HOW WE TEACH | Generalizable Education Research

Structure-function relations in physiology education: Where’s the mechanism?

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Lira ME, Gardner SM. Structure-function relations in physiology education: Where’s the mechanism? Adv Physiol Educ 41: 270–278, 2017; doi:10.1152/advan.00175.2016.—Physiology demands systems thinking; reasoning within and between levels of biological organization and across different organ systems. Many physiological mechanisms explain how structures and their properties interact at one level of organization to produce emergent functions at a higher level of organization. Current physiology principles, such as structure-function relations, selectively neglect mechanisms by not mentioning this term explicitly. We explored how students characterized mechanisms and functions to shed light on how students make sense of these terms. Students characterized mechanisms as 1) processes that occur at levels of organization lower than that of functions; and 2) as detailed events occurring at a lower level of organization and multiple definitions. We interpret these results as evidence that students see mechanisms as holding a more narrow definition than used in the biological sciences, and that students struggle to coordinate and distinguish mechanisms from functions due to cognitive processes germane to learning in many domains. We offer the instructional suggestion that we scaffold student learning by affording students opportunities to relate and also distinguish between these terms so central to understanding physiology.

systems thinking; structure-function; mechanism; causation; instructional scaffolds; mechanistic reasoning

THE SCIENCE OF PHYSIOLOGY demands systems thinking. To illustrate this point, consider learning about pathological conditions such as genetic disorders. Students must connect subcellular concepts from genetics and molecular biology to cellular biology and organismal physiology. They must do so because many diseases involve chromosomal abnormalities, but these abnormalities create downstream effects at the tissue and organ level. Together, these adverse effects at multiple levels lead to morbidity. Yet the critical value of developing students’ systems thinking extends beyond pathological conditions. For students to develop a comprehensive understanding of vital processes such as oxygen homeostasis, they must learn about the role and function of entities from multiple organ systems in the body. Examples include learning about large-scale elements, such as the location and features of oxygen sensors, central nervous system integrating centers, and motor output pathways, as well as cellular and subcellular elements and processes, such as electrochemical signaling in neurons, muscle contraction in sarcomeres, and the gas exchange facilitated, in part, by red blood cells. Disease in any of the cell types and tissues involved could be responsible for negative consequences to an organism’s oxygen homeostasis. Therefore, understanding relations between basic mechanisms, such as those responsible for oxygen homeostasis, position students to understand the body as an integrated system. If students fail to learn how systems relate to each other, they will fail to develop an understanding of physiology. By developing students’ systems thinking, students become better prepared to reason through difficult problems and explain unexpected physiological phenomena.

Many biologists see reasoning about interactions between multiple systems and across multiple levels of organization as playing a critical role in future discoveries. Some scholars who work in integrative biology argue that better links between research and education could promote more creative thinking in learning environments (32). Such creative thinking could drive cutting-edge science and confer later societal benefits according to this line of thought. Although biologists who seek an integrative approach do not share a single definition for integrative biology, we share many of Wake’s (32) ideas because of her emphasis on working “across levels of biological organization and across time [scales] short (ecological or physiological) and long (evolutionary).” Her emphasis on levels of organization resonates with us because it connects to the more trodden educational research area on students’ systems thinking (11).

Similar to the term integrative biology, no single definition captures the composite skill set called systems thinking. For our purposes here in physiology, we construe systems thinking as a general cognitive disposition toward predicting and explaining phenomena by reasoning within and between levels of biological organization and across organ system components. This definition places the concepts of mechanism and scale at its core. In regards to mechanisms, we refer to mechanistic reasoning as a component of systems thinking. Borrowing ideas from several authors (23, 31, 33), we define mechanistic reasoning as a cognitive strategy that involves utilizing knowledge about relevant entities and their properties and interactions occurring at a lower level of organization to predict and explain emergent properties at a higher level of organization.

Returning to our example of oxygen homeostasis, notice that students must coordinate knowledge of different scales. By scale, we refer to the idea of a ratio within a common measurement system (e.g., metric). We note measurement and ratio to clarify our formal disciplinary framing of scale. For characterizing biological entities in physiology, however, we note further that a general distinction between, say, cells and tissues often suffices. When students learn about macroscopic pro-
cesses, such as breathing, they must relate that knowledge with other macroscopic (lungs), microscopic (neurons), and submicroscopic entities (molecular oxygen and carbon dioxide). Moreover, students must reason about interactions that occur within and between the entities that exist across multiple scales because these multilevel interactions together produce the cascade of signaling events and feedback loops that lead to the emergent phenomenon of regulated breathing.

Coordinating such knowledge about mechanism and scale presents challenges to students and can hinder the development of their systems thinking. Students bring into the classroom rich experiences with macroscopic entities. One teaching and learning challenge common to physiology and other disciplines involves the process of coordinating physical properties with their appropriate level of organization. For instance, we observe color as a macroscopic (i.e., visible) property of a physical substance. It would, however, be inappropriate to map the property of color onto submicroscopic entities, such as atoms. Students nevertheless make such inappropriate mappings across a variety of science disciplines (for a developmental perspective on why this is so, see Ref. 30). Students also commit similar errors in the biological sciences (13, 25).

In biology education, such challenges have motivated concerned instructors to modify their instruction to better support student learning. For instance, when describing structures and processes in oxygen homeostasis we can deliberately use the terms “ventilation” and “ventilation rate” to distinguish cellular respiration from the organismic process of moving environmental air to and from the gas exchange membrane through breathing (8).

The learning challenges associated with coordinating spatial scales continue with temporal scales. In physiology, instructors (18) and textbooks (9) consider how mechanisms operate to support the physiological functioning of an organism. Yet instructors and textbooks also seek to explain why organismic adaptations make sense over longer evolutionary time scales. Mayr (17) characterized this temporal distinction as proximate as opposed to ultimate causation. Proximate causation refers to the factors and processes responsible for the immediate life or death of the organism. The idea refers to how an event happens; it often involves physicochemical interactions. In contrast, ultimate causation refers to the factors responsible for the survival of groups of organisms with shared characteristics. The idea refers to why an event happened; it often involves a historical narrative. Students struggle to coordinate the two time scales for explaining causation. When students are asked to explain how a biological event occurs, they often answer the question as if it asked why (28). For instance, when asked how birds form a flying-V, they explain why birds do so by suggesting their need to survive and reproduce as opposed to the mechanics of lift and their sensory detection of drag. Thus, despite receiving instruction targeted at developing students’ capacity to answer “how” questions with proximate causality, many students struggle to reason about physical mechanisms.

Scaffolding students’ systems thinking and mechanistic reasoning in physiology demands principled instruction based on both the knowledge of the discipline and how students learn. The principle of structure-function (S-F) relations provides one such example. Biology instructors have leveraged this principle for many years. As a testament to its perceived value, this principle manifests itself in several standards (e.g., Ref. 20).

Moreover, when a national sample of biologists was surveyed, they agreed independently that S-F relations figure prominently as a big idea that undergraduate students should learn (1). This big idea does not just represent a critical principle for understanding biology. Memory research demonstrates that people in general remember more items on a list (e.g., scissors, paper, and so forth) if they encode the items as holding a functional relationship (e.g., the scissors cut the paper) (2). It should be little surprise that more expert persons encode knowledge in their domain of expertise by organizing knowledge into meaningful chunks of functional relations rather than a laundry list of facts (3). Moreover, scaffolding student learning with function-focused instruction enhances student performance in physiology specifically (14).

Despite this support for the learning of biology and in general, we see a limitation to placing an emphasis simply on S-F relations. In specific terms, the principle does not mention mechanisms explicitly. To be fair, other principles treat the idea in various ways. For instance, principles regarding the transformation of matter and energy highlight mechanisms (34). We contend, however, that by not being explicit and placing mechanisms in direct relation to structures and functions, we may place undue learning challenges on our students.

For instance, when students solve algebra word problems, they struggle to coordinate variables in the equation with their referent in the problem description (15). In such instances, students suggest that one variable refers to many different ideas when it, in fact, refers to only one. In physics, students characterize motion as being “fast” or “slow,” but periodic motion (e.g., pendulums) possesses both frequency and velocity. In such cases, students struggle to identify whether fast means high frequency or high velocity (21). In chemistry, students conflate atoms and ions, despite these terms holding important distinctions related to chemical reactivity (5). At present, we do not know how students distinguish functions from mechanisms.

Coordinating knowledge, although challenging, is germane to learning. Students need opportunities to coordinate and distinguish between different meanings of related ideas. We think that students should relate and also distinguish between the ideas of mechanism and function specifically. During our conversations around this point, we consulted textbooks (e.g., Ref. 19) and observed physiologists characterizing the discipline as a science concerned with understanding “how animals work” and understanding “processes that effect animal function” (see, pg. 4). The former definition strikes us as resting squarely on mechanism, whereas the latter incorporates yet another term, “processes,” and does not distinguish function from mechanism. Students benefit from direct comparisons (16, 29). If underlying mechanisms support higher-order, emergent functions, then students should be taught this explicitly. As noted above, when engaged in systems thinking, we observe students fail victim to “slippage,” whereby students fail to map system properties across levels of organization (33).

One strategy for mitigating these challenges, involves leveraging the Structure-Behaviors-Functions (SBF) framework (see Ref. 10 for an elaborate discussion of the framework). The SBF framework provides a useful representation capable of resolving the limitations of the S-F principle. First, it continues to leverage the affordances of reasoning about functions and the structures that support them. Second, it incorporates be-
behaviors as a bridge that connects structures to functions. Functions refer to the “why” of a system. Behaviors here correspond to mechanisms and, therefore, the “how” of a system. Last, structures refer to the entities or parts and thus specify the “what” of a system. The SBF framework, therefore, distinguishes between mechanisms and functions, but it also builds a logical relation between the three concepts. Distinguishing between concepts can support student learning, but only if students maintain knowledge of the relations between concepts. The SBF framework specifies an asymmetric syntax that relates structures to functions via mechanisms of action (see Fig. 1).

We wish to explore how the SBF framework might provide a lens for understanding student learning. We motivate the value of this aim by noting that the S-F principle may not represent the dynamic nature of physiological systems well. In this paper, we cannot resolve this matter, but we call attention to it because the principle does not specify in explicit terms whether functions refer to physical processes and interactions or simply the consequence of these processes and interactions that lead to a healthy normal organism, as is stated in common discourse. We have stressed the importance of mechanisms because they involve spatio-dynamic interactions between physical structures. By not distinguishing mechanisms from functions, we may fail to support students’ systems thinking.

To explore the full potential of the SBF framework, we must first understand what relevant knowledge students bring to our learning environments. Without this insight, we cannot begin to evaluate the usefulness of either conceptual framing (S-F or SBF). The results we present here were part of a larger project on identifying scaffolds for teaching in physiology. Here, we will explore a sample of this data corpus to investigate how students characterize structures, mechanisms, and functions in the context of physiology.

![Fig. 1. Relations between structures, mechanisms, and functions. The SBF framework calls attention to the idea that mechanisms (behaviors) and functions differ from one another. At the same time, it also constructs relations between the terms to support a meaningful understanding: a specific structure supports a specific mechanism of action that supports a specific biological function. In the example in the figure, neurons reflect structures residing at the cellular level. The ionic mechanism of depolarization occurs at the molecular level, whereas the communicative function occurs at the multicellular level. The framework, therefore, affords a causal or asymmetric syntax that in this case reads, “Neurons depolarize to support communication.”](image)

1 Note that “behavior” does not refer to how organisms learn and interact with others and their environment (i.e., ethology). It more broadly describes physical mechanisms.

### MATERIALS AND METHODS

#### Student Population

We recruited 10 undergraduate students who were enrolled in a course titled Principles of Physiology, an animal physiology course. Students participated during weeks 4–8. These weeks corresponded to the weeks after their first exam and before their second exam. Their first exam covered neurophysiology and basic concepts of homeostasis. Their second exam covered the cardiovascular system. This 300-level course consisted primarily of juniors and seniors. All students who participated self-identified as seniors and had declared an area of the biological sciences as their intended major. All students had completed a sequence of introductory biology, general chemistry, organic chemistry, and cell biology per course requirements. The course itself emphasized the cellular and molecular mechanisms that underlie anatomical and physiological adaptations. A laboratory portion of the course was designed, in part, to reinforce concepts introduced in lecture. This course and this research occurred at a large, research-intensive, Midwestern university.

#### Interviewing Procedure

All interviews were audio and video recorded under an Institutional Review Board-approved protocol (no. 1510016662). Students were first consented and briefed about the study. After completing the interview, students were debriefed, compensated 20 (US dollars), and dismissed.

A single interviewer (MEL) conducted a semistructured interview consisting of four primary interview questions designed for comparative analysis. All students were asked, in order, to describe what “comes to mind” when they hear the words 1) “structure,” 2) “process,” 3) “mechanism,” and 4) “function,” in the context of physiology. Students were asked to answer the question for each word before the interviewer proceeded to ask the student the same question for the subsequent word.

We added the word, “process,” on both theoretical and empirical grounds. First, extant models of student knowledge posit that students do not always enter research studies (or classrooms) with coherent and stable understandings of science concepts (26). This means that a student might possess, say, declarative knowledge but fail to provide evidence of that knowledge because the framing of interview questions and the question’s inclusion of disciplinary jargon. Therefore, any given prompt that uses a given science term may not offer valid insight into student content knowledge. We sought to address this potential problem in a different, earlier pilot study, and we found that students interpreted the terms “structure” and “function” in ways that did offer insight into their knowledge. In contrast, students defined “mechanism” as a general process or operation (i.e., an event) that could not be distinguished from the term “function.” We redesigned our interview to afford students the opportunity to distinguish between mechanisms and general processes by adding the process question.

The interview was semistructured to permit disambiguation. For instance, if a student indicated that process and mechanism were similar or the same, the interviewer would respond, “It sounds like for you process and mechanism mean very similar things. Is that correct or do you mean something else?” This interviewing technique, therefore, permits the online testing of an interviewer’s hypotheses relevant to the study’s aims (see Ref. 12 for a detailed methodological description). The interview’s design, therefore, afforded students the opportunity to reflect on the differences between the four terms and in this way strengthened our analytic capacity to identify meaningful differences in students’ characterizations as opposed to mere semantics.

#### Qualitative Analyses

Our first step involved transforming the audio into transcripts. For our purpose here, we will rely only on students’ talk. This means that we...
excluded prosody (i.e., changes in vocal pitch) and other co-speech phenomenas, such as gestures, facial expressions, and posturing. Therefore, we only analyzed the final transcripts produced from the audio files.

From these same data obtained from this same study, we completed two different analyses. In the first, we applied biological levels of organization to categorize students’ statements. In the second, we allowed data-driven themes to emerge through a constant comparative method (7). We describe these two processes in turn next.

**Levels of organization.** Our initial analytic approach involved a top-down process that began with the design of the protocol itself. Because our broader aims included using the SBF framework as a lens for assessing student knowledge and identifying instructional scaffolds in physiology, we began by simply asking students what these terms meant to them. This means that, during analysis, we used these interview questions as a first step to segment the transcripts to identify patterns across the four questions.

We began the analysis with structures and leveraged a levels-of-organization scheme to code the transcripts. Although we characterize our analysis as top down, we decided to use this scheme because we noticed that many students mentioned different biological entities (e.g., cells) that varied in scale. To capture these varieties of characterizations, we leveraged a constant comparative method (7), whereby we identified all relevant statements and then contrasted all of the students’ statements about structures to refine the scheme and eliminate redundancies or detect failures in systematic inclusion. For instance, if a hypothetical student, Anne, says, “Structures make me think of anatomy,” we might first conclude that the student refers to the organ level (e.g., liver, heart, brain). Another student, Bill, could state that, “Structures are things like brains.” Still another student, Chuck, could suggest that, “Structures refer to cells and the cytosol.” Our process would lead us to conclude that Bill sees structures at the organ level, whereas Chuck sees structures at both the cellular and the subcellular levels. In contrast, Anne would be dropped and categorized as “not specified” because she does not state explicitly what “anatomy” means in terms of levels of organization. Anne could be referring to organs like Bill, but she could also be thinking of histology at the tissue level. From these hypothetical data above, we would not know.

On coding each of the four questions for each of the 10 students, we then assigned numerals to each of the levels of organization. These numerals were applied to each question for each student. Several students mentioned more than one level of organization (see Table 1). In these cases, students’ statements were averaged. Thus, if a student mentions “cells” (a score of 3), and “molecules” (a score of 1), she receives an average score of 2 (“subcellular” in our scheme). Note that mentioning “cells” two or more times would not drive up the average in this case, because we did not weight our scoring. We did not see this as fitting the data or our analytic goals because students often simply repeat themselves (e.g., “Yeah, cells. I think of cells, not molecules, but cells.”) This means that, for any given score, students could have mentioned one or many levels to receive that score. Because instances of students mentioning wide varieties of levels within a category were few (and confined to structures primarily) and because in these instances students did not place an emphasis on one level of organization over the other, we report the averages.

Note that the numerals (0–7), however, do not correspond to an interval or ratio scale (i.e., the coding scheme includes a hierarchy, but one that does not relate to the metric system). Instead, we characterized student knowledge with an ordinal scheme. Note that these codes reflect increasing levels of organization from 0 to 7, thus permitting us to report means. We employed this technique because we did not explicitly ask students to specify precise orders of magnitude, and no students did so spontaneously, given the nature of our questions. Last, note that these results do not provide evidence of more or less accurate conceptual understandings for our students. The results reflect the different varieties of characterizations made by students.

We repeated these analytic procedures for behaviors and then functions. We concluded with a final pass across all three categories to make a final check for redundancies or exclusions. We decided to include multiple levels of organization when a student mentioned them, because this strategy stayed closer to describing, as opposed to interpreting, the data. On reviewing the entire data corpus, we found that students specified levels of organization that ranged from atoms to environments. Because much of our modern understanding of physiology builds on our targeting the appropriate level of organization for investigation, we used biology’s nested hierarchy to develop a coding scheme for categorizing students’ utterances. By “nested,” we refer to the idea that groups consist of organisms, organs consist of tissues, tissues of cells, and molecules of atoms (24). We capped our coding scheme to include molecular through organismic levels.

**How students characterize mechanisms and functions.** This second analysis followed a procedure similar to that described in the above section. Our design of the interview itself again guided how we segmented the data. Recall that we presented all of the terms (structures, processes, mechanisms, and functions) for students to have the opportunity to reflect on their differences. On completing our axial (i.e., first open) rounds of coding (7), we determined that the levels-of-organization scheme captured students’ characterizations of structures. We further determined that, to identify how students characterized mechanisms, we needed to contrast their characterizations of both processes and mechanisms to see how they differed. These decisions led to constant comparative method that aimed to detect differences in how students characterize mechanisms and functions. As a result, we will report on how students characterize these terms and how students’ characterizations of these two terms differ.

**RESULTS AND DISCUSSION**

**Levels of Organization**

Systems thinking demands reasoning about physical mechanisms. In physiology and other STEM (Science, Technology, Engineering, and Mathematics) fields, this involves coordinat-

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Structures</th>
<th>Mechanisms</th>
<th>Functions</th>
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<tbody>
<tr>
<td>1</td>
<td>Organ</td>
<td>Molecule</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Tissue/Organ</td>
<td>Molecule/Sub/Cell/Organ</td>
<td>Molecule/Sub/Cell/Organ</td>
</tr>
<tr>
<td>3</td>
<td>Cell/Organ/Organism</td>
<td>Molecule/Sub/Cell/Organ</td>
<td>Molecule/Sub/Cell/Organ</td>
</tr>
<tr>
<td>4</td>
<td>Subcell/Cell</td>
<td>Molecule/Sub/Cell/Organ</td>
<td>Molecule/Sub/Cell/Organ</td>
</tr>
<tr>
<td>5</td>
<td>Subcell/Subcell</td>
<td>Molecule/Sub/Cell/Organ</td>
<td>Molecule/Sub/Cell/Organ</td>
</tr>
<tr>
<td>6</td>
<td>Cell</td>
<td>Molecule</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Molecule/Sub/Cell/Organ</td>
<td>Molecule/Sub/Cell/Organ</td>
<td>Molecule/Sub/Cell/Organ</td>
</tr>
<tr>
<td>8</td>
<td>Subcell/Subcell</td>
<td>Molecule/Sub/Cell/Organ</td>
<td>Molecule/Sub/Cell/Organ</td>
</tr>
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</table>

Raw data made available to complement the average scores that do not show the multiple levels of organization that students specified.
ing knowledge about how physical structures and their properties follow “rules” or patterns of interaction that lead to emergent phenomena or properties at a different level of organization (33). We, therefore, began our investigation with a general interest in improving our knowledge about how students characterize mechanisms. We undertook this effort by asking how students defined structures, mechanisms, and functions prior to receiving any formal, explicit instruction. In this way, we aimed to gain insight into how students characterized these terms in the context of physiology and how mechanisms figured as distinct ideas. The results indicate that students characterize “structures” as referring to relatively higher levels of organizations (e.g., cells or organs), whereas “mechanisms” refer to lower levels of organization (e.g., molecules). Students appear to characterize “functions” as referring to any level of organization (see Fig. 2).

To clarify how we assigned students to particular levels, consider Monica (pseudonym). Monica suggests that “structures” make her think of “everything.” Thus she indicates that structures can refer to multiple levels of organization.

Interviewer: When I say the word structure to you, what comes to mind?

Monica: In physiology I think of everything. I think of the organisms. I think of all the organs that [they] are comprised of. I think of the brain. I mean that is more like macrostructure of a larger scale. I also think of more like on a molecular scale. The cells, the basic functional unit of life. How cells interact with one another and function. All of the chemical and the physical processes of life and interacting with the environment outside externally and internally.

Notice that Monica suggests that the “basic functional unit of life” is the cell. In addition to the cellular level, she points out that, for life to function, “chemical and physical processes” interact with the “environment outside.” Thus Monica points to the atomic level when she states “chemical,” and to the ecological level when she states “environmental.” We bounded our analysis at the molecular and organismic ends because we focused on physiology and because multilevel inclusion by students to the extent that Monica displays appeared rarely in the data set (i.e., 2 of 10 students).

Some students failed to be as explicit as Monica. One student did not specify any level of organization in relation to any terms; she is excluded from this first analysis. One other student did not do so in relation to function. Thus she remains “unspecified.” But with the exception of one additional (different) student, all students expressed a level of organization spontaneously when characterizing “structures,” “mechanisms,” and “functions.”

Yet, as Monica’s excerpt above might indicate, students said much more. Although the levels of organization coding scheme provided us with an initial insight into the variety of ways that students characterize structures, our analysis made us recognize the selective limitation we placed upon “mechanism” and “function”: students could easily specify a concrete biological structure, such as a cell, and this verbal behavior fit the coding scheme well. More abstract characterizations, such as Monica’s, however, were lost when using this scheme. We, therefore, sought to develop a new scheme not based on already sanctioned categories, but on how students themselves characterized these terms.

**How Students Characterize Mechanisms and Functions**

We aimed to improve our understanding of how students, in their own terms, make sense of physiology. Our protocol allowed us to make this assessment by observing how students characterized mechanisms when they “walk in the door” (i.e., before explicit instruction that defines these terms for students). To complete this assessment, we used a bottom-up analysis to identify themes across students’ characterizations. By making this assessment, we positioned ourselves to better understand how we might design learning environments that leverage student resources toward improved understanding of physiological systems and mechanisms when learning in undergraduate physiology courses.

Of utmost importance was the opportunity to distinguish first between processes and mechanisms. We illustrate below that students characterize mechanisms as processes but with “more steps” and “more detail.” In addition to this finding, we observed a general trend whereby students either characterized mechanism as possessing “more detail” or else they specified one example of a mechanism (e.g., “I think of the Kreb’s cycle”). Last, this second analysis echoed the results of the first in that we observe a similar pattern: after converging on only two varieties of characterizations of mechanisms, students diverge to produce three unsystematic varieties of characterizations of functions (see Fig. 3).

To clarify how we assigned students to particular categories, consider Cindy’s (pseudonym) response when asked to describe “processes.” Cindy first indicates that processes refer to a “physiological thing that is going on.” Thus she construes a process as an event. She then continues to define the term by example when she states explicitly that, an “enzyme pathway” is an example of a process.

Interviewer: When I say the word process, what does that mean to you?
Cindy continues to draw distinctions between terms when she is asked what function means to her. Here she indicates that a function holds a purpose.

Interviewer: When I say the word function, what does that mean to you?
Cindy: That means what the process or mechanism is meant to carry out in that structure. So what is the purpose of it?

Cindy characterizes a function in physiology as holding a “purpose,” and thus her statement is categorized as Purpose. In contrast, other students stated that functions were similar to processes, or mechanisms, or both. In such cases, students described a function as akin to a machine operating (e.g., “everything is functioning OK”) or as in producing a needed output (e.g., “the function is to produce something, like ATP”).

Students who made these statements were categorized as Process or Product, respectively.

Note that we did not ask students to further describe terms such as enzyme pathway when they were used. Therefore, we again emphasize that data such as these do not provide evidence of more or less accurate conceptual understandings in physiology. Instead, they provide a context for assessing how students, when afforded the opportunity, distinguish between constructs within the SBF framework. In this way, the results illustrate that students (3 of 10) sometimes fail to articulate a distinction between mechanisms and general processes, and that students who both do and do not distinguish between these two terms demonstrate a variety of unsystematic understandings of physiological functions. In summary, these results suggest that students do not share one uniform understanding of mechanisms or functions in physiology. This finding holds potential for the design of learning environments in physiology.

Conclusions

Physiology is a science marked by the study of S-F relations. These relations exist within and between levels of biological organization. Physical mechanisms mediate these relations by providing a material explanation for how physical structures interact to support biological function. Learning in physiology, therefore, demands systems thinking in that students must learn to explain and predict physiological phenomena (e.g., ventilation) by reasoning about biological structures, their properties, and the interactions that occur across various levels of biological organization and between different organ systems.

We leveraged the Structures-Behaviors-Functions (SBF) framework in an effort to improve our knowledge of how students characterize mechanisms and functions in physiology. The SBF framework will not resolve all of the many challenges of teaching and learning in physiology. Moreover, it need not

<table>
<thead>
<tr>
<th>Table 2. Qualitative codes describing students’ characterizations of mechanisms and functions</th>
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<tbody>
<tr>
<td><strong>Mechanisms</strong></td>
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<tr>
<td>Whole</td>
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<td>Part</td>
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replace the principle of S-F relations. Instead, we suggest that
the SBF framework holds potential value for instructors who
aim to develop more advanced mechanistic reasoning in their
students. We selected this framework because it links struc-
tures to functions via explicit physical mechanisms and be-
cause juxtaposing mechanisms and functions might make their
semantic distinctions more salient to students. Understanding
how students coordinate the two terms could provide insight
into instructional techniques for scaffolding students’ mecha-
nistic reasoning, a component of systems thinking. The SBF
framework assisted us by providing a guidepost for both
designing an interview protocol and leveraging an analytic
framework for capturing the varieties of students’ character-
izations of mechanisms and functions.

Our design enabled us to determine that students’ charac-
terize structures, mechanisms, and functions as referring to
different levels of organization. More specific, students see
“structures” as referring to more macroscopic entities and
“mechanisms” as referring to more microscopic entities. In
contrast, students characterized “functions” with greater vari-
ability. We see at minimum two mutually supportive explana-
tions for this first finding. Our first explanation involves little
theorizing: students with nearly 4 yr of undergraduate training
in the sciences learned that many sciences decompose systems
into their components when they attempt to predict and explain
phenomena (c.f., Ref. 4). Most often, such analysis moves from
larger levels of organization (e.g., organs) to smaller ones (e.g.,
cells). This explanation suggests that student learning more or
less reflects a positive outcome of instruction.

To continue with this explanation for the first finding, note
that students associated the word “mechanism” with chemistry
and, more specific, organic chemistry. We see evidence in
favor of this explanation for some students. In certain in-
stances, students referred to “reaction mechanisms,” or “chem-
ical reactions,” when characterizing the term mechanism. Our
experiences in organic chemistry, as well as our conversations
with colleagues, suggest that organic chemistry provides a
primary context for learning what the word mechanism means.
This explanation suggests not so much a positive learning
outcome, so much as a potential leverage point for physiology
instruction: instructors who wish to develop students’ mecha-
nistic reasoning may remind students that they learned the
word in organic chemistry and that they should attempt to
accommodate new levels of organization into their understand-
ing of this term. Furthermore, in organic chemistry, mechanism
retains a specific meaning that will likely need to expand for
students, if students aim to learn about cellular mechanisms
and beyond.

Both the first (top down, levels of organization) and the
second (bottom up, student characterizations) analyses revealed
increased variability in how students’ characterized the term
“functions.” For this second result, our explanation involves a
greater degree of theorizing. We noted above that students do
not possess stable understandings of science concepts (26). We
believe that cognitive models of conceptual dynamics might
explain why students generated wider varieties of understand-
ings of the term “function.” Recall that students were asked to
define the term at the end of the task. At this point, students had
exhausted their definitions for “processes” and “mechanisms.”
Moreover, from our pilot data, we knew that students struggled
to distinguish between mechanisms and processes more gen-
erally. By adding the term “function,” we asked student to
distinguish yet another term. Students did not have a stable
definition for this term. As a consequence, students may have
been assembling new knowledge on the spot. Because the
students were not recalling already learned declarative knowl-
dge, they generated more noise.

By both explanatory accounts, these results suggest that, if
instructors wish to use the SBF framework to inform the design
of learning environments in physiology, they must attend
carefully to how students think about mechanisms and func-
tions. We contend that one important lesson for physiology
educators includes attending to literature around conceptual
change and intuitive reasoning from the cognitive and learning
sciences. We note that learning theorists do not agree on how
to characterize student knowledge. Important to the interpre-
tation of our results, some scholars characterize student knowl-
edge as stable and theory-like (6), whereas others view student
knowledge as dynamic (27). We adopted the latter view to
interpret patterns in our data, but this study did not test these
extent theories. Instead, we explored the SBF framework on
the grounds that it could support student thinking and learning.
Past studies in physiology education used related but alterna-
tive frameworks to explore student reasoning. Such studies
echo our findings by illustrating that students do conflate
“how” and “why” questions, but that, when afforded the
opportunity to learn, students rebound to distinguish between
these question types. Studies such as this point to the role that
instruction plays producing and remediating less productive
reasoning in students.

Thus one practical implication is that instructors might create
variable reasoning in students. For instance, biology students
receive instruction on proximate and ultimate mechanisms. As a
consequence, students sometimes misuse ultimate reasoning (i.e.,
evolutionary narratives) when assessment tasks demand prox-
imate reasoning about physical mechanisms (28). To learn to use
knowledge more systematically, students need opportunities to
learn by comparing the different explanation types (22).

For these reasons, instructors could respond to these learning
challenges by designing opportunities for students to reflect
iteratively across the semester. When instructors deem partic-
ular distinctions critical to achieving learning goals, learning
tasks, as well as assessments, could demand that students
distinguish between terms explicitly. Important to this point,
such comparison should be produced in parallel and not in
sequence. For instance, students might write out full sen-
tences that distinguish between cellular respiration and
ventilation. This learning task could be completed on a
worksheet that has the two (or more) terms in parallel
columns—as opposed to the traditional numbered se-
quence—along the portrait view of the paper. Instructions
might provide explicit directions that instruct students to
compare how the terms differ from one another. This design
principle originates from the cognitive science research on
learning through comparison (16, 29). Side-by-side compar-
isons with explicit directions improve encoding of similar-
ities and differences better than comparisons made in se-
quence, because many people fail to make explicit compar-
isons in such conditions.

We intended for this brief study to address an important gap
in undergraduate physiology education research. We did not
know of any study that attempted to capture the varieties of
students’ characterization of mechanisms in the abstract in physiology, although many exist in detail. Past investigations leveraged the SBF framework to design interview protocols, assessments, and learning environments on the whole (10). These studies provided evidence of the utility of the SBF framework in teaching and learning. Yet undergraduate students should be making conceptual frameworks explicit. We, therefore, thought to ask them to characterize the SBF framework explicitly in their own terms and before instruction. This endeavor represents one stepping stone toward more advanced disciplinary practices, such as constructing full mechanistic explanations, problem solving, argumentation, and critiquing the limits of a framework itself. Characterizing terms could nevertheless bootstrap students into developing these skills.

Last, we hope that these results inspire educational researchers and instructors to think further about scale (i.e., levels of organization) and the role of mechanism in explaining physiological phenomena. Students seem to associate the word mechanism with molecular-level explanations, but this level is not always needed or best. For instance, neural development proceeds via synapse elimination, a cellular level phenomenon, and this accounts for behavioral phenomena, such as muscular coordination. Here physiologists are not necessarily obliged to offer a molecular-level mechanism. Similarly, understanding how the arm bears a load does not necessitate molecular and ionic mechanisms below the subcellular level; understanding the elbow as a fulcrum with a load-bearing muscle can account for the mechanical equilibrium observed.

In closing, we hope that this small study generates more questions than it answers. We contend that these findings do not point to mere semantic distinctions. At the same time, these findings do not demonstrate better or worse conceptual understanding in our students. Instead, these findings illustrate how students do and do not distinguish between constructs within a given conceptual framework (SBF). Many other studies across domains and contexts provide examples of this general learning challenge (5, 15, 21). For systems thinking, we often worry about how students relate ideas, and this is particularly true when we want them to think across levels of organization. We think these findings begin to speak to the importance of distinguishing between ideas when learning in physiology.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

M.E.L. and S.M.G. conceived and designed research; M.E.L. performed experiments; M.E.L. analyzed data; M.E.L. and S.M.G. interpreted results of experiments; M.E.L. and S.M.G. prepared figures; M.E.L. drafted manuscript; M.E.L. and S.M.G. approved final version of manuscript.

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