Table 2. Two levels of the homeostasis conceptual framework include “critical components” and “constituent ideas”

| Critical Component | Constituent Ideas |
|--------------------|-------------------|
| H.3                | Homeostatic processes require a sensor inside the body. |
| H.3.1              | Sensors detect the regulated variable and respond by transducing that stimulus into a different signal. |
| H.3.2              | Sensors respond within a limited range of stimulus values. |
| H.3.3              | Sensors generate an output whose value is proportional to the magnitude of the input to the sensor. |
| H.3.4              | Sensors are constantly active. |
| H.3.5              | An organ system may employ a variety of types of sensors. |

Homeostasis was unpacked into a conceptual framework for undergraduate physiology that had two levels: “critical components” (e.g., H.3) and “constituent ideas” (e.g., H3.1). The five constituent ideas underlying critical component H.3 are shown (17). These are 6 of the 30 subideas in the homeostasis conceptual framework.

A process emerged from our work together that was intentionally based on our diversity. Our group included physiologists with different expertise in physiology, and we brought experience teaching different student populations at different types of institutions in both small and large class sizes. As we developed our products—the core concepts, conceptual frameworks, and the homeostasis concept inventory—we deliberately sought and received input from more than 100 physiology faculty across geographical regions, institution types, and other physiological disciplines. As we reported our progress, we successfully solicited physiology instructors to contribute to this work at annual or biannual national meetings, including American Physiological Society (APS), Human Anatomy & Physiology Society (HAPS), APS Institutes on Teaching and Learning (APS-ITL), Physiology Majors Interest Group (P-MIG), and Society for the Advancement of Biology Education Research (SABER) meetings. This inclusive community process helped to make our products robust and useful across the college and university landscape. Inclusion also meant that our products were not “set in stone”: they can and should be revisited as needed by a diverse group of physiology instructors. They were devised as guides or tools; they were not intended to be prescriptive but to be applied broadly across course and departmental contexts.

The work of the P-MIG operates with an inclusive spirit as well. The papers in this collection reflect this spirit of inclusion and have broad applicability across undergraduate physiology education, with contributions from community college, liberal arts institutions, and research universities.

Core concepts are big, abstract ideas. “Unpacking” these big ideas into smaller ideas is necessary to effectively use them to help students learn, assess higher level understanding, and map them within a course, curriculum, or program. We have unpacked four of the core concepts for undergraduate physiology, creating conceptual frameworks that systematically and hierarchically organize the subideas making up the core concept (Table 1). For example, the core concept of “homeostasis” was unpacked into five essential subideas or “critical components” (e.g., H.3: “Homeostatic processes require a sensor inside the body”), as illustrated in Table 2. Each critical component was unpacked into as many as eight hierarchically arranged constituent ideas (e.g., “Sensors are constantly active”). The five constituent ideas underlying one critical component (H.3) are shown in Table 2, which includes 30 subideas in the homeostasis conceptual framework. Four conceptual frameworks have been unpacked and vetted by several (typically 35–50) physiology faculty for flow down gradients or “flux” (21, 22), homeostasis (17), cell-cell communication (20), and cell membrane (25). We have also begun work on two additional core concepts, mass balance and structure/function. These conceptual frameworks allow faculty and students to analyze and apply elements of a core concept and synthesize the individual elements as they develop their conceptual understanding.

Flow down gradients, or “flux,” unpacks into a relatively simple conceptual framework (22), whereas homeostasis, cell-cell communication, and cell membrane result in more complex, hierarchically deep frameworks, as shown in Table 3. We recognize that the conceptual frameworks that we have unpacked overlap in important ways. For example, cell-cell communication is necessary for homeostasis. In many homeostatic systems, chemical messengers are released from cells (in cell-cell communication framework) and carry a signal to the effectors (homeostasis framework). Explicit recognition of these common features can improve student learning and instruction.

Conceptual Assessment in Courses and Departments

The recommended backward design approach to course, curriculum, and program development (40) calls for first determining what students should know and be able to do. Core concepts and conceptual frameworks can provide a set of goals or outcomes for this approach (Table 1). The second step in backward design is to devise and plan assessments (both formative and summative) that can allow instructors and learners to determine students’ progress toward the goal of conceptual understanding.

Concept inventories are reliable, calibrated, and diagnostic assessment tools that can be used to evaluate students’ development of expert-like understanding of specific concepts (1, 32, 34). Beginning with the Force Concept Inventory in physics (12) and later the Concept Inventory for Natural Selection in biology (3), these types of instruments have been used to 1) assess student understanding and application of core concepts (formative and summative); 2) reveal common, persistent misconceptions that interfere with progression to expert-like understanding; and 3) determine conceptual learning gains for particular learning activities, courses, or programs by comparing pre- and posttests. These validated assessment tools now exist for physiology courses and curricula, including EGAD (7), HCI (18), and Phys-MAPS (33). Although these assessment tools are not meant to be used to “grade” students, they can and should be used to assess the progress of student learning in a single course, a sequence of courses, or across an undergraduate physiology program. Phys-MAPS (33) contains

Table 3. Conceptual frameworks vary in size (number of sub-ideas) and number of hierarchical levels

| Conceptual Framework | No. of Subideas | No. of Levels |
|----------------------|----------------|--------------|
| Flow down gradients or flux | 20 | 3 |
| Homeostasis | 30 | 2 |
| Cell-cell communication | 51 | 4 |
| Cell membrane | 27 | 4 |

See Refs. 17, 20, 22, 25.
questions to assess several core concepts: flow down gradients (flux), mass balance, cell-cell communication, cell membrane, and homeostasis. However, this is best suited to assessment across a program, as it has not been shown to be able to measure learning gains in a single course. This instrument can be used to demonstrate changes as students move from lower division to upper division physiology courses.

Core concepts, conceptual frameworks, and concept inventories are helpful tools to guide learning and frame the design and assessment of learning activities, courses, and programs (Table 1). They are not meant to be prescriptive, nor are they intended to create a uniform or standardized curriculum or assessment. Indeed, it would not be best for learners to be asked to focus on all 15 core concepts in a single course, nor would it be possible to have a separate, active-learning activity to target every subidea within a complex conceptual framework (e.g., cell-cell communication). Also, instruments that assess conceptual understanding are not meant to be used in isolation or as high-stakes summative assessment. These instruments can help gauge student understanding in a course to help target learning activities and can help departments and programs track how students’ conceptual understanding develops from novice to more-expert-like through a series of courses or an entire program.

**Current Use of Core Concepts, Conceptual Frameworks, and Conceptual Assessments**

The core concepts, their conceptual frameworks, and conceptual assessments can be used by programs and departments, individual faculty, or group of faculty teaching specific courses, and by students to develop more expert-like understanding in the discipline, as summarized in Table 4. In previous papers, we have described possible ways that programs, departments, instructors, and students can use these tools—core concepts, conceptual frameworks and conceptual assessments—and we have built on this in Table 4 (17, 21). We did not anticipate some ways that this work would be used, especially creative student projects and activities (6, 15). On the other hand, we proposed possible applications of conceptual frameworks that we have not seen in use, e.g., leveraging the hierarchical structure of the frameworks to make relationships between subideas more explicit and to build student understanding.

Three of the papers in the P-MIG collection for *Advances in Physiology Education* report on the use of core concepts. Rogers et al. (31), “The 2019 P-MIG student survey and undergraduate perceptions of physiology programming,” shows that students are aware of core concepts in their physiology courses, that is, they identify core concepts in particular courses. Crosswhite and Anderson (8), “Physiology core concepts in the classroom: reflections from faculty,” summarizes how four physiology instructors use some of the physiology core concepts in their undergraduate courses. Their paper provides examples that demonstrate how different instructors frame their courses around different core concepts, and they use them in different ways. Stanescu, et al. (35) “Evaluation of core concepts of physiology in physiology curricula: results from faculty surveys,” describes how some departments have mapped core concepts in their curriculum and reveals reinforcement of core concepts that students will encounter in different courses. It is important to note that there are differences in the use of core concepts in different institutions. However, this paper suggests that the conceptual frameworks that are available for some of the physiology core concepts have not been used by faculty or departments. We continue to believe that these could be leveraged to map how subideas within a core concept are addressed in different courses within a curriculum. Also, the frameworks could be used by individual physiology faculty to explicitly assess student understanding of individual subideas that make up a core concept. Instructors report (8) that assessment of core concepts is not always explicit or consistent, perhaps because core concepts are big ideas that are difficult to assess with the usual test questions on an exam. However, the conceptual frameworks break them down into components or subideas that are easier to assess.

A growing number of publications demonstrate how physiology faculty used the core concepts in their teaching and influence what students are asked to know and be able to do. The “fictional animal” activity is an example of how a group of physiology faculty use the same exercise to help students address the core concept of “interdependence” or integration across systems within an organism (6). The core concept of flow down gradients or “flux” is addressed in classroom activities targeting flow of air in airways (16) and electrochemical gradients and ion fluxes (9). These three examples demonstrate the different types of activities that can be shared in the

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**Table 4. Applications of core concepts, conceptual frameworks, and concept inventories for teaching, learning, departmental course and curriculum design, and physiology education research**

| Tools Use by: | Examples |
|---------------|----------|
| **By departments to:** | - Inform and direct physiology course design. |
| - Frame curriculum design and reform to focus on particular core concepts (35, 38). |
| - Provide a hierarchical organizational structure for undergraduate physiology, with some constituent ideas addressed in higher level physiology courses. |
| **By faculty to:** | - Reveal connections between critical components (subideas) and bigger (constituent) ideas in the hierarchical structure of a conceptual framework that makes the relationships between these ideas explicit. |
| - Make explicit the tacit knowledge or underlying assumptions of experts (faculty) so that novices (students) can make sense of them and build a more transparent understanding. |
| - Focus active learning exercises on those ideas that are essential and difficult to master (6, 9). |
| - Constructively align students’ learning outcomes with their assessment. |
| - The choice of specific core concepts can alter the sequence of instruction and assessment of student learning (16, 37). |
| **By students to:** | - Explicitly apply particular core concepts to problems in formative and summative assessments (16). |
| - Use core concepts in concept maps of case studies where students identify specific core concepts to particular aspects of a complex problem (15). |
| - Recognize and reflect on the core concepts that they use in their physiology courses (31). |
| **By physiology education researchers to:** | - Refine student learning progressions for specific core concepts (flux) and general models (mass balance) to inform instructional choices and align assessment (11). |
| - Develop concept assessment courses and programs (7, 33). |

See McFarland et al. (17).
literature, and we urge more instructors to share their work through publication. The faculty voices in Crosswhite and Anderson (8) spoke directly to the need for examples of teaching with core concepts to help other physiology instructors adapt their instructional practice.

Integration of core concepts into teaching and curriculum design likely occur far more often in practice than they are reported in publications. Conference presentations are important ways that physiology educators can share their work integrating core concepts into their classes and programs. Talks, posters, and workshops at meetings demonstrate that physiology core concepts can shape course design, teaching, and assessment practices, and these examples are very helpful to the physiology education community. Some conference presentations will likely never be published in the peer-reviewed literature, so, for many instructors, this is the primary method that their work will be shared with others. For example, at the HAPS annual meeting in 2019, Luyster (15) and his students presented extremely detailed concept maps in which students explicitly connected physiology core concepts to reasoning about case studies. The students themselves talked about how this impacted their learning. In another workshop, instructors discussed how they might use core concepts to align course learning outcomes to student assessments, and how choice of specific core concepts can alter the sequence of instruction and assessment of student learning (37).

At the same meeting, Jennifer Doherty and colleagues (11) shared their undergraduate student learning progression for the core concept of “flux” or flow down gradients. Their learning progression reveals the types of ideas students use as they move from novice understanding of memorized “facts” toward the principle-based reasoning of experts. This work on how students learn core concept of flux (flow down gradients) and mass balance (22, 29) has been presented broadly at APS, HAPS, P-MIG, SABER, and other meetings. They have used their learning progressions to tailor instruction and to design assessment tools, like EGAD (7). This is an excellent example of how physiology core concepts and general models can drive our understanding of student learning and lead to changes in how we teach and assess students in physiology courses.

The discussion of physiology core concepts and their use has been central to the annual P-MIG meetings (38). Physiology core concepts are also a focus of presentations at HAPS, APS-ITL, SABER, and other meetings where physiology and biology education is discussed. The presence of P-MIG members at these meetings has engaged others in discussion of curricular guidelines for undergraduate physiology programs that address core concepts, professional skills, and advising. These P-MIG guidelines will be designed to be used in program development and assessment (14, 39), and meetings have been a useful venue for community input.

Conclusions and Recommendations

In the decade since the first publication of physiology core concepts (core principles), tools have been developed to help physiology students develop a deep understanding of the core concepts of our discipline. This work has been advanced by the Physiology Majors Interest Group, which has brought together physiology faculty who are dedicated to integrating core concepts, not only in their own teaching, but also within course sequences and academic departments. As the papers in this collection demonstrate, P-MIG has begun to assess the state of physiology departments and provide tools and guidance for future development at the program and department levels. APS has also been an advocate for focusing teaching and assessment on core concepts, and the APS ITL has featured many sessions on physiology core concepts with the help of several P-MIG contributors and other physiology instructors.

Our discussions with physiology faculty interested in core concepts echo those in Crosswhite and Anderson (8) and ask for more explicit, detailed examples of teaching with core concepts in the classroom. We recommend and encourage faculty who use core concepts, conceptual frameworks, or conceptual assessment in their classrooms to share their practices and their materials. Presentations, including posters, talks, and workshops, at regional and national meetings, help reach other physiology faculty, and presenters receive valuable feedback to improve activities and assessments (11, 15, 37).

Publication of concept-focused activities and tools is also essential and can include papers in Advances in Physiology Education (6, 9, 28), the HAPS Educator (16), Course Source, American Biology Teacher, and other journals that instructors read to use, adapt, and build on the work of colleagues to improve their teaching and help their students. Finally, activities and materials can be submitted to existing online platforms that make vetted and tagged instructional materials available to others; these include the National Center for Case Study Teaching in Science (sciencecases.lib.buffalo.edu) and the Life Science Teaching Resource Community (https://www.lifescitrc.org/).

We are encouraged that the core concepts for undergraduate physiology education described in 2011 continue to help physiologists in their courses and in their departments. Members for the P-MIG community have been particularly successful in applying these concepts to their teaching practices and curriculum assessment (8, 31). However, we recognize that the conceptual frameworks, in particular, are underutilized and recommend their use to help faculty focus instruction on particular subideas within a core concept and align assessment to instruction. We also hope to see more widespread use of the existing assessments, including the HCI, Phys-Maps, EGAD, and others being developed (7, 18, 33). Finally, we appreciate that these descriptions provided in 2011 are not static and may be revised by physiology instructors over time, and we are in the process of revisiting and revising these ourselves. We anticipate that the dedicated and talented physiology education community will continue to use and adapt the core concepts in productive and unexpected ways in the next decade, that P-MIG will continue to support their efforts, and that physiology students will benefit from their creative work.

This paper is published as part of a special collection/special issue from P-MIG, a grassroots organization that has formed to help develop international programmatic guidelines for undergraduate degrees in the discipline and to serve those engaged in undergraduate physiology or physiology-related programs. To find out more about this collective, or get involved, please visit our website (https://www.physiologymajors.org/) and consider joining our list serv.
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DISCLOSURES

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AUTHOR CONTRIBUTIONS

J.L.M. and J.M. drafted manuscript; J.L.M. and J.M. edited and revised manuscript; J.L.M. and J.M. approved final version of manuscript.

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