Learning Goals for Biology Majors at Carleton College

Under the leadership of the American Association for the Advancement of Science and the National Science Foundation, the biology education community developed a common set of core concepts and core competencies and practices for undergraduate biology majors. We are using these national, consensus concepts, competencies, and practices to guide our assessment of our students' progress through the major. These guidelines are excerpted from *Vision and Change in Undergraduate Biology Education* (www.visionandchange.org)

Core Concepts for Biological Literacy

All undergraduates should develop a basic understanding of the following core concepts:

C1. EVOLUTION

The diversity of life evolved over time by processes of mutation, selection, and genetic change.

Darwin's theory of evolution by natural selection was transformational in scientists' understanding of the patterns, processes, and relationships that characterize the diversity of life. Because the theory is the fundamental organizing principle over the entire range of biological phenomena, it is difficult to imagine teaching biology of any kind without introducing Darwin's profound ideas. Inheritance, change, and adaptation are recurring themes supported by evidence drawn from molecular genetics, developmental biology, biochemistry, zoology, agronomy, botany, systematics, ecology, and paleontology. A strong preparation in the theory of evolution remains essential to understanding biological systems at all levels.

Themes of adaptation and genetic variation provide rich opportunities for students to work with relevant data and practice quantitative analysis and dynamic modeling. Principles of evolution help promote an understanding of natural selection and genetic drift and their contribution to the diversity and history of life on Earth. These principles enable students to understand such processes as a microbial population's ability to develop drug resistance and the relevance of artificial selection in generating the diversity of domesticated animals and food plants.

C2. STRUCTURE AND FUNCTION

Basic units of structure define the function of all living things.

Structural complexity, together with the information it provides, is built upon combinations of subunits that drive increasingly diverse and dynamic physiological responses in living organisms. Fundamental structural units and molecular and cellular processes are conserved through evolution and yield the extraordinary diversity of biological systems seen today.

Understanding of biological regulatory systems and communication networks has become increasingly sophisticated, yielding knowledge about the functional responses of the components of those systems and networks at differing scales, from the molecular to the ecosystem level of organization. Knowledge of relationships between biological structure and function is informed by design approaches from engineering and from models based on the quantitative analysis of data. The application of tools from the physical sciences often facilitates our understanding of biological structure–function relationships. For example, anatomical analysis of body morphology and function by means of a biomechanics approach and robotics (e.g., Spenko et al., 2008) provides a venue for discussing the interface between applied physics and biology in an undergraduate biology course. Rational drug design strategies offer useful case studies emphasizing the importance of the basic structure–function concept. For instance, elucidating the molecular structure of a target protein such as HIV protease has provided the basis for novel approaches to the discovery of drugs, leading to important antiretroviral therapies to treat AIDS.

C3. INFORMATION FLOW, EXCHANGE, AND STORAGE

The growth and behavior of organisms are activated through the expression of genetic information in context.

The convergence of systems approaches and powerful bioinformatics tools has dramatically expanded our understanding of the dynamics of information flow in living systems. From gene expression networks to endocrine mechanisms for physiological regulation, and from signal transduction and cellular homeostasis to biogeochemical cycling, all may be understood in terms of the storage, transmission, and utilization of biological information. Moreover, the collection, archiving, and analysis of information about living organisms and their components has created an extraordinary breadth and diversity of data that facilitate analyses of how information flows through systems. Real-time analytical approaches facilitate the study of cellular dynamics in response to environmental changes. Studies of the dynamics of information flow raise questions about topics such as the storage of genetic information and the transmission of that information across generations.

All students should understand that all levels of biological organization depend on specific interactions and information transfer. Information exchange forms the basis of cell recognition and differentiation, the organization of communities from microbial assemblages to tropical forests, and the mating behavior of animals. The introduction of the topic of information exchange offers undergraduates many opportunities to learn how scientists apply quantitative skills and tools in the management and analysis of large data sets.

C4. PATHWAYS AND TRANSFORMATION OF ENERGY AND MATTER

Biological systems grow and change by processes based upon chemical transformation pathways and are governed by the laws of thermodynamics.

The principles of thermodynamics govern the dynamic functions of living systems from the smallest to the largest scale, beginning at the molecular level and progressing to the level of the cell, the organism, and the ecosystem. An understanding of kinetics and the energy requirements of maintaining a dynamic steady state is needed to understand how living systems operate, how they maintain orderly structure and function, and how the laws of physics and chemistry underlie such processes as metabolic pathways, membrane dynamics, homeostasis, and nutrient cycling in ecosystems. Moreover, modeling processes such as regulation or signal transduction requires an understanding of mathematical principles.

For example, knowledge of chemical principles can help inform the production of microorganisms that can synthesize useful products or remediate chemical spills, as well as the bioengineering of plants that produce industrially important compounds in an ecologically benign manner. These are topics of intense current interest.

C5. SYSTEMS

Living systems are interconnected and interacting.

As defined in A New Biology for the 21st Century (NRC, 2009), systems biology seeks a deep quantitative understanding of complex biological processes through an elucidation of the dynamic interactions among components of a system at multiple functional scales. A systems approach to biological phenomena focuses on emergent properties at all levels of organization, from molecules to ecosystems to social systems. Mathematical and computational tools and theories grounded in the physical sciences enable biologists to discover patterns and construct predictive models that inform our understanding of biological processes. Through these models, researchers seek to relate the dynamic interactions of components at one level of biological organization to the functional properties that emerge at higher organizational levels.

Systems biology provides rich opportunities for all students to learn about scientific inquiry and, because of the complex nature of the research involved, to practice in a multidisciplinary context. For example, early applications of systems biology to ecosystem processes resulted in useful simulation models.

Core Competencies and Disciplinary Practice

Knowledge of concepts and the development of competencies form the bases for the practice of any discipline, but particularly in the sciences. All students need to develop the following competencies:

P1. ABILITY TO APPLY THE PROCESS OF SCIENCE

Biology is evidence based and grounded in the formal practices of observation, experimentation, and hypothesis testing.

All students need to understand the process of science and how biologists construct new knowledge by formulating hypotheses and then testing them against experimental and observational data about the living world. Studying biology means practicing the skills of posing problems, generating hypotheses, designing experiments, observing nature, testing hypotheses, interpreting and evaluating data, and determining how to follow up on the findings. In effect, learning science means learning to do science. For example, authentic research experiences in undergraduate biology through course-based projects, independent or summer research, community-based student research, or other mechanisms can be a powerful means of providing students with opportunities to learn science by doing it (Mulnix, 2003; Sadler and McKinney, 2010).

P2. ABILITY TO USE QUANTITATIVE APPROACHES

Biology relies on applications of quantitative analysis and mathematical reasoning.

The application of quantitative approaches (statistics, quantitative analysis of dynamic systems, and mathematical modeling) is an increasingly important basic skill utilized in describing biological systems (Jungck, 1997; Brewer and Gross, 2003). Advances in several fields of the biological sciences provide opportunities for students to appreciate the impact of mathematical approaches in biology and the importance of using them. For example, the dynamic modeling of neural networks helps biologists understand emergent properties in neural systems. Systems approaches to examining population dynamics in ecology also require sophisticated modeling. Advances in understanding the nonlinear dynamics of immune system development have aided scientists' understanding of the transmission of communicable diseases.

All students should understand that biology is often analyzed through quantitative approaches. Developing the ability to apply basic quantitative skills to biological problems should be required of all undergraduates, as they will be called on throughout their lives to interpret and act on quantitative data from a variety of sources.

P3. ABILITY TO USE MODELING AND SIMULATION

Biology focuses on the study of complex systems.

All students should understand how mathematical and computational tools describe living systems. Whether at the molecular, cellular, organismal, or ecosystem level, biological systems are dynamic, interactive, and complex. As new computational approaches improve our ability to study the dynamics of complex systems, mathematical modeling and statistical approaches are becoming an important part of the biologist's tool kit. Biologists must understand both the advantages and the limitations of reductionist and systems approaches to studying living systems. Also important is the advantage of qualitative analyses, including steady-state behaviors (e.g., homeostasis) and associated stability analyses (e.g., responses to perturbations). A combination of these approaches is essential to teasing apart the complexities of biological systems.

A variety of computational educational tools is readily available to examine complexity as it arises in biological systems. These tools can simulate many interacting components and illustrate emergent properties that allow students to generate and test their own ideas about the spatiotemporal complexity in biology. Today, modeling is a standard tool for biologists, so basic skills in implementing computational algorithms for models are increasingly being incorporated into the undergraduate curriculum (Rowland- Godsmith, 2009; NetLogo, n.d.).

4. ABILITY TO TAP INTO THE INTERDISCIPLINARY NATURE OF SCIENCE

Biology is an interdisciplinary science.

Integration among subfields in biology, as well as integration between biology and other disciplines, has advanced our fundamental understanding of living systems and raised a number of new questions. As exciting new areas of study emerge from the interstices, solid grounding in the sciences, including computer science and social science, can advance the practice and comprehension of biology. Accordingly, all students should have experience applying concepts and subdisciplinary knowledge from within and outside of biology in order to interpret biological phenomena.

Interdisciplinary science practice may be achieved in several ways. For future biologists, one way is through developing expertise not just in an area of biology, but also in a related discipline. That way, students will develop the vocabulary of both disciplines and an ability to think independently and creatively in each as well. A second, less intensive approach is to develop deep expertise in one area and fluency in related disciplines. A third option is to serve as a biologist on a multidisciplinary team. All of these routes develop a student’s facility to apply concepts and knowledge across traditional boundaries. For those not majoring in biology, the inherent interdisciplinary nature of biology practice lends itself to forming connections between biology and other sciences and, in so doing, can help all students understand the way science disciplines inform and reinforce each other.

P5. ABILITY TO COMMUNICATE AND COLLABORATE WITH OTHER DISCIPLINES

Biology is a collaborative scientific discipline.

Biological research increasingly involves teams of scientists who contribute diverse skills to tackling large and complex biological problems; therefore, all students should have experience communicating biological concepts and interpretations. As the science of biology becomes more interdisciplinary in practice and global in scope, biologists and other scientists need to develop skills to participate in diverse working communities, as well as the ability to take full advantage of their collaborators' multiple perspectives and skills.

Effective communication is a basic skill required for participating in inclusive and diverse scientific communities. Communicating scientific concepts through peer mentoring helps students solidify their comprehension and develop the ability to communicate ideas not only to other biology students, but also to students in other disciplines. Practicing the communication of science through a variety of formal and informal written, visual, and oral methods should be a standard part of undergraduate biology education.

P6. ABILITY TO UNDERSTAND THE RELATIONSHIP BETWEEN SCIENCE AND SOCIETY

Biology is conducted in a societal context.

Biologists have an increasing opportunity to address critical issues affecting human society by advocating for the growing value of science in society, by educating all students about the need for biology to address pressing global problems, and by preparing the future workforce. Biologists need to evaluate the impact of scientific discoveries on society, as well as the ethical implications of biological research. Cross-disciplinary opportunities for students to explore science in a social context may be generated through real-life case studies embedded in biology courses, or in social science courses designed specifically to explore the effect of science and technology on human beings (e.g., Fluck, 2001; Pai, 2008).

Table 2.1 describes the core competencies as sets of skills linked to disciplinary practice. The development of these skills will enable students to better understand the core concepts presented earlier and, consequently, will advance their ability to practice biology. Biology majors achieve an increasing understanding of the core concepts and greater proficiency in doing biology as they proceed down their chosen academic path, but all students should have opportunities to develop these basic competencies.

Table 2.1: Core Competencies and Disciplinary Practices. A competency-based approach to undergraduate biology education focuses on demonstrating analytical, experimental, and technical skills as measurable outcomes of student learning. Biology literacy is defined primarily in terms of acquired competencies, demonstrated within the context of fundamental biology concepts.

Core Competency	Ability to apply the process of science	Ability to use quantitative reasoning	Ability to use modeling and simulation	Ability to tap into the interdisciplinary nature of science	Ability to communicate and collaborate with other disciplines	Ability to understand the relationship between science and society
Instantiation of Ability in Disciplinary Practice	Biology is an evidence-based discipline	Biology relies on applications of quantitative analysis and mathematical reasoning	Biology focuses on the study of complex systems	Biology is an interdisciplinary science	Biology is a collaborative scientific discipline	Biology is conducted in a societal context
Demonstration of Competency in Practice	Design scientific process to understand living systems	Apply quantitative analysis to interpret biological data	Use mathematical modeling and simulation tools to describe living systems	Apply concepts from other sciences to interpret biological phenomena	Communicate biological concepts and interpretations to scientists in other disciplines	Identify social and historical dimensions of biology practice
Examples of Core Competencies Applied to Biology Practice	Observational strategies Hypothesis testing Experimental design Evaluation of experimental evidence Developing problem-solving strategies	Developing and interpreting graphs Applying statistical methods to diverse data Mathematical modeling Managing and analyzing large data sets	Computational modeling of dynamic systems Applying informatics tools Managing and analyzing large data sets Incorporating stochasticity into biological models	Applying physical laws to biological dynamics Chemistry of molecules and biological systems Applying imaging technologies	Scientific writing Explaining scientific concepts to different audiences Team participation Collaborating across disciplines Cross-cultural awareness	Evaluating the relevance of social contexts to biological problems Developing biological applications to solve societal problems Evaluating ethical implications of biological research