Philosophical Issues in Biology Education

Edited by Kostas Kampourakis

Chapter 1 What is life?

Carol Cleland & Michael Zerella

Distinguishing life from non-life has challenged philosophers at least since Aristotle. In recent years it has taken on increasing scientific importance as researchers seek to understand the origins and extent of life in the universe and explore the possibilities for artificial forms of life. Yet despite spectacular advances in the biological sciences, especially over the last half-century, no consensus among scientists or philosophers has emerged on what life is. In this chapter we describe how this lack of consensus impacts some areas of scientific research, and we discuss what this can teach students about science as a process of discovery. We argue that scientists are not yet in a position to formulate a complete let alone final account of the nature of life, and that for this reason establishing a definition of life can do more harm than good. In order to provide a scientifically compelling answer to the question “what is life?” researchers need access to novel forms of life, and their search should not be constrained by our limited experience with life as we know it on Earth today. In addition to providing an interesting way to present a variety of recent biological discoveries, exploration of these issues is useful in biology education because it demonstrates why science is a fundamentally open-ended and ongoing process of inquiry rather than just a static set of facts and dogmatic principles.

Chapter 2 Biological Explanation

Angela Potochnik

One of the central aims of science is explanation: scientists seek to uncover *why* things happen the way they do. This chapter addresses what kinds of explanations are formulated in biology, how explanatory aims influence other features of the field of biology, and the implications of all of this for biology education. Philosophical treatments of scientific explanation have been both complicated and enriched by attention to explanatory strategies in biology. Most basically, whereas traditional philosophy of science based explanation on derivation from scientific laws, there are many biological explanations in which laws play little or no role. Instead, the field of biology is a natural place to turn for support for the idea that causal information is explanatory. Biology has also been used to motivate mechanistic accounts of explanation, as well as criticisms of that approach. Ultimately, the most pressing issue about explanation in biology may be how to account for the wide range of explanatory styles encountered in the field. This issue is crucial, for the aims of biological explanation influence a variety of other features of the field of biology. Explanatory aims account for the continued neglect of some central causal factors, a neglect that would otherwise be mysterious. This is linked to the persistent use of models like evolutionary game theory and population genetic models, models that are simplified to the point of unreality. These explanatory aims also offer a way to interpret many biologists’ total commitment to one or another methodological approach, and the intense disagreements that result. In my view, such debates are better understood as arising not from different theoretical commitments, but commitments to different explanatory projects. Biology education would thus be enriched by attending to approaches to biological explanation, as well as the unexpected ways that these explanatory aims influence other features of biology. I suggest five lessons for teaching about explanation in biology that follow from the considerations of this chapter.

Chapter 3 What would Natural Laws in the Life Sciences be?

Marc Lange

Much research in the life sciences arrives at generalizations concerning the biological properties characteristic of particular species, or generalizations concerning groups of species or even generalizations concerning broader biological classes. How should we understand these generalizations? In this chapter, I will examine whether the concept of a law of nature can help us to understand them. I will examine several controversies about the applicability of the concept of a natural law to the life sciences, including whether biological generalizations have exceptions, are riddled with ceteris-paribus provisos, or are too historically contingent to qualify as distinctively biological laws. I will not aim to argue that there are in fact biological laws, but rather to understand what would make it the case that there are (or are not). Implications for science education are discussed.

Chapter 4 The Nature of Evolutionary Biology: at the Borderlands between Historical and Experimental Science

Massimo Pigliucci

For some time now both biologists and philosophers of science have been struggling with the nature of evolutionary biology as a discipline. On the one hand, and dating back to Ronald Fisher's fundamental theorem of natural selection, the claim is that evolutionary biology is a predictive science based on rigorous mathematical foundations — indeed, Fisher consciously styled his theorem after the second principle of thermodynamics in physics, the (presumed) queen of sciences. On the other hand, Fisher's historical antagonist, Sewall Wright, emphasized the role of chance events (random drift) in countering and sometimes thwarting natural selection. The debate became central to Stephen Gould's attempt in the 1980s to establish paleontology, the quintessential historical science within biology, as a "nomothetic" (i.e., aiming at the discovery of general laws) enterprise, while at the same time acknowledging the macroevolutionary import of chance events like the asteroidal impact that caused the extinction of so many species at the end of the Cretaceous. In this chapter I will deploy a novel philosophical analysis by Carol Cleland and examine recent experimental results on the replicability of evolutionary trajectories, to clarify the status of evolutionary biology as a discipline and that of the relative role of what Jacques Monod referred to as chance and necessity in biological explanations.

Chapter 5 Evolutionary Theory and the Epistemology of Science

Kevin McCain & Brad Weslake

The sciences offer us a detailed picture of the world in which we live. But why is it rational to accept this picture? Evolutionary theory provides a beautiful case study of the way in which scientific theories are supported by their evidence. In this paper we provide a guide for teachers who wish to use evolutionary theory to explain the way in which scientific theories are supported, and to explain what is required for a theory to be rationally accepted. Our method is to consider evolutionary theory in the light of a range of criticisms that have been made by its critics: that it is a theory rather than a fact, that it cannot be proven, that it is not falsifiable, that it has been falsified, and that it does not make predictions. Using a series of examples, we explain why these criticisms are either false or involve a misunderstanding of the nature of evidential support and scientific knowledge. In the process, we exhibit some of the epistemic principles that are at the heart of scientific inference, and show how they are employed to establish the rational acceptability of evolution.

Chapter 6 Conceptual Change and the Rhetoric of Evolutionary Theory: 'Force Talk' as a Case study and Challenge for Science Pedagogy

David Depew

Darwinian theories vary. Some of the variation consists in differences in conceptual frames. These identify the entities and processes over which natural selection ranges. Different conceptual schemes are most easily identifiable by the different images, similes, analogies, and metaphors—in general, tropes--by which evolutionary theories are brought to bear on particulars. I show how Darwin's metaphors balanced function, chance, and determinism in living things by seeing artificial selection in terms of natural forces and natural forces in terms of artificial selection. I then argue that the Modern Evolutionary Synthesis highlighted Darwin's view of natural selection as a creative process, which earlier Darwinians had abandoned, by shifting to a conceptual framework and family of tropes that made images of force and design recessive. With the use of mathematical game theory to model gene frequency changes in the 1970s, however, design and force metaphors became dominant again, with the predictable result that images of Darwinism as promoting a god-abandoned, dog-eat-dog that had lodged deeply in popular culture long ago, were reawakened. Analysis of evolutionary discourse that hopes to reach students and the public must attend closely to the uses and abuses of conceptual tropes, 'force' and 'design' among them. This poses a question for pedagogy. How well can one teach evolutionary science without teaching some of its conceptual, and hence its rhetorical, history? Will students perceive this history as enhancing their knowledge of evolution, as an irrelevant waste of time, or, in its contentious diversity, as undermining its scientific status? Answering this question calls for empirical research.

Chapter 7 Debating the Power and Scope of Adaptation

Patrick Forber

How often should we invoke adaptation to explain the features of the biological world? Ideally, just as often as a history of natural selection explains the form and function of those features. This is partly an empirical question about evolutionary history. But it is also partly a question about the methods we should use to investigate evolutionary history. And the answers to the question have consequences for our views about our place in the biological world. Controversy over these issues is at least as old as Darwin. In contemporary evolutionary biology this controversy continues as the debate over *adaptationism*, raising a number of deep issues about the science of evolutionary biology and our philosophical understanding of the science. This makes adaptationism particularly relevant to science education, for the controversy provides traction on large scale questions about the nature of evidence and explanation, the plurality of scientific methods, and how science should guide our views about our biological nature. In this chapter I will investigate some of the issues about evidence and methodology brought out by the controversy, and I will argue that the debate over adaptationism provides an excellent and informative example of science in action. This is more than a mere philosophical controversy, for it interacts with the practice of biology in fascinating and complex ways.

Chapter 8 Biology and Religion: The Case for Evolution

Francisco Ayala

The theory of biological evolution is the central organizing principle of modern biology. In 1973, the eminent evolutionist Theodosius Dobzhansky famously asserted that "Nothing in biology makes sense except in the light of evolution." Evolution provides a scientific explanation for why there are so many different kinds of organisms on Earth and gives an account of their similarities and differences (morphological, physiological, and genetic). Science has demonstrated again and again, beyond reasonable doubt, that living organisms evolve and diversify over time, and that their features have come about by natural selection, a process that accounts for their design. Yet, there are many people of faith in the United States and elsewhere who think that science, particularly the theory of evolution, is contrary to the teachings of the Bible and to religious beliefs, such as creation by God. Well before the formulation of the theory of evolution, religious authors over the centuries used the "argument-from-design" to demonstrate rationally, without reference to faith or divine revelation, the existence of God, as the author of the design of organisms. The argument from design has two parts. In one familiar form it asserts, first, that organisms evince to have been designed; second, that only God could account for the design. The argument from design was advanced, in a variety of forms, in Classical Greece and early Christianity. Its most extensive formulation is due to William Paley in his *Natural Theology* (1802). The eye—as well as all sorts of organs, organisms, and their interactions—manifests to be the outcome of design and not of chance, thus it shows to have been created by God. In the 1990s, the design argument was revived in the United States by several authors. The flagellum used by bacteria for swimming and the immune system of mammals, as well as some improbability calculations, were advanced as evidence of "intelligent design," on the grounds that chance processes could not account for the phenomena to be explained. In *The Origin of Species*, Darwin (1859) advanced a scientific explanation of the design of organisms. The adaptations of organisms are outcomes not of chance, but of a process that, over time, causes the gradual accumulation of features beneficial to organisms, whenever these features increase the organisms' chances of surviving and reproducing. There is design in the living world: eyes are designed for seeing, wings for flying, and kidneys for regulating the composition of the blood. The design of organisms comes about not by intelligent design, but by a natural process, which is creative through the interaction of chance and necessity. Organisms are pervaded by imperfections, dysfunctions, cruelties, and even sadism. The theory of evolution accounts for these mishaps by natural selection, as outcomes of natural processes, so that they need not be attributed to God's explicit design. The theory of evolution perceived by some people of faith as contrary to religion, may thus be acknowledged as their "disguised friend." The theory of evolution accounts for the design of organisms, but also for the dysfunctions, oddities, cruelty, and sadism that pervade the world of life, so that these deficiencies need not be attributed to specific agency by the Creator, which might implicitly amount to blasphemy. The foregoing considerations are important both for understanding and for accepting evolution as a fact of life, and should be taken into account by science educators and teachers.

Chapter 9 The Implications of Evolutionary Biology for Religious Belief

Denis Alexander

Evolutionary biology developed as a discipline within cultures influenced by the Christian faith and it was therefore with this religion that the initial exchange of ideas occurred. This chapter introduces some of the general models that have been proposed to describe the relationship between science and religion and then relates these to the particular engagement of Christianity with the theory of evolution. The important distinction between methodological and ontological reductionism is discussed within the context of this engagement. The chapter highlights four disparate issues that are particularly relevant when considering the implications of evolutionary biology for religious belief: biblical hermeneutics, the theological understanding of the term 'creation', the role of chance, and the implications of evolution for morality. It is concluded that the historical emergence of the contemporary scientific enterprise from a theological matrix generates many positive resonances between science and faith, and that, consequently, the biological research community is where a believer should feel particularly at home.

Chapter 10 Intelligent Design and the Nature of Science: Philosophical and Pedagogical Points

Ingo Brigandt

This chapter offers a critique of intelligent design arguments against evolution and a philosophical discussion of the nature of science, drawing several lessons for the teaching of evolution and for science education in general. I discuss why Behe's irreducible complexity argument fails, and why his portrayal of organismal systems as machines is detrimental to biology education and any understanding of how organismal evolution is possible. The idea that the evolution of complex organismal features is too unlikely to have occurred by random mutation and selection (as recently promoted by Dembski) is very widespread, but it is easy to show students why such small probability arguments are fallacious. While intelligent design proponents have claimed that the exclusion of supernatural causes mandated by scientific methods is dogmatically presupposed by science, scientists have an empirical justification for using such methods. This justification is instructive for my discussion of how to demarcate science from pseudoscience. I argue that there is no universal account of the nature of science, but that the criteria used to judge an intellectual approach vary across historical periods and have to be specific to the scientific domain. Moreover, intellectual approaches have to be construed as practices based on institutional factors and values, and to be evaluated in terms of the activities of their practitioners. Science educators should not just teach scientific facts, but present science as a practice and make students reflect on the nature of science, as this gives them a better appreciation of the ways in which intelligent design falls short of actual science.

Chapter 11 Molecular Evolution

Michael Dietrich

Molecular evolution emerged as a new hybrid discipline in the 1960s. Since then the study of the evolution of proteins, RNA, and DNA has profoundly altered the study of evolutionary biology. Any evolutionary biologist who witnessed the rise of molecular evolution can attest to this change. Philosophical analysis, however, allows us to sharpen our understanding of the nature of that change and in doing so appreciate that molecular evolution has split the domain of evolutionary phenomena, diversified the leading causes of evolutionary change, and produced a profound methodological reversal with regard to the testing of evolutionary hypotheses. In a post-genomic era, biology educators face a challenge of explaining evolution at both the molecular and organismal level. Philosophical analysis can clarify what makes these distinct but complementary approaches to evolution, while biologists themselves seek ways to integrate the molecular and organismal in evolutionary biology.

Chapter 12 Educational Lessons from Evolutionary Properties of the Sexual Genome

John Avise

The sexual genome (the full suite of genetic material within each cell of a sexual species) is an object of wonder for scientists and philosophers alike. By any criterion, it ranks among the most complex and sophisticated apparatuses known to humanity, yet it also performs like a Rube-Goldberg device that malfunctions routinely with oft-disastrous consequences for an organism's wellbeing. To reconcile such seemingly contradictory perspectives on genomic operations, gene-centric reasoning that focuses on the concept of selfish DNA appears at present to be a fruitful scientific approach. The basic idea is that sequence proliferation via successful DNA replication is a key aspect of the evolutionary game especially when the best interests of genes versus organisms come into conflict, as they often do. From this neo-Darwinian insight flow biological predictions that reconcile otherwise enigmatic structural and functional properties of sexual genomes, including many recently uncovered features of nuclear DNA in Homo sapiens. Thus, we might suppose that molecular genetics and evolutionary genomics would be centerpieces of academic curricula in biology and medicine. The fact that they are not has historical and sociological roots that help to explain why the genomic revolution, now entering its second decade, has barely begun to reach its tremendous potential for illuminating the human condition.

Chapter 13 Non-genetic Inheritance and Evolution

Tobias Uller

Teaching evolution usually means an exclusive focus on transmission genetics as the basis for heredity. The stability of DNA sequences gives the impression that the developmental history of individuals can be set aside and evolutionary change in phenotypes can be described as change in gene frequencies. This is the textbook version of evolution and the view that the majority of evolutionary biologists subscribe to. The unique position of DNA in heredity is now being challenged, however. Mounting empirical evidence suggests that phenotypic stability within lineages and differences between lineages can originate and be maintained via epigenetic and behavioural mechanisms, even in the absence of genetic variation. This raises questions regarding the evolutionary implications of such non-genetic mechanisms of inheritance, including whether they can bias the rate and direction of evolution or allow inheritance of acquired characters. In this chapter, I outline the historical background to the development of the transmission genetics view of heredity and how recent findings in molecular, developmental, and behavioural biology challenge the textbooks. I continue by showing how the heterogeneous cluster of non-genetic mechanisms of inheritance can contribute to an expanded version of evolutionary theory. Although it turns out that the special role played by genes in evolution can also be played by other inheritance systems, the main conceptual advantage of recognizing non-genetic mechanisms of inheritance is that it stimulates an explicit consideration of developmental processes in evolutionary explanations. This helps us to connect the processes responsible for within-generation change ('proximate questions' or the domain of developmental biology) with among-generation change ('ultimate question' or the domain of evolutionary biology). Furthermore, it shows how the teaching of fundamental concepts in evolutionary biology can benefit from philosophical analysis informed by contemporary biological research.

Chapter 14 Homology

Alessandro Minelli & Giuseppe Fusco

Homology is the core concept of comparative biology. Or, better, a variegated flock of concepts about relationships between character states in different biological units, the latter being either modular parts of one biological individual or conspecific individuals differing either in sex or developmental stage or, more commonly, representative individuals of different species. The chapter includes a historical overview of the subject and a definitional characterization of the many concepts of homology proposed since Owen (1843), contrasting non-historical, historical and factorial notions of homology, followed by a detailed analysis of 'sameness' across evolutionary time, developmental time and body space. A special section presents a selection of fields of application of the concept, like phylogenetic inference, the study of evolutionary novelties, biological nomenclature and reconstruction of the ancestral taxa. The chapter terminates with some educational suggestions.

Chapter 15 Teaching Evolutionary Developmental Biology: Concepts, Problems and Controversy

Alan Love

Although sciences are often conceptualized in terms of theory confirmation and hypothesis testing, an equally important dimension of scientific reasoning is the structure of problems that guide inquiry. This problem structure is evident in several concepts central to evolutionary developmental biology (Evo-devo)—constraints, modularity, evolvability, and novelty. Because problems play an important role in biological practice, they should be included in biological pedagogy, especially when treating the issue of scientific controversy. A key feature of resolving controversy is synthesizing methodologies from different biological disciplines to generate empirically adequate explanations. Concentrating on problem structure illuminates this interdisciplinarity in a way that is often ignored when science is taught only from the perspective of theory or hypothesis. These philosophical considerations can assist life science educators in their continuing quest to teach biology to the next generation.

Chapter 16 Philosophical Issues in Ecology

James Justus

Ecology endeavors to explain significant portions of the living world. The sophisticated experimental tests and mathematical theories developed to do so deserve much more attention from philosophers of science. This paper describes *some* of the main contours of the newly emerging field of philosophy of ecology: how an ecological perspective shaped Darwin's theory, particularly the niche concept and the idea that there is a "balance of nature"; the character and metaphysical status of biological communities; whether there are laws of ecology; and the concept of ecological stability. As these topics illustrate, ecology concerns a diverse conceptual terrain and an interesting set of theoretical and methodological issues that provide rich grist for philosophy.

Chapter 17 Small Things, Big Consequences: Microbiological Perspectives on Biology

Michael J. Duncan, Pierrick Bourrat, Jennifer DeBerardinis, & Maureen O' Malley

Microbiology is a broad-ranging area of research that has developed out of 400 years of observation, analysis and theorizing about microscopic life forms. The study of microbes has not yet received a great deal of attention from philosophy of biology, but there are many reasons why it should. In this chapter, we outline the value of thinking philosophically about microbes and microbiology via a discussion of concepts of life, biological individuals and levels of selection. These discussions will show how taking a philosophical perspective on microbiological studies can enrich not only microbiology but also biology in general and its philosophy. We conclude by drawing out some of the implications of philosophical perspectives on microbiology for educational strategies in the teaching of biology.

Chapter 18 Essentialism in Biology

John Wilkins

Essentialism in philosophy is the position that things, especially kinds of things, have essences, or sets of properties, that all members of the kind must have, and the combination of which only members of the kind do, in fact, have. It is usually thought to derive from classical Greek philosophy and in particular from Aristotle's notion of "what it is to be" something. In biology, it has been claimed that pre-evolutionary views of living kinds, or as they are sometimes called, "natural kinds", are essentialist. This static view of living things presumes that no transition is possible in time or form between kinds, and that variation is regarded as accidental or inessential noise rather than important information about taxa. In contrast it is held that Darwinian, and post-Darwinian, biology relies upon variation as important and inevitable properties of taxa, and that taxa are not, therefore, kinds but historical individuals. Recent attempts have been made to undercut this account, and to reinstitute essentialism in biological kind terms. Others argue that essentialism has not ever been a historical reality in biology and its predecessors. In this chapter, I shall outline the many meanings of the notion of essentialism in psychology and social science as well as science, and discuss pro- and anti-essentialist views, and some recent historical revisionism. It turns out that nobody was essentialist to speak of in the sense that is antievolutionary in biology, and that much confusion rests on treating the one word, "essence" as meaning a single notion when in fact there are many. I shall also discuss the philosophical implications of essentialism, and what that means one way or the other for evolutionary biology. Teaching about evolution relies upon narratives of change in the ways the living world is conceived by biologists. This is a core narrative issue.

Chapter 19 Biological Teleology: the Need for History

James Lennox & Kostas Kampourakis

Teleology is a mode of explanation in which something is explained to be present because of its contribution to some end to which it contributes, and it has its roots in the philosophies of Plato and Aristotle. Aristotle defended a *natural* teleology, free of the Platonic idea that the natural world is the creation of a divine, rational being of some sort, with a plan for his creation. The *philosophical* debate over teleological explanation in natural science during the Scientific Revolution was primarily between those who, under Platonic influence, defended theistic, creationist teleology and those who, for a wide variety of reasons, opposed the use of any sort of teleology in natural science, while the effective *scientific use* of Aristotelian teleological explanation was bearing fruit in the disciplines of anatomy, physiology and medicine. This analysis leads to a crucial distinction between two types of teleological explanations: a) teleological explanations based on design, which suggest that a feature exists for some purpose because it was intentionally designed to fulfill it, and b) teleological explanations based on natural selection, which explain a feature's presence in a population by suggesting that it was selected for its beneficial consequences for organism which have it. In this chapter, we describe a framework that can be implemented in order to help students be able to distinguish between design-teleology and selection-teleology. In doing this, an interesting connection is revealed: two major types of explanations found in conceptual development literature, animism and creationism, are identified as different types of teleology. We conclude that the history of the place of teleological explanations in the scientific study of life is necessary for understanding the philosophical dispute over their place in the biological sciences today, as well as that reference to evolutionary history is necessary for challenging students' intuitive teleological explanations.

Chapter 20 Biology's Functional Perspective: Roles, Advantages and Organization

Arno Wouters

This chapter discusses biology's functional perspective: what it amounts to, why it is essential and why it doesn't assume teleology or design. Using an explanation of the penguin's two-voice system as an example, I outline the main characteristics of the functional perspective: it approaches organisms as solutions to the problem to stay alive, it uses role functions to explain how organisms solve this problem, and explains an organism's features by pointing to the advantages of these features in solving the problems of life. Next, I explain why this perspective pervades biology. An organism's ability to stay alive critically depends not only on the characteristics of its parts but also on the arrangement of those parts and on the order and timing of their activities. The functional perspective is the biologist's way to take this organization into account. Then, I clear up some ambiguities in the use of the terms 'function' and 'functional explanation'. I distinguish three notions of function (function as activity, function as biological role and function as biological value) and two kinds of functional explanation (explanations that use role functions to explain an organism's ability to stay alive and explanations that explain why certain organisms have certain characteristics by elucidating why those characteristics are advantageous in solving the problem to stay alive). Subsequently, I point out that function attributions and functional explanations are independent from assumptions about origin. This distinguishes function from adaptation and functional explanation from selection explanation. I then explain that it is a misunderstanding to think that the functional perspective rests on an analogy between function and design. Finally, I discuss the idea that it is the 'proper function' of a part or behavior to produce the effects for which that part or behavior was maintained in the process of natural selection. I explain that, as long as one is aware that functions in this sense do not explain the presence or structure of their bearer, Darwinian evolutionary theory is not at odds with this leap from past to purpose, but does not justify it either.

Chapter 21 Understanding Biological Mechanisms: Using Illustrations from Circadian Rhythm Research

William Bechtel

In many fields of biology, researchers explain a phenomenon by characterizing the responsible mechanism. This requires identifying the candidate mechanism, decomposing it into its parts and operations, recomposing it so as to understanding how it is organized and its operations orchestrated to generate the phenomenon, and situating it in its environment. Mechanistic researchers have developed sophisticated tools for decomposing mechanisms but new approaches, including modeling, are increasingly being invoked to recompose mechanisms when they involve nonsequential organization of nonlinear operations. The results often are dynamical mechanistic explanations. The steps in mechanistic research are illustrated using research on circadian rhythms.

Chapter 22 Information in the Biological Sciences

Alfredo Marcos & Robert Arp

Information has been a central concept for contemporary work in the biological sciences (and other sciences) especially after the publication of Claude Shannon and Warren Weaver's, *The Mathematical Theory of Communication*, in 1949. In fact, the pervasiveness of Shannon's information theory—as well as of the very terms themselves—becomes evident when one takes a moment to reflect upon just a few of the concepts that are standard in the biomedical sciences, such as genetic *code*, *messenger* RNA, ion *channel*, cell *signal*ing, intracellular *communication*, *signal* transduction, pathogen *transmission*, positive *feedback* loop, expressive *noise* minimization, and many others. In this chapter we first give a historical introduction concerning the concept and nature of information, with a special emphasis upon the biological sciences. Then, we provide a few important examples of information at work in the biological sciences. Next, we consider the debate regarding the reality and nature of bioinformation, arguing that bioinformation is best understood as a relationship between and/or among entities; for instance, DNA is informational only in relation to a given cellular context, and it is misguiding to locate information in a particular molecule. We then go on to show how bioinformation relates to other concepts such as entropy, order, organization, complexity, and knowledge. Finally, we approach education itself as an informational process in order to draw some consequences for the teaching of biology.

Chapter 23 Systems Biology and Education

Pierre Alain Braillard

According to most commentators, systems biology is transforming the biological sciences in many ways, although it is debatable exactly at what levels and to what extent. The formalization and use of computational models, the development of high-throughput experimental techniques, the new links with other scientific domains (like physics, engineering, mathematics, or computer sciences) and the transfers of explanatory models that have resulted, and other changes have had a profound impact on how biological research is conducted and, consequently, how biology must be taught. In this chapter, I will particularly focus on what challenges and opportunities the massive use of formal models has brought to biology. Not only must biologists learn how to use new tools in order to represent and analyze their objects of study, but they also have to realize that new questions must be asked in order to reveal aspects of biological systems that remained hidden in the framework of traditional molecular biology and genetics. Systems biology is integrative and interdisciplinary but transfers of methods, models and concepts are not straightforward and they raise many difficult questions. Another problem is that the transformation of biology into a "complex science" leads to a partial loss of intuitive understanding, which can be troubling for biologists, which are used to think with the help of words and diagrams. How can biologists regain some intelligibility? I will also discuss how systems biology has already started to challenge some of the standard views about the status of biology as a science, the nature of biological explanations, the relation between different domains of biology, or the nature of living systems and their evolution. I will argue that these philosophical analyses of systems biology's foundations must be seriously integrated in contemporary reflections on biology education.

Chapter 24 Putting Mendel in His Place: How Curriculum Reform in Genetics and Counterfactual History of Science Can Work Together

Annie Jamieson & Gregory Radick

Textbook presentations of genetics have changed remarkably little since their earliest days. Typically an initial chapter introduces Mendel's pea-hybridization experiments and the lessons ("laws") drawn from them. Then, in succeeding chapters, those lessons are gradually qualified and supplemented outof existence. The case of dominance is an especially well-discussed example of a concept that has survived in genetics pedagogy despite its diminishing role in genetic theory and practice. To clarify the costs of continuing to organize knowledge of heredity in traditionally Mendelian ways, this chapter recalls criticisms of Mendelism that were made at its start but have since been lost. The criticisms came from the Oxford zoologist W. F. R. Weldon (1860-1906). Although remembered now as a "biometrician", Weldon was by training an embryologist, who toward the end of his life drew upon the latest experimental studies of animal development in order to suggest an alternative and, in his view, superior concept of dominance to that found in Mendel's work. Weldon's dissent from Mendelism could well serve to inspire those attempting now to cast Mendelian tradition aside in order to reshape genetics teaching for a genomic age.

Chapter 25 Against "Genes For": Could an Inclusive Concept of Genetic Material Effectively Replace Gene Concepts?

Richard Burian & Kostas Kampourakis

This chapter focuses on the interactions between developmental, evolutionary, and genetic considerations in thinking about the structure and content of the genetic material and how it is regulated, with additional attention to the role of genetics in biomedical research. We suggest an approach to teaching non-professionals about genetics by paying attention to these issues and how they have been transformed by molecular tools and doctrines. Our main aim is to debunk the intuitive and widespread notion of "genes for". This perspective should help students engage with the issues raised by contemporary biomedicine and biotechnology. We suggest that by replacing the concept of the gene as a vehicle for integrating developmental, evolutionary, and genetic considerations and for understanding the importance of genetics in biomedicine and biotechnology with the concept of the genetic material, questions about genes and about the genetic material become a tool for integrating knowledge of other biological sciences. In the process, one will be able to develop helpful arguments against overly-narrow versions of genetic determinism and for the importance of a broad understanding of genes and inheritance.

Chapter 26 Current Thinking about Nature and Nurture

David Moore

Theories about the origins of people's biological and psychological characteristics have focused for centuries on the contributions of Nature and Nurture to development. Modern psychologists often maintain that it is an error to ask if Nature *or* Nurture determines the form of a particular trait, because the two types of factors interact during development. Instead, some of them have argued, the question of importance is: how *much* does each factor contribute to this process? This is the approach adopted by quantitative behavioral geneticists engaged in twin and/or adoption studies—research designed to yield heritability estimates for a wide variety of traits. In contrast, molecular biologists have learned that the dichotomy at the heart of such questions does not stand up to either conceptual or empirical scrutiny. In fact, it makes little sense to attempt to quantify the extent to which Nature versus Nurture contributes to a trait, precisely because these two classes of factors are *always* essential to—and interactive during—the development of both biological and psychological characteristics. Therefore, the question of importance is: *how* are our traits built during development? That is, how is it that genetic factors, proteins, cells, organs, organisms, and populations of individuals co-act to produce phenotypes in development? There are a number of related insights at the center of this discussion, including that the environments and experiences we encounter as we develop get inside of us in ways that alter our biological/genetic functioning, and that biological factors *collaborate* with environmental factors to build all of our organs, including our brains and their associated behaviors, cognitions, and emotions. Although the conceptualization of Nature and Nurture as dichotomous has a long history, evidence from the biological sciences indicates that it has outlived its usefulness. Consequently, those wishing to teach students about genetics, human nature, inheritance, and development would be well advised to refrain from framing their discussions in terms of this obsolete dichotomy.

Chapter 27 Genomics and Society: Why "Discovery" Matters

Lisa Gannett

Given the commercialized social context within which research in genomics is carried out, concerns have been raised about whether patent applications, consulting agreements, and reliance on industry grants serve to compromise the objectivity of scientists. Traditionally, philosophers of science have defended the objectivity of science against the intrusion of values from the social context by drawing several distinctions: one, between theory and practice, or basic and applied science; two, between the context of discovery and context of justification; and three, between facts and values. In this chapter, I review the various ways in which pragmatists, post-positivist, and feminist critics have challenged these distinctions, and conclude that it is values all the way down: theory is embedded in practice, discovery matters for justification, and facts and values are entangled. A case study that concerns the recent invention of the concept of biogeographical ancestry as a substitute for "race" in population genomics illustrates how the value-free ideal, for the reasons critics have identified, does not succeed in insulating research in genomics from the commercialized social context in which it is carried out. The chapter concludes by outlining some implications for the status of epistemology in philosophy of science and for biology education.

Chapter 28 Philosophical Issues in Human Pluripotent Stem Cell Research

Andrew Siegel

There are few areas of scientific inquiry that have been as fraught with controversy as human pluripotent stem cell research. This research has implicated issues in metaphysics, ethics, and political philosophy. The issues include, among others, the question of when a human life begins, the moral status of the human embryo, whether there is a moral distinction between creating embryos for research and creating them for reproductive ends, the ethics of creating human/non-human chimeras, and the challenge of constructing public policy in a pluralistic society in which there are opposing views about the ethics of the research. It is important that stem cell biology education extend beyond an inquiry into the biological properties of stem cells and further address the philosophical questions that bear on the pursuit of research in the field. This chapter provides an overview of these issues.

Chapter 29 Ethics in Biomedical Research and Practice

Anya Plutynski

Biomedical research raises a host of ethical questions of import to biology education. This chapter covers ethical questions “intrinsic” to the research: e.g., ethical proscriptions on what kinds of research may be conducted, as well as questions “extrinsic” to research: about which research is prioritized and why, how biomedical research is funded and related considerations of allocation and distributive justice. Research ethics is the branch of biomedical ethics that concerns the responsible conduct of research – including, but not limited to: the ethical treatment of human and non-human subjects, avoiding conflicts of interest, the fair representation of authorship, and the scientist as a responsible member of society. The first part of this chapter will focus more narrowly on the ethics of research on human and non-human subjects. After the Nazi "experiments" on vulnerable populations during WWII, the Nuremberg trials and Code that resulted (1947) codified a set of norms for research on human subjects necessary to protect vulnerable populations from abuse. Until relatively recently, vulnerable populations (prisoners, soldiers) were viewed as optimal candidates for biomedical research, and were invited to participate in medical research that posed serious harms and had very little benefit, often to them as patients, and sometimes to science, in general. The most famous example of this is the Tuskegee syphilis study, in which 400 African-American men with untreated syphilis were left untreated and observed over the course of decades, even after treatment became available. With respect to the “extrinsic” issues, a variety of economists, philosophers, sociologists, and biomedical researchers have brought attention to the fact that the overwhelming majority of biomedical research is directed toward diseases that by and large affect the wealthy. Whereas historically, biomedical research was often conducted in non-profit or government sector, a larger percentage of such research today is conducted in the private sector. This raises questions about potential conflicts of interest – e.g., concerning whether clinicians and clinician researchers are unduly influenced by profit in prioritizing some research projects over others, and, whether efficacy of new drugs or treatment regimes is exaggerated and risk minimized as a result. At the end of this chapter, several proposals for addressing these issues will be reviewed. Addressing these ethical issues is important to biology education, because students from a variety of disciplines need to situate biomedical research in social and ethical context, and reflect on its larger import.

Chapter 30 Environmental Ethics

Roberta Millstein

A number of areas of biology raise questions about what is of value in the natural environment and how we ought to behave towards it: conservation biology, environmental science, and ecology, to name a few. Based on my experience teaching students from these and similar majors, I argue that the field of environmental ethics has much to teach these students. They come to me with pent-up questions and a feeling that more is needed to fully engage in their subjects, and I believe some exposure to environmental ethics can help focus their interests and goals. I identify three primary areas in which environmental ethics can contribute to their education. The first is an examination of who (or what) should be considered to be part of our moral community (i.e., the community to whom we owe direct duties). Is it humans only? Or does it include all sentient life? Or all life? Or ecosystems considered holistically? Often, readings implicitly assume one or more of these answers; the goal is to make the student more sensitive to these implicit claims and to get them to think about the different reasons that support them. The second area, related to the first, is the application of the different answers concerning the extent of the ethical community to real environmental issues and problems. Students need to be aware of how the different answers concerning the moral community can imply conflicting answers for how we should act in certain cases and to think about ways to move toward conflict resolution. The third area in which environmental ethics can contribute is a more conceptual one, focusing on central concepts such as biodiversity, sustainability, species, and ecosystems. Exploring and evaluating various meanings of these terms will make students more reflective and thoughtful citizens and biologists, sensitive to the implications that different conceptual choices make.