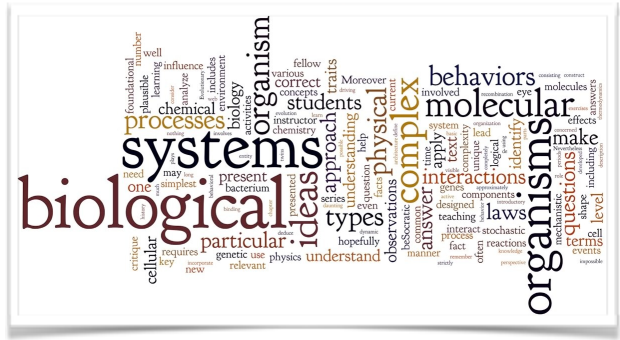
Preface: The biofundamentals approach to teaching and learning basic biology

Our goal is to present the key observations and unifying concepts upon which modern biology is based. Once understood, this is knowledge that should enable you to approach any biological process, from disease to kindness, from a scientific perspective. To truly understand biological systems we will need to consider them from two complementary perspectives; how they came to be (the historic) and how their structure, traits, and behaviors are produced (the mechanistic).



We are biological entities, the product of complex developmental processes, acting on inherited genetic information. We live in complex social arrangements with other humans, whose behaviors influence us in profound ways. We interact with other organisms and our environments through a range of ecological interactions; as we alter our environment, we inevitably alter ourselves. Science is a coherent strategy by which we seek a better understanding of the Universe and ourselves, and how they shape and constrain what is possible. That said, science does not provide a prescription for how things should be, because it does not deal in shoulds but rather (at its best), in what is and what could be. Moreover, our scientific understanding of almost every topic, and particularly the remarkably complex behaviors of biological systems like ourselves, is incomplete. It is not even clear that the Universe is necessarily completely coherent. The difficulties in resolving theories of gravity and particle physics for example raise the possibility that a single theory of everything may not be possible or if possible, may not actually be understandable by us.[1]

"Scientific knowledge is a body of knowledge of varying degrees of certainty-some most unsure, some nearly sure, but none absolutely certain ... Now we scientists are used to this, and we take it for granted that it is perfectly consistent to be unsure, that it is possible to live and not know."
- Richard Feynman.

" ...it is always advisable to perceive clearly our ignorance."
– Charles Darwin.

Periodically, however, an idea known as scientism gains popularity. It holds that science provides a complete and exclusive picture of the Universe, a picture that dictates how we should behave. We caution against this view, in part from the perspective of history and in part because it violates our own deeply held (enlightenment) view that we are each unique individuals who are valuable in and of ourselves, deserving of respect, and not objects to be sacrificed to abstract ideals (e.g. blown up for "scientific," political, religious, or economic reasons). A number of serious crimes against humanity and individuals have been carried out based on purportedly unambiguously established "facts" that later turned out to be untrue, seriously incomplete, tragically misapplied, or more or less irrelevant.[2] Crimes against people in the name of science are just as unforgivable as crimes against people in the name of religion or political ideologies.

---

[1] Correspondence and coherence in science: http://journal.sjdm.org/ccdg/ccdg.pdf

[2] The Undergrowth of Science: http://www.salon.com/2000/11/30/gratzer/

That said, scientific thinking is indispensable if we want to distinguish established, empirically supported observations from fantasies that can often be harmful, such as when anti-vaccine campaigns lead to an increase in deaths and avoidable diseases.[3] When we want to cure diseases, reduce our impact on the environment, and generate useful technologies, we are best served by adopting a dispassionate scientific approach to inform our decisions, to decide between the possible and the impossible, and to assess at least the technical impacts of various interventions, as well as kjtheir costs and benefits.

How biology differs from physics and chemistry

While it is true that biological systems, that is, organisms, obey the laws of physics and chemistry they are more than just complex chemical and physical systems. Why, you might well ask? Because each organism is a unique entity, distinguishable from other organisms of the same type by the genetic information it carries and at the molecular level by the stochastic events that combined to influence its development and behavior. Even identical twins can be distinguished in terms of molecular and behavioral details. Moreover, each organism has a unique history that runs backwards in time for an unbroken period of approximately 3,500,000,000 years. To understand an organism's current shape, internal workings, and visible behaviors requires an appreciation of the general molecular, cellular, developmental, and ecological processes involved in producing these traits. These mechanistic processes are themselves the product of what the great molecular biologist Francois Jacob (1920-2013) referred to as evolutionary tinkering, that is, the organism's history.[4]

No organism, including us, was not designed *de novo* (from the Latin meaning, anew). Rather they (and we) are the products of continuous evolutionary processes that occurred over long periods of time and involved a series of ancestors adapted to their own particular life styles (ecological niches), through a complex process that involved combinations of random (stochastic) and non-random events, including mutational variation, various forms of genetic recombination, various types of selection, and the effects of the organism's interactions with other organisms and with a changing environment. Because of these complex and interacting processes, one cannot readily deduce the exact architecture and the molecular and cellular organization of a particular organism or trait from physical first principles. Take for example the human eye, which behaves completely in accord with physical laws, nevertheless has idiosyncrasies associated with its evolutionary history.[5] Evolutionary processes lead to the emergence of new traits and types of organisms, and at the same time play a conservative role, maintaining organisms against the effects of molecular level noise in the form of deleterious mutations. The interactions between organisms and their environment may be static or highly dynamic and can direct evolutionary changes, albeit often in unpredictable ways, in different organisms. These processes can lead to the extinction of some organismic lineages as well as the appearance of new types of

---

[3] How vaccine denialism in the West is causing measles outbreaks in Brazil: http://www.theguardian.com/commentisfree/2014/apr/28/vaccine-denialism-measles-outbreaks-in-brazil and http://www.historyofvaccines.org/content/articles/history-anti-vaccination-movements

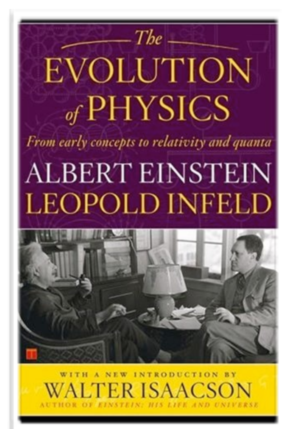
[4] Evolution and Tinkering: http://www.sciencemag.org/content/196/4295/1161.long and Tinkering: a conceptual and historical evaluation: http://www.ncbi.nlm.nih.gov/pubmed/17710845

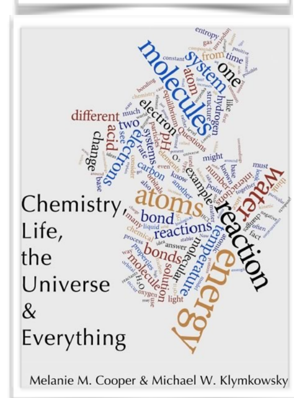
[5] How the Eye Evolved: http://www.nyas.org/publications/detail.aspx?cid=93b487b2-153a-4630-9fb2-5679a061fff7

organisms. These processes have led to the millions of different types of organisms currently in existence.

A second important difference between biological and physicochemical systems is that even the simplest of biological systems, an organism consisting of an individual cell (we will define what exactly a cell is in the next chapter) is more complex than the most complex physical system. Moreover, at the cellular and molecular levels there are often small numbers of specific molecules involved, so behaviors can be noisy and strictly deterministic behaviors are not always of primary importance. A bacterium, one of the simplest types of organisms in terms of molecular components, contains more than 3000 distinct genes, and hundreds to thousands of concurrent and interdependent chemical reactions, whose outcomes influence which genes are active (active genes are often said to be "expressed") and which are not, what ecological/environmental interactions are occurring, and how the bacterium responds to them. Nevertheless there are common themes that we will use and return to over and over again to make biological systems intelligible. We will rely on the fact that we can understand how molecules interact through collisions and binding interactions, how chemical reactions interact with one another, that is, how they are coupled through common intermediates, and how physical laws, in particular the laws of thermodynamics, constrain and shape biological behaviors.

The student's background and our teaching approach





While it is often the case that biology is taught early in a science sequence, this seems rather counterintuitive to us, since biological systems and processes are more complex that non-living physical or chemical systems even though biological systems are based on and constrained by physical and chemical principles. We recognize that it is unlikely that most students will enter the course completely comfortable with physical and chemical concepts, and we have written the text presuming very little. Where reference to physicochemical concepts is necessary, we have attempted to point them out explicitly and addressed them at a level that we believe should be adequate for students to be able to deal productively with the ideas presented. Given that biology students are a large fraction of the target cliental of introductory physics and chemistry courses, one can only hope that over time these courses will evolve to help life sciences students learn what they need to know. We suggest that students interested in learning more about the physical and chemical concepts that underlie biology might want to read Einstein and Infeld's "The Evolution of Physics" and our own "Chemistry, Life, the Universe, and Everything."

A Socratic, learning-centered approach to teaching: The complexity of biological systems can be daunting and all too often biology has been presented as a series of vocabulary terms, while little attention is paid to its underlying conceptual (sense-making) foundations. This emphasis on memorization can be off-putting and, in fact, is not particularly valuable in helping the student to develop a working understanding of biological systems. Our driving premise is that while biological systems are complex, both historically and mechanistically, there is a small set of foundational observations and ideas that apply to all biological systems. Their complexity, and the incompleteness of our understanding, often make a perfect (complete and accurate) answer to biological questions difficult. Nevertheless, it is possible to approach biological questions in an informed, data-based (empirical) and logical manner. In general, we are less concerned with whether you can remember or reproduce the "correct" answer to a particular question and more with your ability to identify the facts and over-arching concepts relevant to a question and to then construct a plausible and logical answer.

Going beyond memorization means that you will be expected to use and apply your understanding of key facts and overarching ideas to particular situations. This will require that you develop (through practice) the ability to analyze a biological situation or scenario; to identify what factors are critical (and recognize those that are secondary or irrelevant) and then apply your understanding to make predictions or critique conclusions. To this end we will repeatedly ask you to mentally dissect various situation to reach your own conclusions or solutions. To give you opportunities to practice, each section of the book includes a number of "questions to answer and ponder." You should be able to generate plausible answers to these questions, answers that we hope you will have an opportunity to present to, and analyze with, your instructor and fellow students. Where you do not understand how to proceed, you should storm into class able to articulate exactly why you are confused (something that often takes some serious thinking). You will need to actively search (and if you cannot find it, demand help in developing) a viable approach that enables you to answer those questions or to explain why the questions makes no sense. As part of this process, we have developed a number of interactive beSocratic activities, accessible through web links (BeSocratic.com) that are designed to develop your ability to construct models and explanations of important phenomena. In many cases, you will receive feedback within the context of the activity. That said, there is no substitute for discussions with other students and your instructors; that is, after all why one has experts in biology teaching biology courses. Ideas that you find obscure or that make no sense to you need to be addressed directly. Learning to critique or question an explanation will help you identify what is relevant, irrelevant, conceptually correct or logically absurd in your and your fellow students' thinking, so that by the time we reach the end of the course, you will have learned something substantial about biological systems.

Revisions to the text: Because this is an introductory course and because the ideas presented are well established and foundational, we expect no need for dramatic revisions of content. That said, we have much to learn about how to help students master and apply complex biological ideas, so we are using student responses both from beSocratic activities, and from classroom interactions to identify effective activities and ineffective parts of the text so that they can be improved. New "editions" will incorporate these insights.