Using Systems and Systems Thinking to Unify Biology Education

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ABSTRACT

As biological science rapidly generates new knowledge and novel approaches to address increasingly complex and integrative questions, biology educators face the challenge of teaching the next generation of biologists and citizens the skills and knowledge to enable them to keep pace with a dynamic field. Fundamentally, biology is the science of living systems. Not surprisingly, systems is a theme that pervades national reports on biology education reform. In this essay, we present systems as a unifying paradigm that provides a conceptual framework for all of biology and a way of thinking that connects and integrates concepts with practices. To translate the systems paradigm into concrete outcomes to support instruction and assessment in the classroom, we introduce the biology systems-thinking (BST) framework, which describes four levels of systems-thinking skills: 1) describing a system's structure and organization, 2) reasoning about relationships within the system, 3) reasoning about the system as a whole, and 4) analyzing how a system interacts with other systems. We conclude with a series of questions aimed at furthering conversations among biologists, biology education researchers, and biology instructors in the hopes of building support for the systems paradigm.

INTRODUCTION AND BACKGROUND

Momentum in undergraduate biology education over the last decade is often attributed to the publication of *Vision & Change* (American Association for the Advancement of Science [AAAS], 2011; hereafter, *V&C*), which catalyzed a movement aimed at re-envisioning how we teach biological science. *V&C* provides a broad vision for undergraduate biology through a framework that identifies core disciplinary practices and concepts. Far from being an end point for which we should aim, the *V&C* report serves as an invitation to the community to engage in research and constructive discussion to interpret its recommendations and translate them into actionable scholarship. Indeed, the document has inspired many projects currently framing thinking about instructional best practices (e.g., Brownell *et al.*, 2014; Couch *et al.*, 2019), assessment development (Smith *et al.*, 2019), textbook design (Campbell *et al.*, 2014), and the trajectory of research in undergraduate biology education (National Research Council [NRC], 2012a; Dolan, 2015; Tripp and Shortlidge, 2019; Aikens, 2020).

Among its significant contributions, *V&C* gave instructors permission to abandon textbooks as curricular frameworks and, instead, focus on developing students' understanding of fewer foundational concepts; specifically, "structure and function," "information flow, exchange, and storage," "pathways and transformations of energy and matter," "evolution", and "systems." In this paper, we examine systems as one of the five core concepts identified as requisite for biological literacy and initiate a conversation about what it means to teach and assess students' systems-thinking skills. Our interest in systems emerges from the convergence of three ideas that, in our opinion, suggest systems could serve as a superordinate and unifying paradigm for life sciences. 1) Systems have the potential to serve as an organizing principle that connects

Brian Sato, *Monitoring Editor*
Submitted May 7, 2021; Revised Feb 11, 2022; Accepted Mar 17, 2022
CBE Life Sci Educ June 1, 2022 21:ar3
DOI:10.1187/cbe.21-05-0118
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and explains relationships among *V&C*'s remaining concepts (Figure 1). While *V&C* presents the core concepts as broadly agreed-upon foundational principles of biology, it does not articulate how and why these concepts are interconnected within the discipline as an integrated whole. A systems perspective makes the relationships among core concepts visible, thus allowing us to conceptually organize biological knowledge in a way that reflects the nature of living systems. 2) The core concept of systems is unique, because it has a deep and expansive research base that defines the thinking skills necessary for reasoning about systems. As such, "systems thinking" (ST) can provide explicit guidance about the skills and competencies we might target in instruction. 3) A focus on systems reflects the perspective of contemporary biological science and reflects the changing character of the domain itself. While biology benefited from technologies that enabled reductionist approaches that revealed life's mechanisms at subcellular and nanoscale levels, current trends in biological research emphasize integration across systems and scales in order to better understand and predict complex macroscale patterns at the levels of whole organisms, populations, and ecosystems.

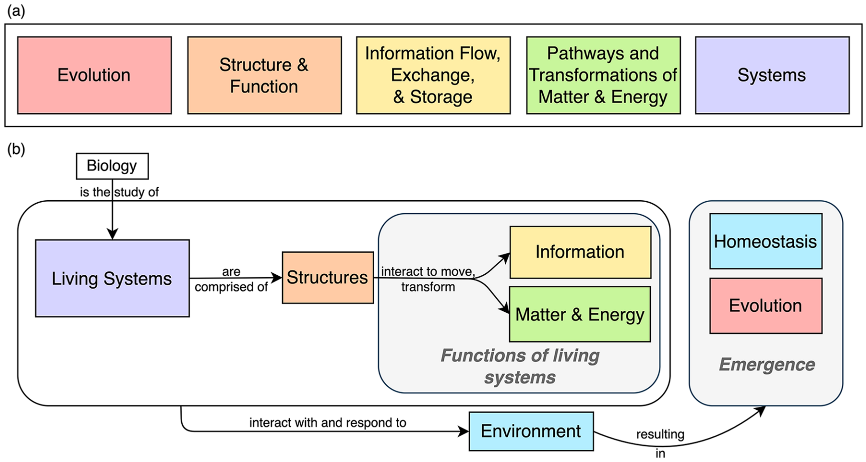

FIGURE 1. The core concepts of biology as identified by *Vision & Change* (a) reconceptualized and expanded into the systems paradigm (b). Here, living systems are composed of structures that interact to perform diverse functions, subsequently interacting with and responding to the environment, giving rise to emergent processes, such as evolution and homeostasis.

In this essay, we present a case for systems as a unifying paradigm for biology teaching and learning and propose a biology systems-thinking (BST) framework aimed at facilitating practical uptake in college biology classrooms. While the BST framework is grounded in more than 60 years of systems and ST literature spanning multiple disciplines (von Bertalanffy, 1968; Checkland, 1981; Senge, 2007), its specific aim is to make broadly recognized ST skills both tractable and assessable in biology contexts. The BST framework is a work in progress, with the intent of facilitating teaching and learning across biology. It is in the spirit of *V&C* that the authors wish to engage the community in meaningful discussions that translate *V&C*'s recommendations into actionable scholarship. In the following sections, we 1) provide an overview of what is meant by "system" in both science, technology, engineering, and mathematics (STEM) and biological contexts, 2) present an argument for why and how systems and ST could shift the paradigm of how we teach undergraduate biology, and 3) discuss limitations and areas for future research.

What Do We Mean by "System"?

Notions of systems are pervasive in discourse across multiple contexts. We commonly apply "system" to refer to a group of interacting or interrelated units (things, or even people or organizations) that function together as a whole. For example, we refer to "systems of government and education" and to the "electrical and plumbing systems" in our homes. Frustration with an institution's dysfunction is often expressed as "it's the system!," and societal problems that have deep and complex roots and manifestations are referred to in terms of systems (e.g., systemic racism). In biological contexts—both professional and colloquial—"system" is frequently used in reference to groups of organs that function together to perform physiological processes (e.g., nervous, circulatory, and reproductive systems) or in reference to larger-scale groups of organisms and their habitats (e.g., marine systems, agricultural systems, the global ecosystem). Regardless of the context in which it is used, there is an implicit understanding that "system" encompasses both the entities it comprises and the operational rules that govern how these entities interact.

Systems in STEM

In STEM, the term "system" carries a meaning that is shared across theoretical and applied domains. A system is succinctly defined as "a group of interacting, interrelated, or interdependent elements (…) forming or regarded as forming a collective entity" (Northrop, 2014, p. 2), and as "an entity that maintains its existence and functions as a whole through the interaction of its parts" (Ben-Zvi Assaraf and Orion, 2005, p. 519). These definitions are consistent with historical descriptions of systems as functional entities that arise as a result of interacting components (von Bertalanffy, 1968; Checkland, 1981; Flood and Jackson, 1991; Jackson, 1994, 2010; Lane and Jackson, 2007; Flood, 2010; Kim and Senge, 1994; Sweeney and Sterman, 2000; Cavana and Mares, 2004; Jacobson and Wilensky, 2006; Best and Holmes, 2010; Boersma *et al.*, 2011). Regardless of how large or heterogeneous systems may be, they can be characterized along a continuum from simple to complex. Although definitions of "simple" and "complex" can be fuzzy and context dependent, it is generally accepted that a simple system (e.g., a basic lever and fulcrum or a sophisticated orbiting satellite) has a predictable behavior that can be explained and modeled mathematically based on knowledge of its component parts and their interactions. In contrast, complex systems have properties and produce effects that are not easily predicted, inferred, or modeled on the basis of the components alone. Specific characteristics that distinguish complex from simple systems include:

1. *Emergence*—complex systems have properties that emerge as a result of interactions among components but are unpredictable based on the properties of the components in isolation.
2. *Hierarchy*—complex systems often have multiple levels of organization. A system may be composed of multiple, interacting subsystems and also nested within additional systems at higher levels of organization.
3. *Control*—Complex systems tend to have regulatory feedback loops that maintain stability, produce the system's functions, and modulate responses to stimuli and perturbations.

Principles underlying complex systems are broadly transferable across disciplines and system types (Goldstone, 2006). Complex systems include both natural systems, such as biological and weather systems (e.g., a cell, organism, ecosystem, or cold front), as well as economic and social systems (e.g., the stock market, the World Wide Web, multinational corporations; Senge, 2006; Northrop, 2014). Some complex systems may be further characterized as dynamic, self-organizing, and adaptive (Northrop, 2014); these properties are typically found in biological systems.

Systems in Biology

A systems perspective is not new to biology. Norbert Wiener described a biological systems perspective in the 1940s (Wiener, 1948), and systems have resurged in recent years with the emergence of *systems biology*. Systems biology, however, is distinguished from more general applications of the term "system," in that it is a research approach explicitly focused on using big data and computation to understand the structure and dynamics of biological systems. Enabled by technological developments that allow high-throughput analyses of entire genomes and collections of molecules (e.g., RNAs, proteins or metabolites), systems biology has shifted the focus from "What are all the parts of a system?" to "How are these parts organized? How do they dynamically interact? How are their interactions controlled?" (Kitano, 2002). As a research area, systems biology is justified and conceptually rooted within systems theory, but it is by no means the only area of biology that focuses on systems (Breitling, 2010). While use of the word "systems" in biology is traditionally confined to specific structures, levels of organization, or research approaches (i.e., organ *systems*, eco*systems*, *systems* biology), all of biology is fundamentally a science that studies systems.

What Do Guiding Documents Say about Expectations for Learning about Systems?

Among the myriad calls for reforming STEM instruction, most reference the utility of systems and/or ST as useful constructs for science instruction (AAAS, 1989, 2011; NRC, 2003, 2009, 2012b; National Academies of Sciences Engineering and Medicine, 2016). For example, *BIO2010* (NRC, 2003) identified biology as the study of living systems and proposed a "New Biology Curriculum" in which "concepts" and "central themes" were articulated in terms of systems. In addition, systems was used to link biology to other disciplines; engineering in particular was emphasized as a discipline accustomed to thinking in systems, and similar approaches were advocated for life science. Throughout, *BIO2010* focused on systems not merely as a component of biology learning, but as a fundamental theme that bridges STEM disciplines.

Vision & Change (AAAS, 2011) identifies systems as one of five core concepts, along with evolution; structure and function; information flow, exchange, and storage; and pathways and transformations of energy and matter. It is important to note that the treatment of these concepts in *V&C* is very brief and stops short of indicating how to translate them into instructional practice. This aligns with the intent of *V&C*, which was to appeal to the broader biology education community to engage in meaningful discourse about expectations and approaches to teaching and learning that will better prepare students for 21st-century biology. Therefore, rather than explicating specific learning objectives, the report broadly discusses themes related to each core concept that might be relevant in guiding instructional decisions.

With respect to systems as a core concept, *V&C* articulates relevant themes, including system interactions, emergence, and the trans-scalar nature of systems: "[A] systems approach to biological phenomena focuses on emergent properties at all levels of organization, from molecules to ecosystems to social systems" (*V&C*, p. 13). Furthermore, it points out that biologists adopt tools and theories from other disciplines to create models that enable them to "relate the dynamic interactions of components at one level of biological organization to the functional properties that emerge at higher organizational levels." It should be noted that these themes are framed in reference to the subdiscipline of systems biology as it was defined in a prior NRC report (NRC, 2009). In *V&C*, as in the earlier NRC report, systems biology is described as focusing on computational and quantitative approaches to identify patterns and build models that predict system properties. As such, it could be argued that *V&C* is advocating for both conceptual understanding about systems as well as using systems as a way to call for increasing quantitative approaches in biology education.

A Framework for K–12 Science Education (NRC, 2012b) includes "systems and system models" as a crosscutting concept. The *Framework* emphasizes the utility of systems for identifying a particular unit or subset of the world for the purpose of investigation. This conception of a system derives from the National Science Education Standards (NRC, 1996), which explain that the world is too large and complex to study at once, so there is value in specifying boundaries that partition subsets of the world (systems) conducive for exploration.

We find the *Framework*'s treatment of crosscutting concepts most useful and inspiring as a way to envisage how and why systems might be leveraged as an organizing principle for all of biology. The *Framework* defines crosscutting concepts as those that "bridge disciplinary boundaries, having explanatory value throughout much of science and engineering. Crosscutting concepts help provide students with an organizational framework for connecting knowledge from the various disciplines into a coherent and scientifically based view of the world (p. 83)." As such, the *Framework*'s conceptualization of a crosscutting concept points to the potential of systems to serve as a paradigm for how we might design a more integrated and coherent presentation of biology for undergraduate learners and connect it in a more meaningful way to other disciplines.

SYSTEMS AS A UNIFYING PARADIGM FOR BIOLOGY EDUCATION

As noted earlier, an important contribution of *V&C* to the broader movement for undergraduate biology education reform was to propose a manageable set of core concepts to organize the field of biology, which at times can feel like an overwhelming avalanche of unrelated facts. *V&C* presented an initial list of focal concepts central to all of biology but did not explain how or why these foundational concepts were related to one another. Just as Tripto *et al.* (2016) envisaged systems and systems thinking as principles that encompass all seven NGSS crosscutting concepts, we similarly see the potential of systems and systems thinking as a way to organize and explain relationships among *V&C* core concepts.

Biology is, fundamentally, the study of living systems. Thus, we see systems not as a core concept within biology, but as the subject of biological science itself. All living systems, from cells and organisms to communities and ecosystems, have components that interact, share common properties, and perform common functions. Functions of biological systems include the ability to: 1) acquire, use, and transform energy and matter; 2) store, use, and transfer genetic information; and 3) receive or sense information about the environment and respond to it. Interactions among components of biological systems, between systems and the physical environment, and among systems result in emergent phenomena such as evolution and homeostasis (Figure 1).

Viewing biology from a systems perspective enables us to organize our thinking in terms of functions (which ultimately align with the *V&C* core concepts of information flow, exchange, and storage and pathways and transformations of energy and matter). Whether we focus on a single cell, a multicellular organism, or a group of organisms, we ultimately can ask the same questions about their system functions: How does a given system acquire energy from the environment? How does it pass genetic information to its offspring? How does it respond to perturbations or cues from its environment? However, adopting a view of biology from a systems perspective also raises new questions about the skills, competencies, and ways of thinking we must foster in our students.

What Do We Already Know about ST in the Biology Classroom?

Given the centrality of systems to biology, we assume that practicing biologists, over time, develop a set of ST skills that support their reasoning about complex biological systems. These ST skills develop implicitly as a consequence of professional experiences, mentoring and training, and the context of their focal systems. Some students will acquire these skills without explicit instruction during their education; however, if we want *all* students to access the nature of science as a way of thinking, we must be explicit and intentional in our instruction about the ST skills students should gain (Goldstone, 2006).

ST has generally been described as the skills and practices that enable one to "understand and interpret complex systems" (Evagorou *et al.*, 2009, p. 655). The NRC describes ST similarly, as "the ability to understand how an entire system works; how an action, change, or malfunction in one part of the system affects the rest of the system" (NRC, 2011, p. 3). Studies across several STEM disciplines have translated these descriptions into skills and practices that we might observe in students' problem solving in disciplines including biology (Sommer and Lücken, 2010; Ben-Zvi Assaraf *et al.*, 2013; Tripto *et al.*, 2013; Tripto *et al.*, 2016), geosciences (Ben-Zvi Assaraf and Orion, 2005, 2010), engineering (Godfrey *et al.*, 2014), chemistry (Vachliotis *et al.*, 2014; Orgill *et al.*, 2019; Talanquer, 2019), and computer science (Arnold and Wade, 2017). This broad body of scholarship reflects a widespread recognition of the centrality of systems and ST in science (Sweeney and Sterman, 2000; Jacobson and Wilensky, 2006; Lane and Jackson, 2007; Trujillo and Long, 2018), and further underscores their value as a unifying paradigm in biology.

Among the profusion of literature on ST (Midgley, 2003; Trujillo and Long, 2018; Verhoeff *et al.* 2018; Trujillo, Momsen, Wyse, Bray Speth, and Long [unpublished data]), we identified two frameworks that resonated with our focus on identifying ST skills (rather than characteristics of systems) and practical applications in natural science classroom contexts: the systems-thinking hierarchical model (STH; Ben-Zvi Assaraf and Orion, 2010) and the framework of system competence (SC; Sommer and Lücken, 2010).

The STH originally emerged from research conducted with middle school students learning about Earth systems (Ben-Zvi Assaraf and Orion, 2005) and has been used since by many researchers interested in the development of ST skills in both K–12 (e.g., Ben-Zvi Assaraf and Orion, 2005, 2010; Ben-Zvi Assaraf *et al.*, 2013; Tripto *et al.*, 2016; Snapir *et al.*, 2017) and college settings (Eilam and Poyas, 2010; Dauer *et al.*, 2013; Reinagel and Bray Speth, 2016; Bergan-Roller *et al.*, 2018). Ben-Zvi Assaraf and Orion (2005, 2010) conducted a review and synthesis of the science education literature to identify eight emergent characteristics of ST and organized them into a three-tiered hierarchy that reflects the stages of ST development observed in K–12 students. These hierarchical levels include: 1) identification of system components, 2) synthesis of system components, and 3) implementation. According to the STH, the most basic level of ST involves the ability to identify system components and processes (level 1). From here, a student can then integrate these elements (level 2) by identifying both simple and dynamic relationships between system components and organizing them into a meaningful "framework of relationships" (Ben-Zvi Assaraf and Orion, 2010, p. 541). Finally, students can make generalizations about the system, identify hidden dimensions and emergent properties, and think temporally (level 3).

The SC, developed by Sommer and Lücken (2010), used the lens of classical systems theory to analyze and describe two broad characteristics of systems: organization and properties. Sommer and Lücken translated these characteristics into the SC framework to describe the skills K–12 students need to successfully solve biological problems. The SC framework includes two levels: modeling and dealing with system properties. At the level of modeling, students are expected to identify and organize system elements into simplified verbal or pictorial representations. In practice, this level involves developing and using conceptual and quantitative models. The second level of the SC framework, "dealing with system properties," focuses on skills related to identifying dynamics, predicting change, and recognizing emergence. Together, the STH and the SC frameworks provided us with a robust starting point for developing our BST framework.

STRUCTURE–BEHAVIOR–FUNCTION: A LANGUAGE FOR DESCRIBING SYSTEMS

While the STH and SC frameworks both provide excellent starting points for identifying ST skills for undergraduate biology education, they do not share a common language for describing systems constructs. In developing the BST framework, we recognized the need for a common, systems-specific language for practical implementation of ST in life science classrooms (Gilissen *et al.*, 2021). Structure–behavior–function (SBF) theory (Goel and Chandrasekaran, 1989; Goel *et al.*, 1996) provides a simple but effective language for experts and learners to describe complex systems and reason about them (Chi *et al.*, 1994; Hmelo *et al.*, 2000). Although SBF originates in artificial intelligence and designed systems engineering, the core principles and language of SBF are broadly conducive for describing *any* system—natural or engineered. *Structure* refers to the elements that comprise the system; *behavior* refers to the mechanisms and relationships operating within the system that explain how structures are related. Together, structures and behaviors interact to result in the system accomplishing a *function*, or what the system does. While the principles and constructs underlying SBF are broadly accessible and intuitive, some have argued that their specific use of language is not (Hmelo-Silver *et al.*, 2017; Snapir *et al.*, 2017). In biological contexts in particular, "structure," "behavior," and "function" each have additional connotations with potential to construe or confuse the meaning of these terms in the context of describing systems and have been replaced with the terms "components," "mechanism," and "phenomenon" (CMP nomenclature) when modeling human body systems (Snapir *et al.*, 2017) or ecosystems (Hmelo-Silver *et al.*, 2017). The CMP nomenclature was, in these authors' view, more appropriate to describe natural systems than SBF, which had been developed to represent engineered systems. In our own classroom experiences and research, we have found that the terms "structure" (what comprises a system) and "function" (what a system does) resonate well and are intuitive to students and instructors, while the term "behavior" tends to elicit different ideas in biology. As a result, we replaced "behaviors" with "relationships," which encompasses either the structural relationships among parts of a system or the mechanisms operating between them. Further, we chose "function" over "phenomenon," because functions differ from biological phenomena. Phenomena (observed events or manifestations) are the results of functions or multiple functions interacting within a system. These interactions often produce novel *emergent* phenomena that are not predictable and/or derivable simply by identifying the structures in the system. For example, understanding the function of a particular cell or even a group of cells tells us very little about the physiology of a particular organism; to understand that physiology, we must consider other cells, tissues, organs, and even the external environment. Hence, our use of structure–relationships–function (SRF) to denote system elements in our classroom practice.

Regardless of the specific monikers used, SBF theory has proven useful for guiding research about student learning, particularly in the context of representing and reasoning about biological systems. Hmelo-Silver *et al.* (2007) applied the SBF lens to design instruction about the respiratory system in a middle school science classroom. Students learned about the respiratory system by building models that explained function by illustrating the interactions among structures and mechanisms (Hmelo *et al.*, 2000). A key finding of that study was that learners tended to focus on the structural features of the system over its functions and relationships. Findings from this and subsequent research (Hmelo-Silver and Pfeffer, 2004; Hmelo-Silver *et al.*, 2007; Goel *et al.*, 2009) are consistent with differences first noted by Chi *et al.* (1981), who found novices focus almost exclusively on structures, while experts view systems in the context of their relationships and functions. Incorporating SBF theory into middle school science pedagogy using hypermedia simulations revealed that "function-first" instruction promotes student understanding of systems (Liu *et al.*, 2005; Hmelo-Silver *et al.*, 2007, 2017; Jordan *et al.*, 2013). SBF has also been used as both a framework to describe and model complex biological systems in the undergraduate classroom (Dauer *et al.*, 2013) and as an analytical tool to measure student understanding (Liu *et al.*, 2005; Hmelo-Silver and Pfeffer, 2004; Hmelo-Silver *et al.*, 2007; Dauer *et al.*, 2013; Dauer and Long, 2015; Bray Speth *et al.*, 2014). Further, SBF theory has been translated into modeling software to support community decision making about complex socioscientific issues (Gray *et al.*, 2013).

While these foundational research contributions inform us about the skills students might bring with them to the college classroom, we anticipate *additional* ST skills will develop as undergraduates progress through their curricula. Furthermore, while prior work justifiably focuses on *students* and their development of ST skills, there is little guidance for instructors on how to develop curricula or instruction that can support the development of ST skills (e.g., learning objectives, assessments, classroom activities). We therefore see a distinct need for a framework that can both organize and communicate desired ST skills for undergraduate biology while also fostering the development and implementation of ST-aligned instructional materials and practices.

THE BIOLOGY SYSTEMS-THINKING (BST) FRAMEWORK

Here, we introduce the BST framework as a synthesis of prior research on systems and ST that expands on the work of Ben-Zvi Assaraf and Orion (2005, 2010) and Sommer and Lücken (2010) to incorporate a broader suite of skills derived from additional literature (Table 1). The BST framework organizes ST skills into four hierarchical levels and uses SRF language to support the development of instructional materials, including assessments. For each level, we present our rationale for the inclusion of specific ST skills at that level, our understanding of the relationships among ST skills within and across levels, and our reasoning for their relevance to learning and teaching biology. It is important that we make three points clear. First, our use of "hierarchy" is consistent with that of other frameworks, such as Bloom's taxonomy (Bloom and Krathwohl, 1956), in which higher-level tiers of skills are thought to be inclusive of skills represented in lower tiers. Second, our hierarchical presentation of ST skills should not be confused with notions of learning progressions, in which students must master lower-level anchoring concepts or skills before they can effectively think, reason, or perform at higher levels. At present, we do not have evidence for a learning progression of ST skills, but this work lends itself to multiple hypotheses that could be explored. Third, the BST framework is a synthesis of existing research and therefore reflective of the skills the STEM community identifies

TABLE 1. Proposed biology systems-thinking (BST) framework

Level[a]	Skills	References[b]
1. Identifying and describing the system	a. Identify the system boundaries and the structures relevant to a particular function.	1, 3–10, 12, 14, 17
	b. Identify relationships among system structures relevant to a particular function.	1, 5–10, 12, 14, 17
	c. Organize system structures and relationships to explain how the system accomplishes its function.	1, 5–10, 12, 14, 16, 17
2. Analyzing and reasoning about relationships	a. Characterize the qualitative nature of relationships (e.g., structural, mechanistic, static, dynamic, within-scale or transcalar).	7–9, 15, 17
	b. Reason about the quantitative (or relative quantitative) properties of relationships (e.g., speed, magnitude, rates of reactions).	5, 8–12, 15
	c. Predict and explain *direct* effects of relationships on system structures (e.g., positive and negative impacts of one structure on another).	2, 6–9, 14
3. Analyzing and reasoning about the whole system	a. Analyze a system to describe *indirect* effects and feedback loops (both negative and positive).	2–4, 6–11, 14, 17
	b. Explain emergent biological phenomena based on broad principles of biology and on knowledge and understanding of specific properties of systems. Recognize that emergent properties of systems often cannot be predicted based on knowing the structures and relationships of that particular system.	1, 4, 8–10, 14, 17
	c. Predict and explain consequences to system function resulting from changes to system boundaries, structures, or relationships (perturbations or disturbances, rate changes of dynamic processes, feedback, etc.).	1, 3, 6–10, 14, 17
4. Reasoning within or across multiple systems	a. Recognize patterns across systems in order to make generalizations about systems with similar underlying structure or function.	1, 4–6, 10, 11, 17
	b. Identify how systems intersect in order to explain the ways that one system's function can impact another system at the *same* level of biological organization.	3, 6, 13
	c. Identify how systems intersect in order to explain the ways that one system's function can impact another system *across* biological levels of organization.	3, 6–8, 13, 16

[a]Each level of the BST is described using structure–relationship–function (SRF) language, where structures are the components that comprise the system; relationships are the mechanisms that explain how structures are related; taken together, structures and behaviors interact to result in a particular system function.
[b]Salient references supporting each skill are listed here; this is not intended to be an exhaustive list of relevant literature but represents the sources that most directly influenced our thinking in articulating the BST skills. 1) Ben-Zvi Assaraf and Orion (2005, 2010); 2) Cavana and Mares (2004); 3) Evagorou *et al.* (2009); 4) Goldstone (2006); 5) Hmelo *et al.* (2000); 6) Hmelo-Silver *et al.* (2007); 7) Hmelo-Silver and Pfeffer (2004); 8) Jacobson (2001); 9) Jacobson and Wilensky (2006); 10) Kitano (2002); 11) Richmond (1993); 12) Richmond (1997); 13) Schneeweiß and Gropengießer (2019); 14) Sommer and Lücken (2010); 15) Sweeney and Sterman (2000); 16) Tripto *et al.* (2016); 17) Wilensky and Resnick (1999).

as comprising ST. Our unique contribution includes the translation of these skills into a hierarchically organized framework to support biology instruction and learning. In this essay, we propose the BST as a potential framework for organizing instruction and assessment in undergraduate biology. Further work to validate the BST is ongoing.

Consistent with other frameworks, level 1 of the BST framework includes the skills of identifying and describing the system of interest. In SRF terms, reasoning about a system should be framed by the function of interest (i.e., a "function-first" approach). Learners, therefore, should be able to identify the structures (1a) and relationships (1b) relevant to a system and organize them in a way that explains how the system accomplishes a given function (1c). Thinking about a system in terms of a specific function requires that learners identify the minimum set of structures and relationships that are necessary and sufficient to explain that function. Just as critically, learners must also make explicit decisions about what to exclude. Although additional structures or relationships may be part of a system, they may not be necessary for explaining its function. Identifying what should and should not be included as part of a given system is a foundational ST skill and has been described as the ability to "determine the extensive boundaries" of a system model (Richmond, 1997).

As an example, students may be asked to reason about the function of carbon cycling through a prairie ecosystem. Students would need to identify relevant ecosystem structures, in this case the major pools of carbon relevant to the prairie system (e.g., atmosphere, grasses, bison, decomposers; 1a). Skill 1a includes establishing the boundaries of the system, which is achieved by identifying system elements that are relevant to explaining the target function (i.e., carbon cycling). In this case, "ecosystem" and other language from the prompt serve as cues to students that the system should be thought of at a macroscale (identifying the system boundaries; 1a). Therefore, biochemical-level structures such as Rubisco or chloroplast grana, while relevant to the process overall, would not be included in explaining carbon cycling at the ecosystem level as students clarify the system boundaries. After determining which carbon pools are relevant to include, students can then identify the relationships that move carbon between them (e.g., photosynthesis, consumption, cellular respiration; 1b). Again, cues about scale signal to students that microscale processes such as stomatal regulation or electron transport mechanisms are not necessary here. Relevant structures and relationships would then be organized (verbally as a written or oral response or graphically as a model) to explain how the function of carbon cycling is achieved in the prairie ecosystem (1c).

The second level of the BST focuses on the relationships within the system and is a direct response to research demonstrating that novice learners struggle to identify and reason about them (e.g., Hmelo-Silver *et al.*, 2007). We propose three skills that make up level 2: characterize the qualitative nature of relationships found within a system (e.g., static, structural, or dynamic; 2a), reason about the quantitative aspects of relationships (e.g., speed, magnitude, or rate; 2b), and describe and predict direct effects (e.g., the impacts of one structure on another; 2c). Overall, skills at level 2 are aimed at engaging students in reasoning about the nature of the relationships that connect system structures and the consequences of those interactions on the structures themselves. Level 2 of the BST framework expands from prior work focused primarily on dynamic relationships (e.g., Hmelo-Silver and Pfeffer, 2004; Sommer and Lücken 2010) to articulate additional dimensions of relationships with which learners should be conversant. In the prairie ecosystem example, photosynthesis is a *dynamic* relationship (2a) that moves carbon from the atmosphere to a plant and its rate can vary (e.g., increase, decrease, speed up, slow down; 2b). The dynamic and variable rate properties of the photosynthesis relationship directly impacts carbon pools acting as both source and sink (2c). We note that it may be tempting to introduce external factors (e.g., a drought or fire) or cross levels of biological organization (e.g., stomatal regulation); however, this would change the boundaries of the system. Although biologists do this regularly and it is an important ST skill, it is not one situated at this level.

The third level of the BST framework focuses on reasoning about the system as a whole. At this level, the focus shifts from direct to indirect effects resulting from chains and networks of direct relationships among system structures. As learners synthesize their understanding of multiple relationships within a system, they can begin to describe and explain *indirect* effects (e.g., chains of cause and effect and feedback loops; 3a) and emergent phenomena occurring within a system (e.g., evolutionary outcomes, phenotypic plasticity, or phenology; 3b). At this level, students would be able to predict and explain how changes to one or more elements of the system would impact indirect effects, and ultimately the function of the whole system (e.g., impacts of perturbations or disturbances on the system's function; 3c). They could analyze a case study (e.g., Knapp *et al.*, 1999) to describe the direct and indirect relationships between bison and grass (3a) in order to explain why a decline in bison grazing resulted in long-term biomass increase in some grass species (3b). Students could also reason about how changes in climate (cool and wet, vs. hot and dry) could moderate bison's effect on grass biomass (3c).

The fourth level of the BST framework extends the reasoning skills of the previous levels to consider a system in relation to other systems, including nested systems. While the first level of the BST framework highlights the importance of students learning to establish the *boundaries* of a system of interest, level 4 leverages the interdependence of biological systems. ST skills at this level include recognizing patterns across systems in order to make generalizations (4a) and explaining how the function of one system can impact that of another system at the same level (4b) or across levels (4c). Level 4a is the ability to recognize core principles or patterns underlying a system and apply them to other systems. For example, students who have practiced modeling the carbon cycle in a prairie ecosystem should recognize the same principles apply to describing the carbon cycle in an aquatic ecosystem, where the specific organisms and environmental pools of carbon are different but the trophic levels (e.g., primary producer, consumer) and carbon-moving mechanisms (photosynthesis, consumption, respiration) are the same.

Levels 4b and 4c require learners to think about systems in relation to other systems, including nested systems, both *within* and *across* levels of biological organization. Reasoning about systems intersecting at the same level of organization (4b), for example, might include relating the cycling of carbon with the cycling of nitrogen in the prairie ecosystem to explain why planting more grasses may not sequester more atmospheric CO_2. Reasoning about systems intersecting across biological levels (4c) requires that students consider living organisms as composed of systems at lower levels of organization (organs, tissue, cell) and nested within systems at higher levels of organization (populations, communities, ecosystems). Explaining the effects of a cellular-level process like photosynthesis on biomass production exemplifies thinking about the effect of one system on the functions of higher-level (or even, as it often happens, lower-level) systems (4c).

Unique Contributions of the BST Framework

In our view, the BST framework is distinguished from existing ST frameworks because it:

1. supports a systems paradigm for biology education by explicitly articulating ST skills in a manner consistent with recommendations from national reports;
2. is purposefully designed to inform both instruction and assessment, not merely characterize student thinking;
3. adopts a common language (SBF theory) that explicitly links research with practice and serves as an organizing principle that aligns system theory with systems teaching and learning; and
4. expands previously described ST skill sets to include a level explicitly focused on the interdependence of systems.

We recognize additional work is essential to gather validity evidence for the BST framework, including evidence to support the skills and levels as distinct yet hierarchical in nature. We present the BST framework here not as a finished product, but as an invitation to researchers in discipline-based education research to dialogue about the specific ST skills we wish to develop in our undergraduates.

We believe the BST framework can help distill an ever-expanding biology curriculum, enabling instructors to readily adapt and respond to advances in biology. While a full discussion of curricular design is beyond the scope of this essay, in the following section we briefly introduce several core elements of a BST-informed curriculum that can support systems-based pedagogy.

Systems and ST as a Paradigm for Instructional Design

A central paradigm that unifies learning about a subject provides structure to the discipline, facilitates curricular development and instructional design, and helps learners organize their knowledge in meaningful ways (Bruner, 1960). Nehm (2019) recently argued for a unifying paradigm for both biology and biology education. We argue that the concept of systems is uniquely suited to serve as an organizing paradigm, because 1) biology is fundamentally a science of living systems and 2) a systems approach allows us to explain the remaining four core concepts in terms of their relationships to one another. Our experiences in our own biology classrooms have made it increasingly evident that systems and ST can be a unifying paradigm for informing and guiding biology curriculum design and instruction—both in terms of the content we teach and the science practices we emphasize in our teaching. For example, to explain, model, or reason about a biological function, one must identify the structures and relationships necessary for accomplishing that function and connect them through mechanisms and interactions that explain how the function is achieved. Systems and ST can therefore enable more cohesive approaches to instructional design that simultaneously target scientific core ideas as well as practices (Cooper *et al.*, 2015). In fact, viewing *V&C* core concepts through a systems lens enables us to better understand them as interconnected, rather than as discrete and separable subjects (Figure 1).

In an effort to identify the principles or foundational ideas that we rely on in our teaching, and that, for us, define a systems approach to teaching and learning biology, we converged on three big ideas.

Function as Starting Point. Biology curricula and courses are often designed around levels of biological organization or topics (e.g., genetics, ecology, cells, and molecules). Designing instruction from a systems perspective necessitates first identifying the function of interest (e.g., gene expression in a cell). In doing so, the learning objectives clearly emerge: students need to know the relevant structures (gene, mRNA, amino acids, etc.) and relationships (transcription, translation, etc.) enabling the cell to accomplish this function. Students can demonstrate their understanding through a written explanation or model that communicates how information stored in a gene results in a protein and, ultimately, a phenotype.

Modeling as Foundational. Model-based instructional practices are particularly well suited for representing and reasoning about systems and promoting ST. The learning benefit of modeling is grounded in the idea that deep understanding of complex natural phenomena is facilitated by the construction, use, and revision of models (Gilbert, 2004; Gilbert and Justi, 2016). Model building is not intended as an end point, but as a step in the iterative and progressive process of model-based learning. Moreover, model-based teaching practices emphasize collaboration, discussion and testing of models, and engaging students in productive dialogue that promotes deeper, systems-oriented learning (see review by Wilson *et al.*, 2020).

Systems Support Integration. A systems perspective/paradigm creates instructional opportunities to integrate seemingly disparate concepts and skills, including those that cross multiple levels of biological organization. For example, expanding a system's boundaries can allow students to see how molecular genetics underpins evolution, rather than treating these concepts as distinct and unrelated. Similarly, exploring one function (e.g., natural selection) in multiple systems allows students to uncover patterns, make predictions, and generalize their understanding rather than be distracted by nuances of specific cases.

We recognize the scarcity of instructional resources designed with systems as an organizing principle. In our experience, typical educational resources (e.g., textbooks, videos, case studies) are valuable, but require deliberate curation. For example, we rarely assign entire chapters at a time, but may find it useful to assign select pages from multiple chapters to help students begin building the content knowledge that we subsequently work to integrate in class. Although resources are currently lacking, focusing on function first, incorporating model-based instructional practices, and using systems to integrate concepts will guide biology instruction toward a systems paradigm.

Future Conversations

Our focus on systems and ST emerged in response to calls for authentic approaches to teaching biology that were grounded within the nature of the discipline (NRC, 2009). Over the last several decades, systems has surfaced as a core concept for undergraduate biology education (NRC, 2003; AAAS, 2011) and as a crosscutting concept for K–12 STEM education (NRC, 2012b, 2013). Inspired by Nehm's call (2019) for integrative, unifying frameworks in biology education and education research, we propose systems as a paradigm for biology and introduce the BST framework as a tool to develop instruction and curricula in biology and offer perspectives to engage researchers, practitioners, and curriculum developers in this ST conversation.

Research Perspectives. The BST framework defines a set of ST skills that students should develop through the course of the undergraduate biology curriculum. Our proposed framework will require validation by biologists and biology educators, through interviews and surveys. Further, more research is necessary to better understand how learners develop ST skills, what instructional practices are best suited to foster skill development, and how assessment can promote and reveal ST in students. Open questions that will need to be addressed include:

- What are appropriate benchmarks toward development of ST skills?
- Which ST skills are most difficult to acquire?
- Could an ST learning progression be developed for undergraduate biology?
- What kinds of assessments or instructional practices best promote and reveal different ST skills?
- How would a systems and ST paradigm impact curricular development?
- What may be the long-term outcomes of student engagement with ST?

Instructional Perspectives. We recognize designing learning around systems and ST is not without challenges. For example, we know that, when reasoning about complex systems, experts take into account multiple causality, indirect effects, regulatory feedback loops, and the role of randomness, while undergraduate students tend to favor simple explanations, single and linear causality, and predictability (Jacobson, 2001). Faced with the complexity of natural systems, including biological phenomena, learners do not readily integrate concepts and mechanisms at multiple levels of organization. The connections between biological levels that are self-evident to experts can be difficult for students, who often confuse the properties of levels (Wilensky and Resnick, 1999; Schneeweiß and Gropengießer, 2019) and struggle to generate causal and mechanistic explanations (van Mil *et al.*, 2011; Southard *et al.*, 2017). While experts think about systems in terms of underlying patterns and principles, novice learners tend to focus on the structural, observable features, which are cognitively easier to grasp (Hmelo-Silver *et al.*, 2007). In particular, macroscopic phenomena that result from multiple unobservable, microscopic mechanisms are not intuitive and pose a considerable explanatory challenge for learners (van Mil *et al.*, 2011).

Despite these challenges, engaging learners in ST is feasible and productive, even in early stages of science education (Hmelo *et al.*, 2000, 2008; Jordan *et al.*, 2008; Schwarz *et al.*, 2009; Ben-Zvi Assaraf and Orion, 2010; Sommer and Lücken, 2010; Boersma *et al.*, 2011), and expertise about systems develops with practice (Hmelo-Silver and Pfeffer, 2004; Hmelo-Silver *et al.*, 2007), and ST skills, although interconnected, can be practiced and acquired gradually and individually for the purpose of mastery acquisition (Richmond, 1993). These broader principles, based on research and on educators' experiences, strongly support the idea that learners can and should be engaged in ST within their formal education. Our own research and classroom experiences evidence some of the benefits of systems-centered instructional practices in college biology. For example, modeling the connection between genes and evolution in introductory biology engaged all learners in constructive learning processes, with greater learning gains for otherwise lower-achieving students (Dauer *et al.*, 2013).

Curricular Perspectives. Systems, as a paradigm for biology and a crosscutting concept (NRC, 2012b, 2013), can unify STEM instruction more broadly, supporting students' transfer of knowledge and skills across disciplines (NRC, 2003). For example, students often have a fragmented understanding of energy that may be tightly coupled to context (Kohn *et al.*, 2018). A systems approach might enable students to translate their understanding of energy from one domain to another, developing a more coherent understanding of the concept (Talanquer *et al.*, 2020). To be sure, this is a lofty goal, and warrants further exploration:

- Would a systems perspective create avenues for interdisciplinary collaborations among academic fields, resulting in integrative courses and curricula?
- Could we leverage ST to prepare students for careers and citizenship in an increasingly complex and changing world?

We recognize systems and ST are not a panacea and will not solve all of the challenges currently facing biology education; systems represent just one of potentially many paradigms that may enable students to more fully consider complex or "wicked" problems. We welcome further dialogue on the BST, in the hopes that we can refine the framework and develop additional assessment approaches and, in so doing, improve students' learning experiences in biology.

ACKNOWLEDGMENTS

We dedicate this article to Diane Ebert-May, our mentor, friend, and persistent voice over our shoulder, always asking, "And what are our students *doing*?" We also thank Caleb Trujillo, Joseph Dauer, and Vicente Talanquer for conversations that supported the development of these ideas. This material is based upon work supported by the National Science Foundation under grants DRL 1420492, DRL 0910278, DUE 1245410, DUE 2012933, DUE 2012208, DUE 2012950, and DUE 2012438.

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