Structure and Function Relationships in the Educational Expectations of Professional Societies Across the STEM Disciplines

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The concept of structure and function is a fundamental example of a crosscutting concept found in the educational reform documents in multiple STEM disciplines. However, the terms structure *and* function *are words used in everyday language, and their use in various disciplines may be a source of lexical ambiguity for students. Discipline-specific professional societies often define pathways of research dissemination as well as the educational expectations for students pursuing a career path related to their discipline. We investigated 16 professional societies' educational expectations related to structure and function, revealing the presence of multiple discipline-specific disambiguations. As a conservative estimate, the professional societies studied cover the collective interests of at least half of a million practitioners of these disciplines and represent the areas of biology, microbiology, biochemistry and molecular biology, ecology, botany, physiology, chemistry, mathematics, statistics, engineering, and physics. The nature of this crosscutting concept and its discipline-specific uses are a potential learning challenge for students. This work provides an overview of the use of structure and function in multiple STEM disciplines from which instructors can contextualize their teaching.*

Instructors across multiple disciplines use the phrase *structure and function* in undergraduate courses from introductory to advanced levels. This phrase has an extensive history in science at multiple scales and contexts. Historically, it has been used in anatomy and physiology for investigations of the human body (Allchin, 1903; Ophüls, 1907) and what became evolutionary biology, exemplified by Darwin (1859). Searching this phrase reveals over 40,000 entries on Web of Science (Clarivate Analytics) in fields such as mathematics, cancer biology, proteins, cell biology, developmental biology, cardiovascular research, physiology, and biochemistry.

Similar to other key concepts, instructors have an expert-level understanding of the concept of structure and function within their disciplines, and perhaps even among disciplines, developed over many years. As novices, however, students encounter these concepts in a number of different contexts, inside and outside of the classroom. This represents lexical ambiguity, when words that are commonly used in everyday language are applied differently within a specific domain (Barwell, 2005; Kaplan, Fisher, & Rogness, 2009; Lemke, 1990), and may impose a learning barrier. The structure–function concept is encountered throughout a science curriculum, starting in kindergarten (Anderson, Ellis, & Jones, 2014) and is foundational within individual disciplines and a crosscutting concept among multiple STEM and non-STEM disciplines.

Disciplinary intersections

Structure and function is a quintessential representation of a crosscutting concept in education (National Research Council [NRC], 2012; NGSS Lead States, 2013) and this is exemplified by many cutting-edge research areas in STEM involving structure and function being interdisciplinary. *The Mathematical Sciences in 2025* (NRC, 2013) shows the applications and vitality of mathematics and discusses the protein folding problem (summarized by Dill & MacCallum, 2012) as an intersection with multiple science disciplines.

Next Generation Science Standards

Our interdisciplinary interpretation of the structure and function relationships is based, in part, on the *Next Generation Science Standards* (*NGSS*; NGSS Lead States, 2013), based on the *Framework for K–12 Science Education* (NRC, 2012). The *NGSS* is the result of significant work among experts considering what K–12 students should be thinking about. The *Framework* presents structure and function as "the way in which an object or living thing is shaped and its substructure determine many of its properties and functions" (NRC, 2012, p. 84). This is said to be both related to other crosscutting concepts and existing as a stand-alone concept "that occurs in virtually all areas of science and is an important consideration for engineered systems as well" (NRC, 2012, p. 85). Spanning from K–2 to high school, this is found in 11 learning concepts across all four domains of disciplinary core ideas (NGSS Lead States, 2013).

Professional societies

To understand this crosscutting concept in greater detail, we analyzed the definition of, and expectations related to, structure and function relationships in the educational guidelines of multiple professional societies across the STEM disciplines. These societies represent some of the most prominent STEM professional societies in the United States today (see Table 1). This is by no means an exhaustive list but is meant to provide an interdisciplinary snapshot. We've included the phrase *structure and function* as well as the individual terms and related concepts. This overview provides context for instructors to assist students along the path toward expertise in their disciplines and context for effectively using the term(s) to communicate among disciplines.

General biology and microbiology

For the biological sciences, there is no main professional organization; however, a number of subdisciplinary organizations as well as national calls for educational reform have been supported by prominent organizations (e.g., see American Association for the Advancement of Science [AAAS], 2011; Association of American Medical Colleges, 2009; Jarmul & Olson, 1996; NRC, 2003). Of these, the most relevant and widely used educational reform document is *Vision and Change* (AAAS, 2011).

Vision and Change presents structure and function as one of the five main core concepts for undergraduate life sciences majors. Explained as "basic units of structure define the function of all living things," the concept is based on the organization of subunits shaping the complexity and dynamics of living organisms and includes different scales (AAAS, 2011, p. 12). The AAAS presents the interconnectedness of structure and function in the life sciences with other disciplines through examples of engineering design approaches, robotics, physical sciences tools, quantitative analysis, and rational drug design.

The Partnership for Undergraduate Life Sciences Education (PULSE) presents a rubric for life sciences departments to self-evaluate the implementation of *Vision and Change* (AAAS, 2011) "based on the features expected in a department that had fully implemented" (http://www.pulsecommunity.org/page/about). The goal presented is to self-assess, compare the progress of the department with peer institutions, and create a system for peer review.

The microbiology education core concepts from the American Society for Microbiology (ASM) affirm and roughly mirror the five core concepts of *Vision and Change* and add the "impact of microorganisms" (Merkel et al., 2012). Reflecting the scale of interest to this society, the ASM names the concept "cell structure and function" (ASM, 2012, p. 4).

Biochemistry and molecular biology

The molecular life sciences are increasingly interdisciplinary and many current research directions lie at the interfaces with other disciplines (Bell, 2001; Tansey et al., 2013). In a call to educational reform, Bell (2001) outlined the "fundamentals of macromolecular structure and function" when answering the question, "what do budding biochemists need to understand?" The American Society for Biochemistry and Molecular Biology (ASBMB) provides curricular recommendations that strongly emphasize structure and function relationships, using keywords such as "atomic structure," "structure/bonding/nomenclature," "biomolecule structure and function," and "protein structure/function," among many others (Tansey et al., 2013; Voet et al., 2003). Recent core concept outlines also reflect *Vision and Change* (AAAS, 2011) and the molecular scale (Tansey et al., 2013). Currently, the ASBMB reports "macromolecular structure determines function and regulation" as one of the four "core concepts and learning objectives" (ASBMB, 2017). Overall, the biochemistry and molecular biology goals for structure and function are comparatively the most detailed of those examined in this report, with themes, example goals, and subgoals (ASBMB, 2017; Tansey et al., 2013).

Focusing instead on the doctoral degree, the International Union of Biochemistry and Molecular Biology (IUBMB) emphasizes educational activities including professional development and degree expectations (IUBMB, 2017). Without explicit organizational ties to *Vision and Change* (AAAS, 2011), the IUBMB emphasizes structure and function relationships at the outset of the knowledge expectations for graduating PhDs. These expectations are delineated with "knowledge of a Bioscience implies familiarity with: the structure, properties and functions . . ." (IUBMB, 2011, p. 6). It is interesting that "properties" is included in the relationship, with "structure, properties and functions" (IUBMB, 2011). Unlike the concept's form in *Vision and Change* (AAAS, 2011), this

TABLE 1

The professional STEM societies investigated, their acronyms, and their membership information listed in the order in which they are introduced. Collectively, these represent approximately half of a million or more practitioners in these disciplines.

Professional societies and disciplinary organizations	Approximate membership or representation
Partnership for Undergraduate Life Sciences Education (PULSE)	40 leadership fellows as Biology Department representatives (http://www.pulsecommunity.org/page/about)
American Society for Microbiology (ASM)	50,000 (https://www.asm.org/index.php/about-the-american-society-for-microbiology)
American Society for Biochemistry and Molecular Biology (ASBMB)	12,000 (https://www.asbmb.org/aboutus/)
International Union of Biochemistry and Molecular Biology (IUBMB)	No individual membership, represents professionals through adhering bodies and associate adhering bodies in >70 countries (M. P. Walsh, personal communication, July 10, 2017; http://iubmb.org/about-iubmb); "Friends of IUBMB" (not membership) is >12,000 individuals (M. P. Walsh, personal communication, July 10, 2017)
Ecological Society of America (ESA)	>9,000 (https://www.esa.org/esa/about)
Botanical Society of America (BSA)	3,059 as of 2012 (BSA, 2012)
The American Physiological Society (APS-Physiological)	10,500 (http://www.the-aps.org/fm/About)
American Chemical Society (ACS).	>150,000 (https://www.acs.org/content/acs/en/about.html)
Mathematical Association of America (MAA)	22,000 (J. M. Pearson, personal communication, July 10, 2017), MAA is the "world's largest community of mathematicians, students, and enthusiasts " (http://www.maa.org/about-maa)
American Mathematical Association of Two-Year Colleges (AMATYC)	~1,800 individual members (http://www.amatyc.org/?page=AboutUs)
American Statistical Association (ASA)	18,944 as of September 2015 (Ghosh-Dastidar et al., 2016); "members serve in industry, government, and academia in more than 90 countries" (http://www.amstat.org)
Society for Industrial and Applied Mathematics (SIAM)	>14,000 (https://www.siam.org/about/more/overview.php)
ABET	N/A, "currently accredit 3,852 programs at 776 colleges and universities in 31 countries" (http://www.abet.org/about-abet/)
American Physical Society (APS-Physical)	>55,000 (https://www.aps.org/about/index.cfm)
American Association of Physics Teachers (AAPT)	6,500 voting members in 2015 (http://www.aapt.org/Publications/upload/2015_Annual_Report.pdf)
American Institute of Physics (AIP)	>120,000 (https://www.aip.org/aip/about-aip)

presentation is similar to the *Framework*'s "structure and properties of matter" (NRC, 2012, p. 106), for example. This juxtaposition reflects a common phrase modification, similar to structure-behavior-function (Hmelo, Holton, & Kolodner, 2000). Likely, these reflect discipline-based understandings.

Plant biology and ecology

Explicitly aligning with *Vision and Change* (AAAS, 2011) and the *Framework* (NRC, 2012), the American Society of Plant Biologists (ASPB) and Botanical Society of America (BSA) presented their members' consensus including "from molecules to organisms: structures and processes" (ASPB, 2017a, p. 1). The ASPB self-identifies as "active in the Vision and Change in Undergraduate Biology Education (V&C) movement" (ASPB, 2017b).

Although using fewer of the words chosen by other disciplines to explicitly outline structure and function relationships, the Ecology Learning Framework (created by a partnership between ESA and CourseSource; Doherty, Ebert-May, & Pohlad, 2017) presents a list of ecology educational goals. Although open to some interpretation, several of the learning goals are relevant to the general ideas of structure and function relationships. For example, changes in biodiversity at different scales (genetic, species, niche) and population changes over time are examples of specific structure/function relationships (e.g., mutations, changes in protein expression, structural adaptations). As Klemow discussed (1991), the study of ecology itself is highly interdisciplinary, bridging topics such as physiology, genetics, evolution, chemistry, physics, Earth science, and meteorology. As the field is highly interdisciplinary, we propose that many of the *Vision and Change* (AAAS, 2011) crosscutting concepts are strongly applicable in ecology, including structure and function.

Anatomy and physiology

The biological sciences core concepts (AAAS, 2011) also apply to anatomy and physiology. For the field as a whole, physiology is defined by the understanding of structure and function relationships (Lira & Gardner, 2017; Michael, 2007; Michael & McFarland, 2011). It is important to note that these relationships apply at multiple scales and extend to the focus of physiology education centering on the idea of systems thinking and the application of mechanisms. In a ranked list of 15 of the top "big ideas" in physiology, faculty ranked structure and function seventh (Michael & McFarland, 2011). In a follow-up survey, approximately 90% considered structure and function as highly important for their students to know (Michael & McFarland, 2011). This relationship was defined as "the function of a cell, tissue, or organ is determined by its form." Recently, the APS-Physiological produced a thorough guide for their discipline-specific educational reform recommendations in *The Core Concepts of Physiology* that includes structure and function relationships (Michael, Cliff, McFarland, Modell, & Wright, 2017).

Chemistry

The American Chemical Society (ACS; https://www.acs.org/content/acs/en/about.html) places a strong emphasis on science education, particularly at the undergraduate level. Similar to the ASBMB, the ACS also provides certification to undergraduate programs meeting predefined educational requirements. In these requirements, the introductory course includes "basic chemical concepts," including "molecular structure and bonding" (ACS, 2015a). General laboratory competencies include "determination of structures," whereas literature and informational skills include instruction in "effective methods for performing and assessing the quality of searches using keywords, authors, abstracts, citations, patents, and structures/substructures" (ACS, 2015a). Although these expectations (ACS, 2015a) include structure, nothing can be found relating these to any particular "function." We propose that these examples are discipline-specific uses of "structure," especially chemical structures. Additionally, the corresponding functions of those structures (e.g., bonding and reactions) may be an implicit knowledge expectation in chemistry.

The ACS also presents biochemistry guidelines for undergraduate education. Three primary "conceptual topics" are outlined as (a) biological structures and interactions, (b) biological reactions, and (c) biological equilibria and thermodynamics (ACS, 2015b). We propose that "biological structures and interactions" represents another disambiguation of the structure and function concept. Similarly, the role of structure and function relationships is seen in chemistry education, but with discipline-specific interpretations. Chemistry education and laboratory research includes other phrases, such as structure-properties and structure-properties-function (Cooper, Underwood, & Hilley, 2012; Cooper, Underwood, Hilley, & Klymkowsky, 2012; Meijer, Bulte, & Pilot, 2009; Meredith et al., 2006).

Mathematics and statistics

The American Mathematical Association of Two-Year Colleges (AMATYC) presents content guidelines including number sense, symbolism and algebra, geometry and measurement, function sense, continuous and discrete models, and statistics

(AMATYC, 2006). We propose that these ideas represent discipline-specific applications. Similar guidelines for functions and equations are well established for college algebra by the Mathematics Association of America (MAA; 2015), including subgoals for conceptual understanding, the use of multiple perspectives, applications to real-world situations, and the use of multiple methods, among others (reproduced in Saxe & Braddy, 2015).

From college algebra (Saxe & Braddy, 2015) to theoretical mathematics (NRC, 2013), structure and function applications are deeply rooted. Mathematical structures are defined as "a mental construct that satisfies a collection of explicit formal rules on which mathematical reasoning can be carried out" (NRC, 2013, p. 29). For the lay audience, the definition of *function* includes a subset in mathematics including both "a mathematical correspondence" and "a variable (such as a quality, trait, or measurement) that depends on and varies with another" (https://www.merriam-webster.com/dictionary/function). However, the terms are not often found together. A notable exception is found when defining mathematical systems with an application in "partial differential equations (PDEs) are a class of mathematical structure built on the most basic of mathematical structures—functions" (NRC, 2013, p. 29).

The MAA provides an overview of the mathematics education movement (MAA, 2015), whereas the NRC (2013, p. 62) emphasizes the scope and importance of mathematics with the "aim to understand the world by performing formal symbolic reasoning and computation on abstract structures" and two applications of structures. Although less explicit, we propose that the principles for mathematics also apply for statistics education. Similar ideas are found in statistical functions and the computational aspects where a function "does" something based on its structure (examples found in American Statistical Association [ASA], 2016). Other examples are found in modeling of problems with the structure of observations, assumptions, interactions, system responses, and control (Society for Industrial and Applied Mathematics [SIAM], 2012). SIAM (2014) also emphasizes teacher preparation, including the Common Core State Standards Initiative (2017) where students are expected to "look for and make use of structure."

Engineering

Although there are many professional associations for the various engineering subdisciplines, ABET is the accreditation body for engineering education programs. We suggest that many of the expectations for engineering are representations of structure and function. Examples include components, processes, systems, engineering design, and engineering problem solving (ABET, 2016). We propose that the structure and function relationships are similar, but not identical, to those of other fields. For example, the life sciences discuss "emergent properties" that, while vague (O'Connor, 1994), result from the interactions of structure and function for the organism or are discussed with evolution or adaptation (e.g., Cheetham & Caplan, 1998; Davidson, Dassa, Orelle, & Chen, 2008; Doschak & Zernicke, 2005; Ellis, Dodds, & Pryor, 2000; Kageyama, 2002; Ketten, Odell, & Domning, 1992; Li, Korol, Fahima, & Nevo, 2004; Polacek & Mankin, 2005; Sheehan, Meade, & Foley, 2001). In contrast, engineering structure and function are often the product of specific, design-based approaches to meet predetermined goals or work within specific parameters (Dym, Agogino, Eris, Frey, & Leifer, 2005). Although these ideas are fundamentally different, we present them here as discipline-specific applications of structure and function.

Physics

While partially overlapping with chemistry, physics often describes structure and function relationships from the subatomic to galactic scales. Several crosscutting physics themes are outlined in Phys21, a collaboration between the American Physical Society and the American Association of Physics Teachers (Heron & McNeil, 2016), within which structure and function relationships are fundamental, yet not explicitly defined. For example, fundamental themes include "conservation laws, symmetry, systems, models and their limitations, the particulate nature of matter, waves, interactions, and fields" (Heron & McNeil, 2016). Although structure and function are not as explicitly presented in the professional society educational expectations in physics, the K–12 *Framework* emphasizes these ideas by connecting structure and function with systems at many scales (NRC, 2012).

Although the scale may partially overlap with chemistry, physics programs may be similar to engineering in the course requirements for students outside of the major (e.g., mathematics, statistics, and chemistry), which strongly emphasize structure and function relationships also within their respective disciplines (ABET, 2016; Hilborn, Howes, & Krane, 2003). Overall, the engineering and physics disciplines emphasize the connections among other fields as well as the integration of knowledge within and among disciplines (ABET, 2016; Hilborn et al., 2003).

Summary

Professional societies across the STEM disciplines expect students in their disciplines to be able to understand, analyze, and synthesize concepts related to structure and function. This is perhaps one of the most fundamental crosscutting concepts among disciplines. Beyond those described here, many other disciplines such as computer science, languages, the arts, and humanities include potential discipline-specific applications of the general concept of structure and function relationships.

Although the disciplinary societies provide examples and learning goals, we found a glaring lack of definitions for the meaning of *structure and function* as a phrase representing the educational concept or as individual terms, *structure* and *function*. From our observations across multiple disciplines and professional societies, we speculate that there may be additional ambiguity in the meaning of the phrase *structure and function* as a whole as well as the individual contributing terms, *structure* and *function*, especially among STEM disciplines.

Although the disciplines and professional societies described here are not an exhaustive list of the societies or the calls-to-action for undergraduate educational reform, the importance of the concept of structure and function across the disciplines cannot be overstated. From an educational perspective, the vague definitions and idiosyncratic uses within definitions are likely confusing to students. Considering that structure and function relationships are expected to be crosscutting concepts, it is imperative that students be able to form these connections and work with the ideas among disciplines. For instructors teaching disciplinary courses, it is crucial to explicitly address crosscutting concepts, help students make connections, and help them understand the multiple disambiguations of structure and function. ■

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