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Essay

BioCore Guide: A Tool for Interpreting the Core Concepts of Vision and Change for Biology Majors

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Vision and Change in Undergraduate Biology Education outlined five core concepts intended to guide undergraduate biology education: 1) evolution; 2) structure and function; 3) information flow, exchange, and storage; 4) pathways and transformations of energy and matter; and 5) systems. We have taken these general recommendations and created a Vision and Change BioCore Guide—a set of general principles and specific statements that expand upon the core concepts, creating a framework that biology departments can use to align with the goals of Vision and Change. We used a grassroots approach to generate the BioCore Guide, beginning with faculty ideas as the basis for an iterative process that incorporated feedback from more than 240 biologists and biology educators at a diverse range of academic institutions throughout the United States. The final validation step in this process demonstrated strong national consensus, with more than 90% of respondents agreeing with the importance and scientific accuracy of the statements. It is our hope that the BioCore Guide will serve as an agent of change for biology departments as we move toward transforming undergraduate biology education.

> The intent of the Vision and Change conversations and national conference was to move toward a consensus framework in the biology community that would be broadly adaptable, given the unique structures, capacities, and constraints of individual life sciences programs . . . We pose these core concepts . . . as a resource and starting point based on the collective experience and wisdom of a broad national community of biological scientists and educators.
>
> *Vision and Change* (AAAS, 2011, p. 11)

Biology is without question the most diverse of the science, technology, engineering, and mathematics (STEM) disciplines. What began as an observational science has blossomed into a wide-ranging set of subdisciplines, each with its own set of key concepts, experimental techniques, and approaches to the study of life. The discipline is currently so segmented that biologists who work in particular subdisciplines attend separate scientific meetings, publish in specialty journals, and are sometimes housed in different departments.

The rapid expansion and increased diversity of the field has greatly expanded the scope and impact of biological discoveries but creates a challenge for instructors. The exponential rate of discovery in biology makes it difficult to decide what to teach in a 4-yr undergraduate curriculum. Given that we cannot teach everything, can we reach consensus about what is most important to teach?

IDENTIFICATION OF CORE CONCEPTS IN UNDERGRADUATE BIOLOGY

In an effort to consolidate the ever-expanding volume of biological knowledge to a more manageable set of ideas, several groups have outlined the "big ideas" in biology (Table 1). Some of these efforts are focused on biology as a whole, whereas others are targeted to specific subdisciplines. Collectively, this literature has laid a strong foundation for articulating the most important aspects of biology and several common "big ideas" have emerged. While these efforts have enhanced awareness, many lack large-scale validation,

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Table 1. Previous efforts to define the core ideas of biology

Report/title	Date	Big ideas of biology	Audience	Citation
BIO2010	2003	Eighteen one- to two-sentence concepts for undergraduate biology curriculum	General undergraduate biology	NRC, 2003, pp. 32–33
Biology Concept Framework (BCF)	2004	Hierarchical, cross-referenced concepts related to genetics and molecular biology	Subdiscipline undergraduate biology	Khodor *et al.*, 2004
Core ideas in pathogen–host interactions	2007	Identified common anchor organisms and six topic areas that would be integrated across all courses in a series of courses	Subdiscipline undergraduate biology	Marbach-Ad *et al.*, 2007
Core ideas in biochemistry	2011	Used conceptual lens to demonstrate how core ideas in biochemistry fit under Vision and Change core concepts	Subdiscipline undergraduate biology	Rowland *et al.*, 2011
Big ideas in physiology	2009–2011	Unpacked five most important core principles in physiology, including cell membranes, homeostasis, cell-to-cell communications, interdependence, and flow-down gradients.	Subdiscipline undergraduate biology	Michael *et al.*, 2009; Michael and McFarland, 2011
Editorial	2001	Evolution should be overarching framework of biology	General undergraduate biology	Alles, 2001
Editorial	2010	Three core conceptual foundations of modern biology are evolutionary thinking, molecular foundations, and network behavior	General undergraduate biology	Klymkowsky, 2010
Editorial	2010	Conceptual framework for biology that includes five general theories: cells, organisms, genetics, ecology, and evolution	General undergraduate biology	Scheiner, 2010
A framework for Advanced Placement Biology	2002–2009	College Board's revision of the AP Biology curriculum around four "big ideas" and seven science practices	AP Biology	Wood, 2009 http://apcentral.collegeboard.com/apc/public/courses/teachers_corner/2117.html
A framework for K–12 science education	2011	Crosscutting concepts that unify the study of science; scientific and engineering practices; and disciplinary core ideas	General K–12 biology	Quinn *et al.*, 2011
Vision and Change in Undergraduate Biology Education: A Call to Action	2011	Identified five core concepts of biology	General undergraduate biology	AAAS, 2011

which may explain why few have gained significant traction in the wider community. The most notable exception to this is the framework for K–12 education, which has recently been adopted as a set of scientific standards for elementary and secondary schools, but the focus of this set of recommendations is on K–12 and not undergraduate biology.

At the undergraduate level, the most extensive effort has come from a collaboration between the National Science Foundation (NSF) and the American Association for the Advancement in Science (AAAS), which culminated in the report *Vision and Change in Undergraduate Biology Education: A Call to Action* (AAAS, 2011). Through a series of conversations at regional and national meetings, more than 500 biologists and biology educators discussed the need to reform undergraduate biology education and provided a set of unifying recommendations. Specifically, *Vision and Change* outlined five core concepts that are important for undergraduate biology majors to understand by the time they graduate (Table 2).

While it successfully distilled the complexity of biology down to only five core concepts, the recommendations set forth in *Vision and Change* were intentionally broad. They were meant to serve as "a resource and starting point" (AAAS, 2011, p. 11) for further delineation into subconcepts. The challenge is to elaborate the core concepts, so faculty members have a better grasp on how to teach them.

Taking the next step, the Society for Microbiology (Merkel, 2012), the American Society for Biochemistry and Molecular Biology (Tansey *et al.*, 2013), and the American Society of Plant Biologists and Botanical Society of America (American Society of Plant Biologists, 2012) have outlined how the core

Table 2. Core concepts outlined in *Vision and Change: A Call to Action* (AAAS, 2011)

1. Evolution
2. Structure and function
3. Information flow, exchange, and storage
4. Pathways and transformations of energy and matter
5. Systems

concepts of Vision and Change could be interpreted in each of their subdisciplines. While these society-specific efforts have been useful in making the core concepts more concrete for instructors teaching courses in these subdisciplines, their statements are often too specific for general biology majors, who are tasked with gaining a conceptual understanding of the discipline as a whole. To build on the important work coming out of the subdisciplines, we set out to interpret what the core concepts of Vision and Change mean for a general biology curriculum.

TARGET AUDIENCE FOR BIOCORE GUIDE: GRADUATING GENERAL BIOLOGY MAJORS

Although a unified curriculum for all undergraduate biology majors has not been established (Cheesman *et al*., 2007), there have been efforts focused on identifying both a common set of courses (Heppner *et al*., 1990; Marocco, 2000; National Research Council [NRC], 2003; Cheesman *et al*., 2007; Labov *et al*., 2010) and a common set of essential topics (Ledbetter and Campbell, 2005; Timmerman *et al*., 2008; AAAS, 2011; Gregory *et al*., 2011). However, in line with the increased specialization of biology, curricula have also been recommended for biochemistry (Voet *et al*., 2003), zoology (Russell, 2009), physiology (Silverthorn, 2003), and neuroscience (Wiertelak and Ramirez, 2008).

Would the biology community as a whole benefit more from recommendations for general biology majors or for subdiscipline-specific majors? To answer this question, we examined the structure of biology departments and majors at a randomly selected sample of 183 institutions throughout the United States (see Supplemental Material for methodology). As the data in Table 3 indicate, the vast majority of colleges and universities in our sample have general biology departments and confer a general biology degree. On the basis of these results, we concluded that the most useful approach for most institutions would be to articulate what the Vision and Change core concepts mean to faculty and students in a general biology program.

Table 3 Prevalence of general biology departments and general biology degrees[a]

Institution type by highest degree granted	Percentage of institutions with a general biology department	Percentage of institutions that confer a general biology degree
Bachelor	74.1	96.3
Master's	87.5	95.8
Doctorate	90	93.3

[a]Out of a random sample of 10% of the total number of Carnegie-classified institutions that confer bachelor's, master's, and doctoral degrees (n = 183 institutions), the majority has general biology departments and confer a general biology degree.

CONCEPTUAL FRAMEWORK: CREATING THE BIOCORE GUIDE FOR VISION AND CHANGE'S CORE CONCEPTS

With the core concepts of Vision and Change as a guide, we delineated a set of general principles for each concept. These principles are cross-disciplinary elaborations of each larger core concept intended to illustrate central themes that can be applied to different subdisciplines of biology. We also outlined a set of statements that were more specific interpretations of each of the core concepts within the three major subdisciplines of biology: molecular/cellular/developmental biology, physiology, and ecology/evolution. Although artificial—the three subdivisions do not exist as separate entities in organisms—they do represent the typical components of an introductory biology curriculum and span the scale of biology, from molecules to ecosystems. Thus, we used these subdisciplines as an attempt to sample the diversity of biology.

Collectively, we refer to the principles and statements as the Vision and Change BioCore Guide. Figure 1 summarizes the relationship between the different BioCore Guide elements and how the BioCore Guide itself relates to the broader goals of Vision and Change. We expect that the organization of core concepts, principles, and statements will be useful to the biology community as departments strive to adhere to the recommendations of Vision and Change. For example, test questions could be written that assess student understanding of each statement, and by extension, each principle and core concept.

A GRASSROOTS APPROACH TO DEVELOPING THE VISION AND CHANGE BIOCORE GUIDE

To develop a tool that biology faculty would use and endorse, we involved biology faculty at each step of the process. This bottom-up, grassroots approach differs from more traditional efforts that rely on small working groups, often composed of faculty members who are on education committees and/or engaged in education research, to investigate an issue, write a report summarizing their findings, and then disseminate these "best practices" to the broader academic community. Despite the popularity of these top-down methods, they have not been shown to be particularly effective for catalyzing faculty and institutional change (Henderson *et al*., 2010, 2011). Although we incorporated feedback from biology education researchers who have been policy makers at specific points in the development process, the goal of our "faculty-first" approach was to produce a tool that would resonate with instructors and thereby encourage implementation. An overview of our process is shown in Figure 2.

Phase I. Home Institution Development and Review

As a first step, we obtained input from biology faculty at the University of Washington. Specifically, we engaged faculty members with Vision and Change by having them consider whether the five core concepts of Vision and Change were important for graduating biology majors to understand. Using an online survey, we found strong alignment between the national goals of Vision and Change and faculty goals in this

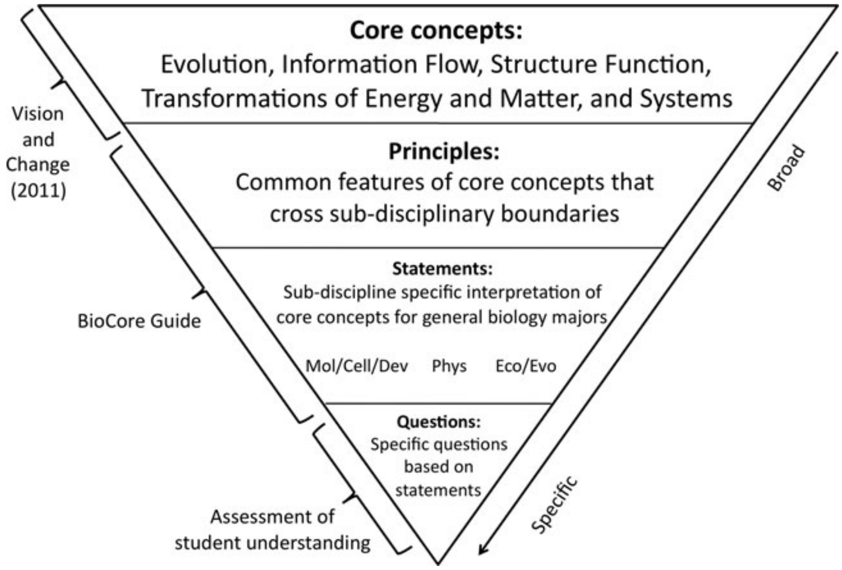

Figure 1. Conceptual framework for interpreting the core concepts of Vision and Change. Based on the core concepts of Vision and Change, the BioCore Guide consists of two levels: principles and statements. Specific questions based on the statements can be developed to assess student understanding of these concepts.

department; all of the core concepts of Vision and Change were judged to be as important or more important than previously established departmental learning goals.

Our next step was to begin operationalizing the core concepts of Vision and Change into specific statements for each of the three major subdisciplines of biology. We did this by recruiting faculty to join one of three different focus groups with expertise in 1) molecular/cellular/developmental biology, 2) physiology, and 3) ecology/evolution. Faculty groups, each composed of three faculty members, independently brainstormed ideas for how each of the Vision and Change core concepts could be interpreted for their subdiscipline. They then refined their ideas to produce two to three statements for each of the core concepts, with each statement intended to capture features of their subdiscipline that they wanted general biology majors to master before graduation. We then assembled all the statements into a first-draft BioCore Guide. The "local" phase of the development process closed after three iterative revisions, based on discussions with the University of Washington (UW) Biology Education Research Group ($n = 4$), the Undergraduate Curriculum Committee ($n = 11$), and attendees at departmental faculty meetings ($n \sim 25$).

Phase II. National Review and Validation

In the second phase of developing the BioCore Guide, we solicited feedback on the initial draft from biologists and biology educators with different subdiscipline expertise in biology at a diverse set of national institutions. Using a convenience-sampling approach, we identified biology faculty members who were content experts and asked them to evaluate each statement and provide feedback on: 1) its scientific accuracy/wording and 2) its importance in terms of what a general biology major should understand by the time he or she graduates. We encouraged respondents to provide written edits of each statement and also asked them to identify additional or missing concepts. Participants were reminded to focus on the level of understanding expected of a general biology major, not a specialist from one of the subdisciplines. Twenty-five biologists (nine ecologists/evolutionary biologists, seven physiologists, and nine molecular/cellular biologists) provided written feedback. We then summarized their suggestions, identified consensus ideas, and modified the BioCore Guide accordingly. While we did not incorporate all of the suggestions, we did discuss each contribution and weighed its relevance in relationship to other suggestions.

Using the newly revised version of the BioCore Guide, we then solicited feedback from the biology education research community in two ways. We organized a focus group composed of five biology education researchers at the national meeting of the Society for Advancement in Biology Education (SABER) and asked participants to comment on the "big picture" organization of the document. This discussion resulted in two major changes to the BioCore Guide: 1) we developed broader principles under each concept, as a way to better organize the specific statements and see commonalities among subdisciplines; and 2) the biologically artificial boundaries among the subdisciplines were supplemented by a biologically relevant scale of molecules to ecosystems. In addition, we requested feedback on the BioCore Guide from professionals at SABER's national meeting whose work focused on instruction and discipline-based education research. Ten additional participants provided written comments on the accuracy of the statements and their importance for a graduating general biology major; these comments were used to further modify the BioCore Guide.

As a final step, we sought national validation of the BioCore Guide. We administered an anonymous online survey, distributed through mailing lists of a diverse group of scientific societies and education research groups (for a list of the organizations contacted, see the Supplemental Material). The voluntary survey asked reviewers to rate on a 4-point Likert scale ranging from "strongly disagree" to "strongly agree" whether each principle and statement in the BioCore Guide was 1) scientifically accurate and 2) important for a graduating biology major to understand. We intentionally did not provide reviewers will the option of a "neutral" response, because we wanted the reviewers to take a stance on each

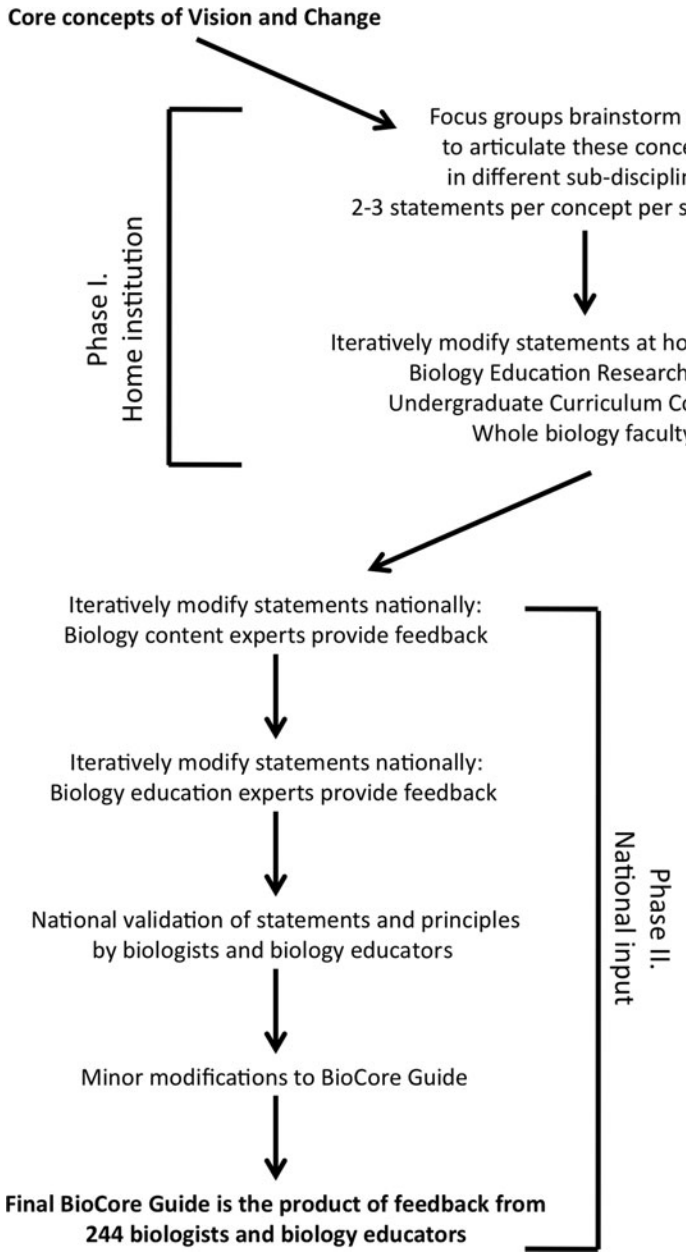

Figure 2. The development process for the BioCore Guide. In this two-phase process, we began developing the BioCore Guide by soliciting input from faculty at the University of Washington. We then obtained feedback from biologists and biology educators nationally. In total, the BioCore Guide was iteratively revised six times.

statement and felt that practicing biologists should be comfortable with all the topics required of a general biology major. Reviewers were also given the opportunity to provide specific edits or comments, including whether any major topics were missing from the BioCore Guide. We obtained feedback from 184 participants, who varied by subdiscipline expertise and type of institution (Table 4).

In sum, we collected individual written feedback from 244 biologists and biology educators. The comments and edits were extensive, indicating that respondents took the time to provide a thorough and thoughtful review of the BioCore Guide. The large number of written responses supports the claim that the BioCore Guide represents the most extensive and systematic collection of faculty opinion on the core concepts of Vision and Change to date.

VISION AND CHANGE BIOCORE GUIDE OF CORE CONCEPTS FOR GENERAL BIOLOGY MAJORS

Through our national validation, we received input on whether the principles and statements achieved scientific accuracy and whether they were important for a graduating general biology major to know. Table 5 summarizes the validation data for the five principles and 40 statements in the BioCore Guide by showing average percent agreement for each section.

More than 95% of respondents agreed that each of the principles was important for a general biology major to master before graduation (Table 5). In addition, more than 89% of respondents agreed with the scientific accuracy of each of the

Table 4. Demographics of survey respondents for national validation ($n = 184$)

Institution type	
Research university	40.2%
Comprehensive university	26.6%
Small liberal arts college	19.0%
Community college	11.4%
Other	2.7%
Position	
Assistant/associate/full professor	67.9%
Lecturer/instructor	18.5%
Postdoctoral scholar	4.3%
Graduate student	3.3%
Other	6.0%
Subdiscipline expertise	
Molecular/cellular/developmental biology	41.85%
Physiology	16.3%
Ecology/evolutionary biology	41.85%

principles. Because reviewers had an opportunity to provide specific feedback on the principles, we were able to modify each principle to reflect the consensus feedback; the revised principles appear in Figure 3.

In the national validation of the statements, respondents agreed that all 40 of the statements were important for a graduating general biology major to know, with average agreement for each section being more than 93% (Table 5). Reviewers also rated the scientific accuracy of the 40 statements highly; average agreement for scientific accuracy was more than 90% for each section. Reviewers suggested minor modifications to some statements. If at least three people in the national validation made the same suggestion, the alterations were incorporated into the BioCore Guide; the revisions are shown in Figure 3.

We gave reviewers the opportunity to recommend other concepts that may be important to include for a general biology major that we had not included on the BioCore Guide. No concepts were suggested by more than 5% of our sample, which we interpreted to mean that reviewers did not think that the BioCore Guide was missing any critically important statements. However, we do provide a list of these additional ideas in Supplemental Table S1, organized by core concept. Although these suggestions have not been validated, they could serve as a resource for biologists interested in incorporating a greater number of ideas into the BioCore Guide.

In addition to providing the version of the BioCore Guide that was sent for national validation, Supplemental Figure S1 indicates which principles and statements were modified to produce Figure 3 and reports the averages on the Likert scale of 1–4 (1 = strongly disagree; 4 = strongly agree) and percentages of agreement for importance and scientific accuracy for each statement and principle based on the national survey.

The final Vision and Change BioCore Guide of core concepts, shown in Figure 3, has been built by 244 members of the biology community and iteratively revised a total of six times. For each core concept, the BioCore Guide consists of a set of cross-disciplinary principles and two to three statements for each subdiscipline.

WHERE DO THE CORE COMPETENCIES OF VISION AND CHANGE FIT IN?

Vision and Change outlined a set of core competencies in addition to the five core concepts. These include the ability to: 1) apply the process of science, 2) use quantitative reasoning, 3) use modeling and simulation, 4) tap into the interdisciplinary nature of science, 5) communicate and collaborate with other disciplines, and 6) understand the relationship between science and society. We chose to focus on explicating the core concepts of biology rather than the core

Table 5. Percentage of national agreement with BioCore Guide principles and statements[a]

	Principles			Statements	
	Scientific accuracy	Important for graduating biology major to know		Scientific accuracy	Important for graduating biology major to know
Evolution	96%	98%	Mol/Cell	96%	99%
			Phys	91%	95%
			Eco/Evo	95%	97%
Information flow	97%	99%	Mol/Cell	98%	97%
			Phys	98%	97%
			Eco/Evo	98%	99%
Structure function	91%	97%	Mol/Cell	97%	96%
			Phys	96%	93%
			Eco/Evo	95%	94%
Transformations of energy and matter	89%	95%	Mol/Cell	99%	96%
			Phys	98%	94%
			Eco/Evo	97%	95%
Systems	94%	97%	Mol/Cell	99%	93%
			Phys	98%	95%
			Eco/Evo	95%	96%

[a]Data shown are average percentage agreement for each principle and for all the statements for each subdiscipline from 184 respondents.

Major Subdisciplines of Biology

	Molecular/ Cellular/ Developmental Biology	Physiology	Ecology/ Evolutionary Biology
EVOLUTION	**Overarching Principles:** **All living organisms share a common ancestor.** **Species evolve over time, and new species can arise, when allele frequencies change due to mutation, natural selection, gene flow, and genetic drift.**		
	Multiple molecular mechanisms, including DNA damage and errors in replication, lead to the generation of random mutations. These mutations create new alleles that can be inherited via mitosis, meiosis, or cell division.	Mutations that change protein structure and/or regulation can impact anatomy and physiological function at all levels of organization.	The characteristics of populations change over time due to changes in allele frequencies. Changes in allele frequencies are caused by random and nonrandom processes--specifically mutation, natural selection, gene flow, and genetic drift. Not all of these changes are adaptive.
	Mutations and epigenetic modifications can impact the regulation of gene expression and/or the structure and function of the gene product. If mutations affect phenotype and lead to increased reproductive success, the frequency of those alleles will tend to increase in the population.	Most organisms have anatomical and physiological traits that tend to increase their fitness for a particular environment.	All species alive today are derived from the same common ancestor. New species arise when populations become genetically isolated and diverge due to mutation, natural selection, and genetic drift. Phylogenetic trees depict relationships among ancestral and descendant species, and are estimated based on data.
		Physiological systems are constrained by ancestral structures, physical limits, and the requirements of other physiological systems, leading to trade-offs that affect fitness.	Fitness is an individual's ability to survive and reproduce. It is environment-specific and depends on both abiotic and biotic factors. Evolution of optimal fitness is constrained by existing variation, trade-offs and other factors.

Molecules (smaller and faster) → **Ecosystems (larger and slower)**

Biological Scale

Figure 3. BioCore Guide: a nationally validated tool for interpreting the core concepts of Vision and Change. We present the principles and statements that encompass the BioCore Guide, which have been built by more than 200 people in the biology community. The columns represent the three major subdisciplines of biology (molecular/cellular/developmental biology, physiology, and ecology/evolutionary biology), which are also depicted on a biological scale from the molecular to the ecosystem level. Each concept is represented by a separate box, with a set of overarching principles that cross subdisciplinary boundaries at the top and then two to three statements for each of the subdisciplines. (*Continued on next page*)

competencies, simply because we found the concepts to be more controversial with faculty—we observed much lower consensus among faculty members regarding what the five core concepts mean for their subdiscipline. Although this essay focuses solely on the core concepts, it is not because the competencies are less important. In our view, it is essential to address both core concepts and competencies as we work toward undergraduate biology reform.

THE BIOCORE GUIDE SPANS A 4-YR UNDERGRADUATE BIOLOGY CURRICULUM

Although many of the BioCore Guide statements are addressed in introductory biology courses because of their fundamental importance, some may be more appropriately taught in advanced courses. We did not determine at what level each statement should be taught, but emphasize that the BioCore Guide is intended to be used beyond introductory biology. We strongly encourage its use across the curriculum in ways that will promote an emphasis on the core concepts—even in upper-level courses with highly specialized topics. We hope that the BioCore Guide will promote dialogue about when each of these statements should be taught and how basic concepts can be elaborated on and reinforced in upper-level courses. Students need multiple opportunities to work with an idea to help them understand it at a deeper level. Additionally, engaging with the same concepts across the curriculum will help students understand the importance of using these core concepts as a way to structure their thinking about biology.

INFORMATION FLOW

Overarching Principles:

Organisms inherit genetic and epigenetic information that influences the location, timing, and intensity of gene expression.

Cells/organs/organisms have multiple mechanisms to perceive and respond to changing environmental conditions.

In most cases, genetic information flows from DNA to mRNA to protein, but there are important exceptions.	Information stored in DNA is expressed as RNA and proteins. These gene products impact anatomical structures and physiological function.	Individuals transmit genetic information to their offspring; some alleles confer higher fitness than others in a particular environment.
Gene expression and protein activity are regulated by intracellular and extracellular signaling molecules. Signal transduction pathways are crucial in relaying these signals.	Organisms have sophisticated mechanisms for sensing changes in the internal or external environment. They use chemical, electrical, or other forms of signaling to coordinate responses at the cellular, tissue, organ, and/or system level.	A genotype influences the range of possible phenotypes in an individual; the actual phenotype results from interactions between alleles and the environment.
The signals that a cell receives depend on its location, and may change through time. As a result, different types of cells express different genes, even though they contain the same DNA.		

STRUCTURE FUNCTION

Overarching Principles:

Biological structures exist at all levels of organization, from molecules to ecosystems. A structure's physical and chemical characteristics influence its interactions with other structures, and therefore its function.

Natural selection leads to the evolution of structures that tend to increase fitness within the context of evolutionary, developmental, and environmental constraints.

The structure of a cell--its shape, membrane, organelles, cytoskeleton, and polarity--impacts its function.	Physiological functions are often compartmentalized into different cells, tissues, organs, and systems, which have structures that support specialized activities.	Natural selection has favored structures whose shape and composition contribute to their ecological function.
The three dimensional structure of a molecule and its subcellular localization impact its function, including the ability to catalyze reactions or interact with other molecules. Function can be regulated through reversible alterations of structure e.g. phosphorylation.	The size, shape, and physical properties of organs and organisms all affect function. The ratio of surface area to volume is particularly critical for structures that function in transport or exchange of materials and heat.	Competition, mutualism, and other interactions are mediated by each species' morphological, physiological, and behavioral traits.
The structure of molecules or organisms may be similar due to common ancestry or selection for similar function.	Structure constrains function in physiology; specialization for one function may limit a structure's ability to perform another function.	

Molecules (smaller and faster) → **Ecosystems (larger and slower)**

Biological Scale

Figure 3. (*Continued*)

Outlining how topics could be taught across the curriculum could help us develop learning progressions for these concepts in undergraduate biology (Duncan and Rivet, 2013). It may be important to reinforce statements that are introduced early in an undergraduate's career—restating and reminding, but perhaps also elaborating. An increasingly sophisticated understanding might focus on the complexity of biological interactions and processes, helping students move from thinking about single molecules, signal transduction pathways, or communities to analyzing the complex interactions that exist among these different entities. Further, while general or canonical examples might be presented in introductory courses, upper-level classes could explore important exceptions, delve into the primary literature, or challenge students

TRANSFORMATIONS OF ENERGY AND MATTER

Overarching Principles:

Energy and matter cannot be created or destroyed, but can be changed from one form to another.

Energy captured by primary producers is necessary to support the maintenance, growth and reproduction of all organisms.

Natural selection leads to the evolution of efficient use of resources within constraints.

Energy captured by primary producers is stored as chemical energy. This stored energy can be converted through a series of biochemical reactions into ATP for immediate use in the cell.	Energy captured by primary producers is stored as chemical energy. This stored energy can be converted into ATP, which is required for energetically demanding activities necessary for life, including synthesis, transport, and movement.	Energy captured by primary producers is stored as chemical energy. At each trophic level, most of this energy is used for maintenance, with a relatively small fraction available for growth and reproduction. As a consequence, each trophic level in an ecosystem has less energy available than the preceding level.
In cells, the synthesis and breakdown of molecules is highly regulated. Biochemical pathways usually involve multiple reactions catalyzed by enzymes that lower activation energies. Energetically unfavorable reactions are driven by coupling to energetically favorable reactions such as ATP hydrolysis.	Due to the inefficiency of biochemical reactions and other constraints, physiological processes are never 100% efficient.	Chemical elements are transferred among the abiotic and biotic components of an ecosystem; changes in the amount and distribution of chemical elements can impact the ecosystem.
Intracellular and intercellular movement of molecules occurs via 1) energy-demanding transport processes and 2) random motion. A molecule's movement is affected by its thermal energy, size, electrochemical gradient, and biochemical properties.	Organisms have limited energetic and material resources which must be distributed across competing functional demands. These include movement of material across gradients, growth, maintenance, and reproduction, inevitably leading to trade-offs.	

SYSTEMS

Overarching Principles:

Biological molecules, genes, cells, tissues, organs, individuals, and ecosystems interact to form complex networks. A change in one component of the network can affect many other components.

Organisms have complex systems that integrate internal and external information, incorporate feedback control, and allow them to respond to changes in the environment.

Cells receive a complex array of chemical and physical signals that vary in time, location, and intensity over the lifespan of the organism; a cell's response depends on integration and coordination of these various signals.	Organ systems are not isolated, but interact with each other through chemical and physical signals at the level of cells, tissues, and organs.	The size and structure of populations are dynamic. A species' abundance and distribution is limited by available resources and by interactions between biotic and abiotic factors.
During development, the signals a cell receives depend on its spatial orientation within the embryo and its intercellular interactions. As a consequence, cells adopt different cell fates depending on their local environment and/or cell lineage.	An individual's physiological traits affect its interactions with other organisms and with its physical environment.	Ecosystems are not isolated and static--they respond to change, both as a result of intrinsic changes to networks of species and as a result of extrinsic environmental drivers. Within an ecosystem, interactions among individuals form networks; changes in one node of a network can cause changes in other nodes--directly or indirectly.
Alteration of a single gene or molecule in a signaling network may have complex impacts at the cell, tissue or whole-organism level.	In the face of environmental changes, organisms may maintain homeostasis through control mechanisms that often use negative feedback; others have adaptations that allow them to acclimate to environmental variation.	Biodiversity impacts many aspects of ecosystems.

Molecules (smaller and faster) → **Ecosystems (larger and slower)**

Biological Scale

Figure 3. (*Continued*)

to engage more with the Vision and Change core competencies.

Consider a BioCore Guide statement from the information flow concept under molecular/cellular biology: "In most cases, genetic information flows from DNA to mRNA to protein, but there are important exceptions." We imagine that most introductory courses cover the basic ideas of transcription and translation but may not address the exceptions to the DNA → mRNA → protein pathway or how the flow of genetic information is controlled. In upper-level molecular biology courses, more of the details and exceptions will likely be introduced. For example, students may be asked to explore the role of microRNAs in gene regulation or to analyze examples of successive reduction in genome size in somatic cells during development in organisms such as *Tetrahymena* or lamprey. Finally, upper-level courses may have students read primary literature or interpret data that either support or refute a given statement related to this core idea.

USING THE BIOCORE GUIDE TO IMPROVE THE UNDERGRADUATE CURRICULUM

We envision at least five major purposes for this BioCore Guide, which we outline below.

Strengthening Connections between Course-Specific Learning Goals and the Core Concepts from Vision and Change

There are few guidelines for faculty to use when developing course goals and learning outcomes. The BioCore Guide furnishes a nationally validated guideline for identifying student learning objectives and other course outcomes. If a faculty member aligns course goals with statements from the BioCore Guide, that instructor, along with other faculty teaching in the department, should gain a better understanding of how specific course activities can help students reach nationally validated goals for biology majors. In addition, students may be able to see which courses target the same statements and better appreciate common themes among courses or how course sequences build on each other.

Aligning a Curriculum with the BioCore Guide to Identify Gaps

Most departments strive to offer a cohesive curriculum for general biology majors. But currently, faculty members who teach upper-level courses are often unaware of what their colleagues are teaching in introductory courses. If so, courses and curricula can become disconnected from one another. Identifying which concepts are addressed in which courses—by mapping a suite of required courses onto the BioCore Guide—could allow departments to identify gaps in their curriculum (e.g., statements not targeted by any courses) and assess whether prerequisite courses introduce the core concepts that upper-level courses build upon.

Help Undergraduates See the "Big Picture" of Biology

Undergraduate majors frequently wrestle with how the details they are learning in various courses fit into a larger, synthetic view of biology. Faculty advisors could use the BioCore Guide to help students see how their required biology and non–biology courses fit together and how courses with differences in subject matter (e.g., ecology and molecular biology) have common underlying principles.

Accreditation and Certification

Department chairs, committee heads, and deans could use the BioCore Guide during the accreditation process to articulate larger curricular goals. In addition, work has begun on developing a certification program for departments that align their programs with the goals of Vision and Change. The Partnership for Undergraduate Life Sciences Education (PULSE) is a collaborative effort developed and funded by the National Institute of General Medical Sciences of the National Institutes of Health and the Howard Hughes Medical Institute to catalyze the adoption of the goals outlined in the *Vision and Change* report. The PULSE organization has started the process by creating rubrics for departments to use in assessing alignment (PULSE Community, 2014). The BioCore Guide could be used in conjunction with the PULSE rubrics as a way for departments to self-assess their current status at meeting curricular learning outcomes aligned with the core concepts.

Use the BioCore Guide as a Basis for Diagnostic Programmatic Assessments

The biology community is largely in agreement that undergraduate biology majors should master the core concepts outlined in *Vision and Change* by the time they graduate. We now need a way of assessing whether they have achieved that understanding. There are a number of different approaches for testing student understanding of fundamental concepts (e.g., Nehm and Schonfeld, 2008; Shi *et al*., 2010; Hartley *et al*., 2011; Smith *et al*., 2013), each with its own strengths. However, the community currently lacks a test that could be easily administered to thousands of students to serve the needs of biology departments interested in assessing general biology majors' understanding of the core concepts spanning the subdisciplines.

Thus, as part of a multi-institution team (University of Washington, University of Maine, University of Colorado–Boulder, Arizona State University, and University of Nebraska–Lincoln), we are using this BioCore Guide to develop a restricted-response programmatic assessment that will track undergraduate biology majors' understanding of core concepts as they progress through the major. As our goal is to produce a test that could be used at the departmental or programmatic level—not the individual course level—we are proposing that it be administered to students at multiple time points in a curriculum: 1) before introductory biology, to assess students' incoming knowledge; 2) after completion of an introductory biology series, to gauge students' intermediate progress; and 3) before graduation, to determine the summative impact of the biology curriculum. Collecting baseline scores for students will allow institutions that have students transferring in at different points in the curriculum or students entering with different abilities to see the specific impact of their program on student understanding of the core concepts. We are intentionally structuring questions to target both introductory and advanced levels of thinking so that we can monitor improvement of student thinking as students progress through the curriculum. Success with the advanced-level questions would require higher-order cognitive understanding of one topic and/or across-discipline thinking that requires students to think broadly about biological concepts. Taking an integrative approach, focused on assessing student learning of diverse topics in biology at multiple stages of a general biology curriculum, will make this test distinct from previously developed concept inventories, capstone assessments, and subdiscipline-specific efforts. We are currently developing questions for this diagnostic tool, each of which will be aligned with the BioCore Guide, and thus Vision and Change, with the goal of producing a general biology test that would be available to interested institutions in the next few years. Departments could then use this programmatic assessment to monitor student learning and make evidence-based revisions to their curricula.

ADAPTING THE BIOCORE GUIDE FOR USE AT YOUR OWN INSTITUTION

We offer this BioCore Guide as a starting point for the five applications listed above and acknowledge that the goals of undergraduate biology education will evolve as the field of biology changes. Thus, the framework is not intended to be static; it will need to be modified and updated over time.

Departments may even wish to adapt this BioCore Guide immediately, so that it conforms more closely to their interests, needs, and departmental culture. Although a departmentally modified BioCore Guide will not have national validation, it may be more effective in terms of promoting faculty acceptance and institutional change.

In addition, the BioCore Guide is not meant to be prescriptive. The statements should not be viewed as a checklist for faculty instruction or be used to constrain what biology faculty teaches. Much of what excites us and our students lies in the details of our fields: a rare genetic disease, the crystal structure of a G protein–coupled receptor, the impact of climate change on salamander populations, the relationship between stress and Alzheimer's disease. Far from pushing faculty away from a personalized view of biology, our goal is to give instructors an organizing framework to position specific examples, moving the focus away from a collection of facts and toward a more cohesive picture of our science.

This BioCore Guide, implemented in conjunction with the PULSE community's rubrics and ultimately with our programmatic assessment, could help departments incorporate the Vision and Change call to action into their institutional culture. We envision this BioCore Guide as an agent of change to help us complete this journey.

ACKNOWLEDGMENTS

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Supplemental Material

CBE—Life Sciences Education

Brownell *et al.*

Major Sub-disciplines of Biology

	Molecular/ Cellular/ Developmental Biology	Physiology	Ecology/ Evolutionary Biology

EVOLUTION

Overarching Principles:

Evolution is a change in allele frequencies caused by mutations, natural selection, gene flow, or genetic drift. Populations can diverge, leading to the formation of new species.

Mutations are changes in DNA that occur at random in every generation in every population. Natural selection occurs when individuals with certain heritable traits have higher reproductive success than individuals without those traits. Genetic drift occurs when allele frequencies change by chance.

Importance for graduating biology major	Scientific accuracy
3.82 (0.04)	3.55 (0.05)
SA: 85.9% A: 12.5% D: 0% SD: 1.6%	SA: 60.9% A: 35.3% D: 2.2% SD: 1.6%

Molecular/ Cellular/ Developmental Biology		Physiology		Ecology/ Evolutionary Biology	
Multiple molecular mechanisms, including DNA damage and errors in replication, lead to the generation of random mutations. These mutations create new alleles that can be inherited via mitosis (through asexual reproduction) or meiosis (through sexual reproduction).		Mutations that change protein structure and/or regulation can impact anatomy and physiological function at all levels of organization.		The characteristics of populations change over time due to changes in allele frequencies. Changes in allele frequencies are caused by random and nonrandom processes--specifically mutation, natural selection, gene flow, and genetic drift. Not all of these changes are adaptive.	
Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.79 (0.04)	3.58 (0.05)	3.73 (0.04)	3.65 (0.04)	3.81 (0.03)	3.72 (0.04)
SA: 81.5% A: 16.9% D: 0.5% SD: 1.1%	SA: 64.1% A: 31.5% D: 2.7% SD: 1.6%	SA: 75% A: 22.8% D: 2.2% SD: 0%	SA: 70.1% A: 25.5% D: 3.8% SD: 0.5%	SA: 81.0% A: 19.0% D: 0% SD: 0%	SA: 73.4% A: 25.0% D: 1.6% SD: 0%
Mutations and epigenetic modifications can impact the regulation of gene expression and/or the structure and function of the gene product. If mutations affect phenotype and lead to increased reproductive success, the frequency of those alleles will increase in the population.		*Most organisms have anatomical and physiological traits that maximize their fitness for a particular environment.*		All species alive today are derived from the same common ancestor. New species arise when populations become genetically isolated and diverge due to mutation, selection, and drift. Phylogenetic trees depict relationships among ancestral and descendant species, and are estimated based on data.	
Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.77 (0.03)	3.60 (0.04)	3.50 (0.05)	3.27 (0.06)	3.73 (0.04)	3.55 (0.05)
SA: 78.3% A: 20.7% D: 1.1% SD: 0%	SA: 63.6% A:33.1 % D: 3.26% SD:0 %	SA: 60.3% A: 31.0% D: 7.6% SD: 1.1%	SA: 46.7% A: 35.9% D: 15.2% SD: 2.2%	SA: 77.2% A: 19.6% D: 2.2% SD: 1.1%	SA: 63.0% A: 30.4% D: 4.9% SD: 1.6%
		Physiological systems are constrained by ancestral structures, physical limits, and the requirements of other physiological systems, leading to trade-offs that affect fitness.		Fitness is an individual's ability to survive and reproduce. It is environment-specific and depends on both abiotic and biotic factors. Natural selection's ability to optimize fitness is constrained by trade-offs, existing variation, and other factors.	
		Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
		3.61 (0.04)	3.60 (0.05)	3.68 (0.04)	3.57 (0.05)
		SA: 66.8% A: 28.3% D: 4.4% SD: 0.5%	SA: 66.3% A: 28.3% D: 4.9% SD: 0.5%	SA: 73.9% A: 21.7% D: 3.3% SD: 1.1%	SA: 65.2% A: 28.8% D: 3.8% SD: 2.2%

Molecules (Smaller and faster) ▸ **Ecosystems (Larger and slower)**

Biological Scale

<table>
<tr><td></td><td colspan="6">Major Sub-disciplines of Biology</td></tr>
<tr><td></td><td colspan="2">Molecular/ Cellular/ Developmental Biology</td><td colspan="2">Physiology</td><td colspan="2">Ecology/ Evolutionary Biology</td></tr>
<tr><td rowspan="13">INFORMATION FLOW</td><td colspan="6"><u>Overarching Principles</u>:
Organisms inherit genetic and epigenetic information that contribute to an individual's phenotype. The timing and degree of gene expression is highly regulated, in a way that affects phenotype.
Cells/organs/organisms constantly monitor their internal and external environment. Perception and transmission of this information allows organisms to respond to changing conditions.</td></tr>
<tr><td colspan="3">Importance for graduating biology major</td><td colspan="3">Scientific accuracy</td></tr>
<tr><td colspan="3">3.74 (0.03)</td><td colspan="3">3.58 (0.04)</td></tr>
<tr><td colspan="3">SA: 75.0%
A: 23.9%
D: 1.1%
SD: 0%</td><td colspan="3">SA: 61.4%
A: 35.3%
D: 3.3%
SD: 0%</td></tr>
<tr><td colspan="2">In most cases, genetic information flows from DNA to mRNA to protein, but there are important exceptions.</td><td colspan="2">Information stored in DNA is expressed as RNA and/or proteins that impact anatomical structures and physiological function.</td><td colspan="2">Individuals transmit genetic information to their offspring; some alleles confer higher fitness than others.</td></tr>
<tr><td>Importance for graduating biology major</td><td>Scientific accuracy</td><td>Importance for graduating biology major</td><td>Scientific accuracy</td><td>Importance for graduating biology major</td><td>Scientific accuracy</td></tr>
<tr><td>3.66 (0.04)</td><td>3.59 (0.04)</td><td>3.73 (0.04)</td><td>3.65 (0.04)</td><td>3.71 (0.04)</td><td>3.64 (0.04)</td></tr>
<tr><td>SA: 69.0%
A: 28.8%
D: 1.6%
SD: 0.5%</td><td>SA: 62.5%
A: 34.8%
D:2.2 %
SD: 0.5%</td><td>SA: 76.6%
A: 20.1%
D: 2.7%
SD: 0.5%</td><td>SA: 69.0%
A: 27.7%
D: 2.7%
SD: 0.5%</td><td>SA: 72.3%
A: 26.1%
D: 1.6%
SD: 0%</td><td>SA: 65.8%
A: 32.1%
D: 2.2%
SD: 0%</td></tr>
<tr><td colspan="2">Gene expression and protein activity are regulated by intracellular and extracellular signaling molecules. Signal transduction pathways are crucial in relaying these signals.</td><td colspan="2">Organisms have sophisticated mechanisms for sensing changes in the internal or external environment. They use chemical, electrical, or other forms of signaling to coordinate responses at the cellular, tissue, organ, and/or system level.</td><td colspan="2">A genotype influences the range of possible phenotypes in an individual; the actual phenotype results from interactions between alleles and the environment.</td></tr>
<tr><td>Importance for graduating biology major</td><td>Scientific accuracy</td><td>Importance for graduating biology major</td><td>Scientific accuracy</td><td>Importance for graduating biology major</td><td>Scientific accuracy</td></tr>
<tr><td>3.62 (0.04)</td><td>3.69 (0.03)</td><td>3.70 (0.04)</td><td>3.72 (0.03)</td><td>3.79 (0.03)</td><td>3.70 (0.04)</td></tr>
<tr><td>SA: 66.3%
A: 29.4%
D: 4.4%
SD: 0%</td><td>SA: 69.0%
A: 31.0%
D: 0%
SD: 0%</td><td>SA: 71.2%
A: 27.2%
D: 1.6%
SD: 0%</td><td>SA: 72.3%
A: 27.7%
D: 0%
SD: 0%</td><td>SA: 79.9%
A: 19.0%
D: 1.1%
SD: 0%</td><td>SA: 71.7%
A: 26.1%
D: 2.2%
SD: 0%</td></tr>
<tr><td colspan="2">The signals that a cell receives depend on its location, and change through time. As a result, different types of cells express different genes, even though they contain the same DNA.

Importance for graduating biology major | Scientific accuracy
3.77 (0.03) | 3.64 (0.04)
SA: 78.3%, A: 20.6 %, D: 1.1%, SD: 0% | SA: 66.3%, A: 31.5%, D: 2.2%, SD: 0%</td><td colspan="4"></td></tr>
<tr><td></td><td colspan="2">Molecules
(Smaller and faster)</td><td colspan="2">▸</td><td colspan="2">Ecosystems
(Larger and slower)</td></tr>
<tr><td></td><td colspan="6">Biological Scale</td></tr>
</table>

Major Sub-disciplines of Biology

	Molecular/ Cellular/ Developmental Biology	Physiology	Ecology/ Evolutionary Biology

STRUCTURE FUNCTION

Overarching Principles:

Biological structures can be studied at all levels of organization, from molecules to ecosystems.

Natural selection favors the evolution of structures that maximize fitness within the context of evolutionary and environmental constraints.

A structure's function is a product of its physical characteristics (e.g size and chemical composition).

Importance for graduating biology major	Scientific accuracy
3.71 (0.04)	3.45 (0.05)
SA: 73.9% A: 22.8% D: 3.3% SD: 0%	SA: 54.4% A: 37.0% D: 8.1% SD: 0.5%

Molecular/ Cellular/ Developmental Biology		Physiology		Ecology/ Evolutionary Biology	
The structure of a cell--its shape, organelles, and polarity--impacts its function.		Physiological functions are often compartmentalized into different cells, tissues, organs, and systems, which have structures that support specialized activities.		Natural selection has favored structures whose shape and composition contribute to their ecological function.	
Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.70 (0.04)	3.64 (0.04)	3.63 (0.04)	3.64 (0.04)	3.47 (0.05)	3.38 (0.05)
SA: 71.7% A: 26.1% D: 2.2% SD: 0%	SA: 67.4% A: 29.3% D: 3.3% SD: 0%	SA: 67.9% A: 27.2% D: 4.4% SD: 0.5%	SA: 66.3% A: 31.5% D: 1.6% SD: 0.5%	SA: 56.5% A: 35.3% D: 7.1% SD: 1.1%	SA: 48.9% A: 41.3% D: 8.7% SD: 1.1%
The three dimensional structure of a molecule and its subcellular localization impact its function, including the ability to catalyze reactions or interact with other molecules.		The size, shape, and physical properties of organs and organisms all affect function. The ratio of surface area to volume is particularly critical for structures that function in transport or exchange of materials and heat.		Competition, mutualism, and other interactions are mediated by each species' morphological, physiological, and behavioral traits.	
Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.70 (0.04)	3.68 (0.04)	3.59 (0.04)	3.64 (0.04)	3.61 (0.04)	3.60 (0.04)
SA: 72.8% A: 22.8% D:3.8% SD: 0.5%	SA: 71.2% A:26.6 % D: 1.6% SD: 0.5%	SA: 65.2% A: 28.8% D: 6.0% SD: 0%	SA: 65.8% A: 32.1% D: 2.2% SD: 0%	SA: 65.2% A: 31.0% D: 3.8% SD: 0%	SA: 60.9% A: 38.0% D: 1.1% SD: 0%
The structure of molecules or organisms may be similar due to common ancestry or selection for similar function.		Structure constrains function in physiology; specialization for one function limits a structure's ability to perform another function.			
Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy		
3.64 (0.05)	3.64 (0.04)	3.47 (0.05)	3.50 (0.05)		
SA: 70.1% A: 23.9% D: 5.4% SD: 0.5%	SA: 67.4% A: 29.9% D: 2.2% SD: 0.5%	SA: 56.0% A: 35.3% D: 8.2% SD: 0.5%	SA: 56.5% A: 37.0% D: 5.4% SD: 1.1%		

Molecules (Smaller and faster) ► **Ecosystems (Larger and slower)**

Biological Scale

Major Sub-disciplines of Biology

TRANSFORMATIONS OF ENERGY AND MATTER

	Molecular/ Cellular/ Developmental Biology	Physiology	Ecology/ Evolutionary Biology

Overarching Principles:

Life takes work – it can only be sustained with inputs of energy.

Natural selection has favored the evolution of regulatory systems that allow individuals to use limited resources efficiently.

Importance for graduating biology major	Scientific accuracy
3.70 (0.04)	3.43 (0.05)
SA: 73.4% A: 21.7% D: 4.3% SD: 0.5%	SA: 56.0% A: 33.1% D: 9.2% SD: 1.6%

Molecular/ Cellular/ Developmental Biology	Physiology	Ecology/ Evolutionary Biology
Energy captured by primary producers is stored as chemical energy and used to drive production of ATP via cellular respiration and other processes.	*Energy captured by primary producers is stored as chemical energy. Organisms use chemical energy to drive the production of ATP. ATP is required for energetically demanding activities necessary for life, including movement, transport and synthesis.*	*Primary producers convert solar and other types of energy into chemical energy. At each trophic level, most of this energy is used for maintenance, with a relatively small fraction available for growth and reproduction. As a consequence, each trophic level in an ecosystem has less energy available than the preceding level.*

Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.80 (0.03)	3.66 (0.04)	3.77 (0.03)	3.67 (0.04)	3.65 (0.05)	3.58 (0.04)
SA: 81% A: 17.9% D: 1.1% SD: 0%	SA: 66.9% A: 32.1% D: 1.1% SD: 0%	SA: 78.8% A: 19.6% D: 1.6% SD:0 %	SA: 70.7% A: 26.1% D: 3.3% SD: 0%	SA: 71.2% A: 22.8% D: 5.4% SD: 0.5%	SA: 62.5% A: 33.7% D: 3.3% SD: 0.5%

Molecular/ Cellular/ Developmental Biology	Physiology	Ecology/ Evolutionary Biology
In cells, the synthesis and breakdown of molecules is highly regulated. Biochemical pathways usually involve multiple reactions, each catalyzed by an enzyme that lowers the activation energy. Energetically unfavorable reactions are driven by coupling to energetically favorable reactions such as ATP hydrolysis.	Due to the inefficiency of biochemical reactions and other constraints, physiological processes are never 100% efficient.	Chemical elements are transferred among the abiotic and biotic components of an ecosystem; changes in the amount and distribution of chemical elements can impact the ecosystem.

Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.70 (0.04)	3.69 (0.03)	3.60 (0.05)	3.62 (0.04)	3.64 (0.04)	3.69 (0.04)
SA: 73.9% A: 21.7% D: 4.3% SD: 0%	SA: 69.6% A: 29.9% D: 0.5% SD: 0%	SA: 66.8% A: 26.1% D: 7.1% SD: 0%	SA: 66.3% A: 29.9% D: 3.3% SD: 0.5%	SA: 67.4% A: 29.3% D: 2.7% SD: 0.5%	SA: 70.6% A: 27.7% D: 1.6% SD: 0%

Molecular/ Cellular/ Developmental Biology	Physiology	Ecology/ Evolutionary Biology
Molecules move within and between cells via 1) energy-demanding transport processes and 2) random motion. A molecules' movement is affected by its thermal energy, size, concentration gradient, and biochemical properties.	Organisms have limited energetic and material resources which must be distributed across competing functional demands. These include movement of material across gradients, growth, maintenance, and reproduction, inevitably leading to trade-offs.	

Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.58 (0.05)	3.61 (0.04)	3.56 (0.05)	3.66 (0.04)
SA: 65.2% A: 28.3% D: 6.0% SD: 0.5%	SA: 63.0% A: 34.8% D: 2.2% SD: 0%	SA: 65.8% A: 25.5% D: 8.2% SD: 0.5%	SA: 66.9% A: 32.6% D: 0.5% SD: 0%

Molecules (Smaller and faster) ► **Ecosystems (Larger and slower)**

Biological Scale

Major Sub-disciplines of Biology

SYSTEMS

Overarching Principles:

Biological molecules, cells, tissues, organs, and individuals do not exist in isolation— they interact in a highly regulated way.

Organisms have evolved complex systems to integrate internal and external information and respond to their changing environments.

Importance for graduating biology major	Scientific accuracy
3.77 (0.04)	3.60 (0.05)
SA: 80.4% A: 16.8% D: 1.6% SD: 1.1%	SA: 68.5% A: 25.0% D: 4.9% SD: 1.6%

Molecular/ Cellular/ Developmental Biology		Physiology		Ecology/ Evolutionary Biology	
Cells receive a complex array of chemical and physical signals that vary in time, location, and intensity over the lifespan of the organism; a cell's response depends on integration and coordination of these various signals.		Organ systems are not isolated, but interact with each other through chemical and physical signals at the level of cells, tissues, and organs.		The size and structure of populations are dynamic. A species' abundance and distribution is limited by available resources and by interactions between biotic and abiotic factors.	
Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.50 (0.05)	3.65 (0.04)	3.72 (0.03)	3.75 (0.03)	3.73 (0.03)	3.71 (0.03)
SA: 59.8% A: 31.5% D: 0.5% SD: 0%	SA: 66.3% A: 32.6% D: 1.1% SD: 0%	SA: 72.8% A: 26.6% D: 0.5% SD: 0%	SA: 75.5% A: 23.9% D:0.5 % SD: 0%	SA:74.5% A: 24.4% D: 1.1% SD: 0 %	SA: 72.3% A: 26.1% D: 1.6% SD: 0%
During development, the signals a cell receives depend on its spatial orientation within the embryo and its intercellular interactions. As a consequence, cells adopt different cell fates depending on their local environment.		An individual's physiological traits affect its interactions with other organisms and with its physical environment.		Ecosystems are not isolated and static--they respond to change, both as a result of intrinsic changes to networks of species and as a result of extrinsic environmental drivers. Within an ecosystem, interactions among individuals form networks; changes in one node of a network can cause changes in other nodes--directly or indirectly.	
Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.54 (0.05)	3.67 (0.04)	3.52 (0.04)	3.60 (0.04)	3.68 (0.04)	3.68 (0.04)
SA: 60.3% A: 33.2% D: 6.5% SD: 0%	SA: 67.0% A: 31.5% D: 0.5% SD: 0%	SA: 58.2% A: 35.9% D: 6.0% SD: 0%	SA: 62.5% A: 34.8% D: 2.7% SD: 0%	SA: 70.6% A: 27.2% D: 2.2% SD: 0%	SA: 69.6% A: 29.3% D: 1.1% SD: 0%
Alteration of a single gene or molecule in a signaling network may have complex impacts at the cell, tissue or whole-organism level.		In the face of environmental changes, organisms may maintain homeostasis through control mechanisms that often use negative feedback; others have adaptations that allow them to acclimate to environmental variation.		*Biodiversity impacts many aspects of an ecosystem. In general, species-rich ecosystems function are more stable and productive than species-poor ecosystems.*	
Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy	Importance for graduating biology major	Scientific accuracy
3.61 (0.04)	3.68 (0.03)	3.60 (0.05)	3.54 (0.04)	3.48 (0.05)	3.34 (0.05)
SA: 65.2% A: 30.4% D: 4.4% SD: 0%	SA: 68.5% A: 31.5% D: 0% SD: 0%	SA: 67.9% A: 25% D: 6.5% SD: 0.5%	SA: 58.7% A: 37.5% D: 3.3% SD: 0.5%	SA: 56% A: 35.9% D: 8.1% SD: 0%	SA: 47.8% A: 39.7% D: 11.4% SD: 1.1%

Molecules (Smaller and faster) ▶ **Ecosystems (Larger and slower)**

Biological Scale

Supplemental Table 1. Additional Concepts for the BioCore Guide. *National validation respondent suggestions for additional important concepts for graduating biology majors to know that are not currently included in the BioCore Guide. If multiple reviewers suggested a concept, the number of reviewer is shown in parentheses. We have organized them into the categories of the core concepts of Vision and Change when possible.*

Evolution	Life has three domains of diversity: Bacteria, Archaea, and Eucarya; each of which has unique characteristics and differences and has descended from a common ancestor (5) Commonality of developmental mechanisms used by a wide variety of disparate organisms (3) Communication between individuals; behavior is an important adaptation (3) History of life and patterns of extinction (2) Common ancestry – understanding that all life is related (2) Evolution of sex and sex differences How Darwin formulated the theory of evolution Timing of evolution Differentiate acclimation and adaptation Evolution of molecules Understanding that many of the cell and molecular mechanisms/processes in humans originated in prokaryotes Role of species interactions in structuring communities and shaping evolutionary patterns Natural history of plants and animals where they live Macroevolution
Information Flow	Osmosis/equilibrium/diffusion (2) Different steps of gene regulation The importance of randomness in biological systems, interactions, mutations, etc. Feedback loops (including both positive and negative feedback)

	Biological plasticity (behavioral, developmental, and genetic) Genetic code is approximately universal
Structure Function	Immune system, including innate and adaptive (2) Other non-organelle cell structures (cell membranes, ribosomes, etc.) (2) Influence of structure and behavior of water on molecular/cellular functions Stem cells – what they are, how they are created, and their roles Organisms provide environment that houses other organisms and pathogens Biomes is a critical concept relating to the ecological level of structure Ecological structure changing over times relates to disturbance and succession Conformational change in macromolecules
Transformations of Energy and Matter	Definition of life – living cells that are taking in energy and giving off waste (2) Energy sources on Earth and spectral distribution of energy that reaches the Earth from the sun Light capture is mechanism by which energy is transformed Biogeochemical cycling and decomposition are important for understanding ecosystems Importance of Carbon and Oxygen for life
Systems	Metagenomics Community structure Emergent properties Life is so diverse because of myriad interactions among species
Other	Competencies (11) Parasitism Cancer Climate change Disease/infection

Supplemental Information

Identifying prevalence of institutions with general biology departments or conferring a general biology degree

We systematically accessed the online directory for Carnegie Classifications of institutions and retrieved all institutions in each of the major categories based on the degree that it predominately grants: bachelor's degrees, master's degrees, or doctoral degrees. Baccalaureate granting institutions (total n=810) are either considered basic (n=271), diverse (n=392), or combined baccalaureate and associates (n=147). Master's Colleges and Universities (total n=724) are considered small (n=126), medium (n=185) or large (n=413). Doctoral granting institutions (total n=297) are distinguished based on the level of research activity; they can be classified as research institutions with very high research activity (n=108), research institutions with high research activity (n=99), or research institutions (n=90).

In order to sample as diverse a group of institutions as possible, we assigned each institution a random number using Microsoft Excel's random number generator program and selected 10% of the total number of each category for analysis (n= 183 total). From this randomly generated list, we used departmental websites and descriptions of undergraduate degrees offered at each institution to identify (1) whether the institution conferred a biology-related degree and (2) whether the institution had a general biology department. If an institution did not offer a biology-related major (e.g. if it was a music school), then we removed it from the dataset and replaced them with another institution that did offer a biology-related degree.

We found that 82% of the random sampling of institutions had a general biology department (150/183). 74.1% (60/81) of Bachelor institutions, 87.5% (63/72) of Masters institutions, and 90% (27/30) of Doctoral institutions had general biology departments. Those institutions that did not have a general biology department either had more specific sub-discipline specific departments (e.g. Botany or Neuroscience) or had more general departments that offered biology as a major (e.g. Natural sciences).

We also assessed how many of these institutions offered a general biology major as opposed to only offering a more specialized degree in biology (e.g. Immunology or ecology). We found that 95.6% of these institutions we assessed offered a general biology major (175/183). Specifically, 96.3% of Bachelor institutions (78/81), 95.8% of Masters institutions (69/72), and 93.3% of Doctoral institutions (28/30) have a general biology major.

National validation lists

We sent requests for validation to participants in the 2013 Vision and Change meeting, Introductory Biology Project (IBP), National Academies Summer Institute

on Undergraduate Education in Biology, Biology Scholars Program, Society for the Advancement in Biology Education (SABER), University of Washington Biology Education Research Group (BERG), and education members of the American Society for Cell Biology (ASCB), American Society for Microbiology (ASM), American Society for Biochemistry and Molecular Biology Education (ASBMB), Faculty for Undergraduate Neuroscience (FUN), American Physiological Society (APS), Human Anatomy and Physiology Society (HAPS), and Ecology Education. We posted a link to the survey on the PULSE community website. We also sent the request for validation to faculty, postdocs, and graduate students in the Department of Biology at the University of Washington. We encouraged faculty to forward the request for validation to others, so some respondents likely received it through their colleagues or other mailing lists.

Reviewers of the BioCore Guide

We would like to thank the numerous individuals who dedicated their time to reviewing and commenting specifically on the BioCore Guide. These people include: Joel Abraham, John Alcock, Joe Ammirati, Shivanthi Anandan, Tessa Andrews, Peter Armbruster, Ed Barlett, Ken Belanger, Janet Branshaw, Ruth Buskirk, Anne Casper, Bill Cliff, Patricia Colberg, Brian Couch, Jenny Dauer, Lauren DeBey, Michael Fleming, Stephanie Gardner, Janet Germeraad, Ron Gerrits, Craig Heller, Janneke Hille Ris Lambers, Sally Hoskins, Ben Kerr, Hannah Kinmonth-Schultz, Jenny Knight, Mary Rose Lamb, Judith Leatherman, Paula Lemmons, Tammy Long, Jenny McFarland, Jenny Momsen, Eileen O'Connor, Pam Pape-Lindstrom, Alex Paredez, Kathryn Perez, Karen Petersen, Cathy Pfister, Bob Podolsky, Carol Pollock, Becca Price, Jeff Riffell, Jen Ruesink, Dee Silverthorn, Michelle Smith, Brianna Timmerman, Keiko Torii, Ella Tour, Liz Van Volkenburgh, Barbara Wakimoto, Nat Wheelwright, Greg Wilson, Bill Wood, Peter Wyckoff, and J. Michael Wyss.

Supplemental Material

CBE—Life Sciences Education

Brownell *et al.*

MAJOR SUBDISCIPLINES OF BIOLOGY

EVOLUTION

Principles: All living organisms share a common ancestor. Species evolve over time, and new species can arise, when allele frequencies change due to mutation, natural selection, gene flow, & genetic drift.

Molecular / Cellular/ Developmental Biology	Physiology	Ecology / Evolutionary Biology
Multiple molecular mechanisms, including DNA damage and errors in replication, lead to the generation of random mutations. These mutations create new alleles that can be inherited via mitosis, meiosis, or cell division.	Mutations that change protein structure and/or regulation can impact anatomy and physiological function at all levels of organization.	The characteristics of populations change over time due to changes in allele frequencies. Changes in allele frequencies are caused by random and nonrandom processes--specifically mutation, natural selection, gene flow, and genetic drift. Not all of these changes are adaptive.
Mutations and epigenetic modifications can impact the regulation of gene expression and/or the structure and function of the gene product. If mutations affect phenotype and lead to increased reproductive success, the frequency of those alleles will tend to increase in the population.	Most organisms have anatomical and physiological traits that tend to increase their fitness for a particular environment.	All species alive today are derived from the same common ancestor. New species arise when populations become genetically isolated and diverge due to mutation, natural selection, and genetic drift. Phylogenetic trees depict relationships among ancestral and descendant species, and are estimated based on data.
	Physiological systems are constrained by ancestral structures, physical limits, and the requirements of other physiological systems, leading to trade-offs that affect fitness.	Fitness is an individual's ability to survive and reproduce. It is environment-specific and depends on both abiotic and biotic factors. Evolution of optimal fitness is constrained by existing variation, trade-offs and other factors.

INFORMATION FLOW

Principles: Organisms inherit genetic and epigenetic information that influences the location, timing, and intensity of gene expression. Cells/organs/organisms have multiple mechanisms to perceive and respond to changing environmental conditions.

Molecular / Cellular/ Developmental Biology	Physiology	Ecology / Evolutionary Biology
In most cases, genetic information flows from DNA to mRNA to protein,but there are important exceptions.	Information stored in DNA is expressed as RNA and proteins. These gene products impact anatomical structures and physiological function.	Individuals transmit genetic information to their offspring; some alleles confer higher fitness than others in a particular environment.
Gene expression and protein activity are regulated by intracellular and extracellular signaling molecules. Signal transduction pathways are crucial in relaying these signals.	Organisms have sophisticated mechanisms for sensing changes in the internal or external environment. They use chemical, electrical, or other forms of signaling to coordinate responses at the cellular, tissue, organ, and/or system level.	A genotype influences the range of possible phenotypes in an individual; the actual phenotype results from interactions between alleles and the environment.
The signals that a cell receives depend on its location, and may change through time. As a result, different types of cells express different genes, even though they contain the same DNA.		

Molecules (smaller and faster) ⟶ **Ecosystems** (larger and slower)

BIOLOGICAL SCALE

MAJOR SUBDISCIPLINES OF BIOLOGY

STRUCTURE FUNCTION

Principles: Biological structures exist at all levels of organization, from molecules to ecosystems. A structure's physical and chemical characteristics influence its interactions with other structures, and therefore its function. Natural selection leads to the evolution of structures that tend to increase fitness within the context of evolutionary, developmental, and environmental constraints.

Molecular / Cellular/ Developmental Biology	Physiology	Ecology / Evolutionary Biology
The structure of a cell--its shape, membrane, organelles, cytoskeleton, and polarity--impacts its function.	Physiological functions are often compartmentalized into different cells, tissues, organs, and systems, which have structures that support specialized activities.	Natural selection has favored structures whose shape and composition contribute to their ecological function.
The three dimensional structure of a molecule and its subcellular localization impact its function, including the ability to catalyze reactions or interact with other molecules. Function can be regulated through reversible alterations of structure e.g. phosphorylation.	The size, shape, and physical properties of organs and organisms all affect function. The ratio of surface area to volume is particularly critical for structures that function in transport or exchange of materials and heat.	Competition, mutualism, and other interactions are mediated by each species' morphological, physiological, and behavioral traits.
The structure of molecules or organisms may be similar due to common ancestry or selection for similar function.	Structure constrains function in physiology; specialization for one function may limit a structure's ability to perform another function.	

TRANSFORMATIONS of ENERGY & MATTER

Principles: Energy and matter cannot be created or destroyed, but can be changed from one form to another. Energy captured by primary producers is necessary to support the maintenance, growth and reproduction of all organisms. Natural selection leads to the evolution of efficient use of resources within constraints.

Molecular / Cellular/ Developmental Biology	Physiology	Ecology / Evolutionary Biology
Energy captured by primary producers is stored as chemical energy. This stored energy can be converted through a series of biochemical reactions into ATP for immediate use in the cell.	Energy captured by primary producers is stored as chemical energy. This stored energy can be converted into ATP, which is required for energetically demanding activities necessary for life, including synthesis, transport, and movement.	Energy captured by primary producers is stored as chemical energy. At each trophic level, most of this energy is used for maintenance, with a relatively small fraction available for growth and reproduction. As a consequence, each trophic level in an ecosystem has less energy available than the preceding level.
In cells, the synthesis and breakdown of molecules is highly regulated. Biochemical pathways usually involve multiple reactions catalyzed by enzymes that lower activation energies. Energetically unfavorable reactions are driven by coupling to energetically favorable reactions such as ATP hydrolysis.	Due to the inefficiency of biochemical reactions and other constraints, physiological processes are never 100% efficient.	Chemical elements are transferred among the abiotic and biotic components of an ecosystem; changes in the amount and distribution of chemical elements can impact the ecosystem.
Intracellular and intercellular movement of molecules occurs via 1) energy-demanding transport processes and 2) random motion. A molecule's movement is affected by its thermal energy, size,electro-chemical gradient, and biochemical properties.	Organisms have limited energetic and material resources which must be distributed across competing functional demands. These include movement of material across gradients, growth, maintenance, and reproduction, inevitably leading to trade-offs.	

Molecules (smaller and faster) ⟶ **Ecosystems** (larger and slower)

BIOLOGICAL SCALE

MAJOR SUBDISCIPLINES OF BIOLOGY

SYSTEMS

Principles: Biological molecules, genes, cells, tissues, organs, individuals, and ecosystems interact to form complex networks. A change in one component of the network can affect many other components. Organisms have complex systems that integrate internal and external information, incorporate feedback control, and allow them to respond to changes in the environment.

Molecular / Cellular/ Developmental Biology	Physiology	Ecology / Evolutionary Biology
Cells receive a complex array of chemical and physical signals that vary in time, location, and intensity over the lifespan of the organism; a cell's response depends on integration and coordination of these various signals.	Organ systems are not isolated, but interact with each other through chemical and physical signals at the level of cells, tissues, and organs.	The size and structure of populations are dynamic. A species' abundance and distribution is limited by available resources and by interactions between biotic and abiotic factors.
During development, the signals a cell receives depend on its spatial orientation within the embryo and its intercellular interactions. As a consequence, cells adopt different cell fates depending on their local environment and/or cell lineage.	An individual's physiological traits affect its interactions with other organisms and with its physical environment.	Ecosystems are not isolated and static--they respond to change, both as a result of intrinsic changes to networks of species and as a result of extrinsic environmental drivers. Within an ecosystem, interactions among individuals form networks; changes in one node of a network can cause changes in other nodes--directly or indirectly.
Alteration of a single gene or molecule in a signaling network may have complex impacts at the cell, tissue or whole-organism level.	In the face of environmental changes, organisms may maintain homeostasis through control mechanisms that often use negative feedback; others have adaptations that allow them to acclimate to environmental variation.	Biodiversity impacts many aspects of ecosystems.

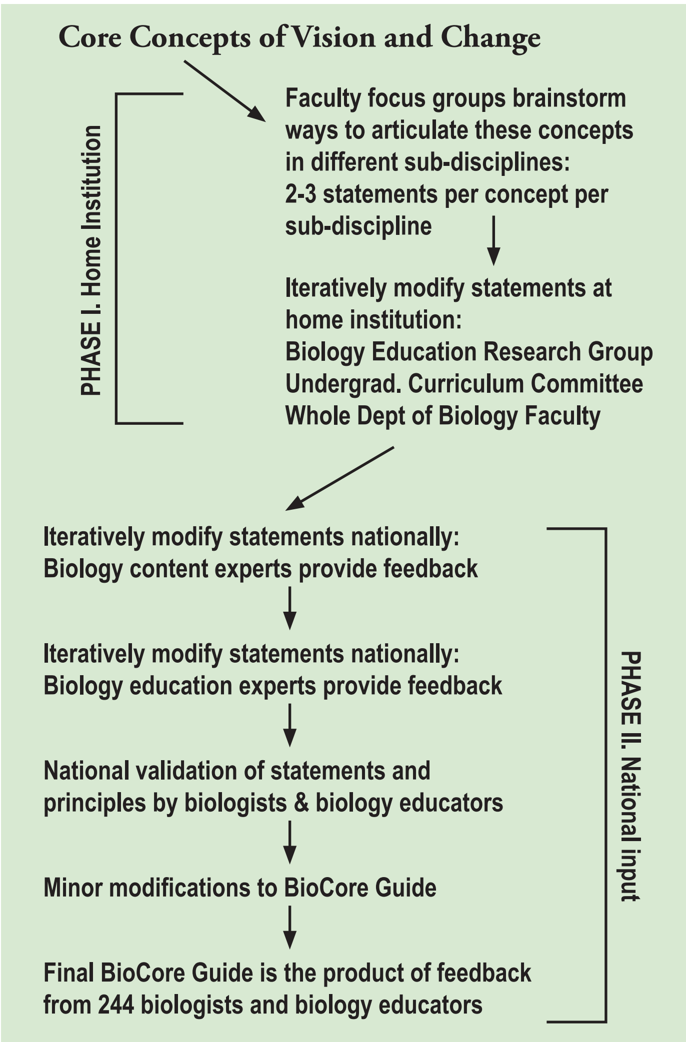
Molecules (smaller and faster) ⟶ **Ecosystems** (larger and slower)

BIOLOGICAL SCALE

FOR MORE INFORMATION:

Brownell SE, Freeman S, Wenderoth MP, Crowe AJ (2014). BioCore Guide: A Tool for Interpreting the Core Concepts of Vision and Change for Biology Majors. *CBE Life Sci Educ* 13, 200-211.

We used a grassroots approach to generate the BioCore Guide. We began with faculty ideas and engaged in an iterative process that incorporated feedback from over 240 biologists and biology educators at a diverse range of academic institutions throughout the U.S. The final validation step demonstrated strong national consensus, with over 90% of respondents agreeing with the importance and scientific accuracy of the statements.



DEPARTMENT OF BIOLOGY

UNIVERSITY of WASHINGTON

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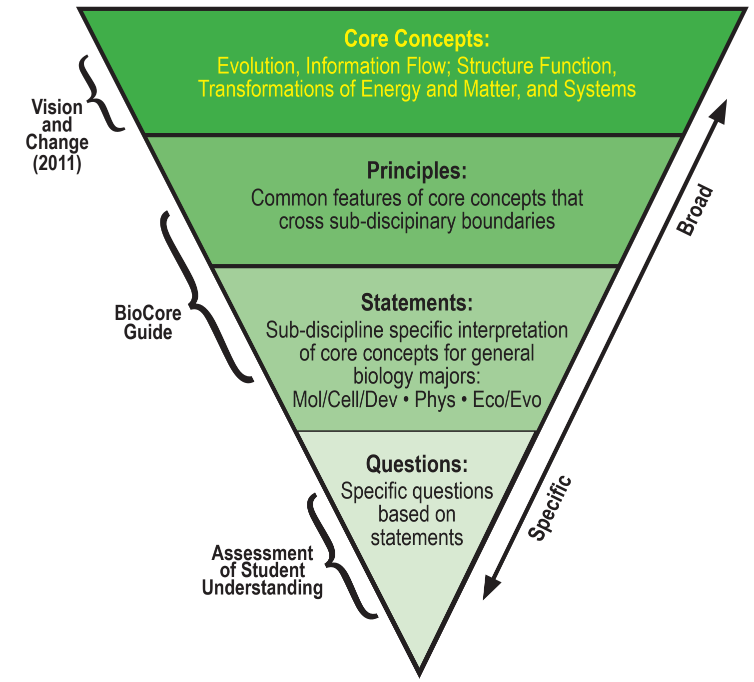
BIOCORE GUIDE:

A TOOL FOR INTERPRETING THE CORE CONCEPTS OF VISION AND CHANGE FOR BIOLOGY MAJORS



The BioCore Guide is a set of general principles and specific statements that expand upon the five core concepts outlined in *Vision and Change,* creating a framework that biology departments can use to align with the goals of Vision and Change.

It is our hope that the BioCore Guide will serve as an agent of change for biology departments as we move towards transforming undergraduate biology education.