An Overview of Biology[1]

Reading assignment: Campbell Chapter 1 (you've read some of it previously).

We will start this overview with a discussion of the characteristics of life. Besides thinking about what is characteristic of living things, try to answer the question of whether or not we can really come up with a simple definition of life. This is especially appropriate as we increasingly begin to search for extra-terrestrial life and as we ponder the origins of life. Some say that self-replicating computer programs are a form of life. What do you think?

What Are the Characteristics of Life?

The only presently known examples of what we call living organisms come from the Earth. This said, what characteristics do we use to distinguish life from non-living entities? You have undoubtedly seen lists of characteristics before. It would be fair to say that the main way these list differ is in how many characteristics they include -- in other words, how detailed they are. The following list emphasizes over-arching characteristics of life as we know it instead of details. It is reflects the view that we will take in this course.

Complexity and Organization. Compared to non-living systems, living ones are highly complex. By this I mean that they contain a large number of distinct, non-identical components. Complexity and organization are the opposites of random or entropic and so we say that one characteristic of living systems is that they are relatively **low entropy and therefore highly improbable systems**. However, just because something is complex and highly organized, that does not mean that it is alive in the sense we use the term. Cars, airplanes and computers are highly complex and organized but not many of us would call them alive.

Metabolism -- controlled thermodynamic processes used in growth and maintenance Complexity is not something that occurs spontaneously. Systems tend towards disorder, not high degrees of orderliness. In order to produce and maintain complex structures and to cause other improbably events (such as movement), organisms make use of energy. Energy is transferred from one molecule to another in the process generally termed metabolism. Without metabolism, organisms cannot grow, reproduce or maintain themselves. Moreover, the processes whereby energy is moved from molecule to molecule and chemical structures are built up and degraded are all controlled by various catalysts, many of which are in turn controlled (regulated) by other processes.

This said, the controlled use of energy does not by itself constitute a defining factor of life – if it did, then lawnmowers (complex entities that use energy to accomplish otherwise highly improbable actions) would be considered alive.

Response and Adaptation: To varying degrees, living organisms are able to respond to environmental changes, if nothing else so as to minimize or take advantage of changes in the environment. Obviously, the extents to which organisms do these things vary greatly. However, yet again this is not a unique attribute of living systems. Cars adjust their air and fuel mixture according to altitude and under many conditions, rainfall is determined by surface temperatures – high surface temperatures encourage the initiation of rain from water-laden clouds and then the cooling effect of the rain decreases the likelihood that it will continue.

Continuity and Reproduction Organisms possess internal instruction sets that largely control their functioning. Moreover, these sets remain within an individual for its entire life span and these can be passed on to other organisms (vertically from parent to offspring or horizontally between members of a generation – more on this one later). To a large degree, individuals that share the more of these instructions in common are more similar. Similarity caused by similar internal instructions is a fundamental feature of living systems -- one that is not generally observed in non-living entities.

Cellular life comfortably incorporates all of the characteristics mentioned above. In fact, this list is nothing more than a series of inductive generalizations that spring from our observations of things that we commonly call living. But what about viruses and other

things such as prions and viroids or even rickettsians that show some but not all of these features? The easiest way to handle this quandary is to simply state that they are in special categories – that they are semi-living, that they are related to things we think of as unambiguously living, but that they are clearly different and simpler than what we normally choose to call living.
This said, what about computer programs that copy themselves, that may even grow, that can respond to some degree to the actions of other computer code? Are they like cellular life, like viruses or like nothing at all except themselves? And what will happen if we eventually discover something that has many of the features of cellular life plus some others on a distant world? Such an event may well call for a major paradigm shift.

Major Unifying Laws, Theories and Principles of Modern Biology

Despite the diverse subject matter and approaches to studying life, there exist several major inductive generalizations that unify the field of biology as a whole. To a large degree you will see that these are restatements of the characteristics of life mentioned above – with a couple of additions.

Organisms are opened systems and are constrained by the laws of chemistry and physics, particularly relevant and ubiquitous are the laws of thermodynamics: This traces back to materialism as compared to vitalism and implies we can, in principle, understand living systems in the same terms as machines. We will cover thermodynamics shortly but suffice it say that among other things it places essential constrains how matter and behavior can behave and therefore on the ways that organisms function. In any case, organisms are just as bound by these laws as are simple chemicals in a reaction flask. The idea of an open system simply indicates that organisms are constantly incorporating and releasing matter and energy.

Regulation: Biological processes, unlike non-biological processes, tend to be regulated. For instance, reactions that should be feasible may be prevented from occurring or they will only occur at a slow rate. Likewise, reactions that might normally proceed very slowly can be speeded up when appropriate. More on this later.

<u>Evolution</u>: The law of evolution simply states that biological populations evolve over time. Only someone with an agenda of self-deception could come to any other conclusion after examining the behavior of present day populations and the fossil record. Theories that explain evolution include **natural selection** and **genetic drift** -- these are mechanisms to explain the pattern of change that we see and the creation of the diversity of life. If all life is composed of cells and all cells come from pre-existing cells, why is it that living beings are so different and can be classified as belonging to different species? **Darwin**[2] and **Wallace** explained this as **"descent with modification in response to natural selection"** and Wright explained some of the change as the result of chance events in small populations. In both cases, these theories seek to explain how*,* as life perpetuated itself over time, differences appeared and these differences gradually transposed living beings into different species. Thus, from a common cellular origin there arose differences and these differences accumulated over time to produce the diversity of species we observe today.

<u>The Cell Theory (Law):</u> The **cell theory** was promulgated independently in 1839 by the zoologist, **Schwann** and the botanist, **Schleiden**, and it provides a common basis for all living things studied by biologists. The theory states that **<u>all living beings are composed of cells</u>**, and thus establishes the cell as the smallest unit of independently existing life. In 1858 **Virchow** went even further by adding to the cell theory his **<u>THEORY of BIOGENESIS</u>** (or theory of cell lineage) that states that **<u>all cells come from pre-existing cells</u>**. These two statements (all life is composed of cells and all cells come from pre-existing cells) constitute **<u>the cell theory,</u>** as it is known today. The force of this theory is to provide a unitary basis for life and continuity over time among all living organisms.

---

[2] In his monumental book, *On the Origin of Species by Means of Natural Selection*, Darwin present a wealth of evidence supporting evolution and proposed a specific theory (natural selection) to explain the process behind this pattern of change. Although his hypothesis/ theory (also hit on by Alfred Russell Wallace) of how evolution operates was not immediately accepted, he did convince the scientists of his day that evolution had occurred, and so his name is forever linked to the concept of evolution.

The Central Dogma of Molecular Biology: This is a relatively recent addition to the list of significant unifying principles in biology and is a result of 20th century genetics. It states that all organisms are unified by using DNA (or sometimes RNA) as a hereditary molecule. Moreover, information flow is **from** the DNA **to** the cell, and although information flows to the nucleus (we will discuss this when we talk about gene regulation) this information does not alter what stored in nucleus (it only affects what parts are used at a particular time and place).

Curiously, although no one seriously doubts the validity of inductive generalizations 1, 2, 4 and 5, the inductive generalization of evolution is under constant attack by nonscientists and even a few scientists.
The reason is partially that the other four generalizations have minor historical implications in regard to human nature as compared to the theory of evolution.
The difference in popular acceptance of evolution compared to the other generalizations given above points to the importance of human history in understanding the development of biology as a science.

The Phenotype and Genotype

In one sense, organisms can be seen as a sort of duality. There is the **genotype** – the set of inherited instructions on how to construct and (largely) operate the organism and then the result of this construction and operation – the phenotype. The **phenotype** of an organism includes all of its measurable internal and external structures and processes. It also includes externally directed processes such as its behavior and the artifacts (results) of its behavior[3].

Phenotypes vary between individuals and within the same individual over time. Biological individuals are never absolutely identical nor is an individual identical over time. Compare this with the situation in chemistry. If I consider molecules of diatomic oxygen (O_2) where both atoms are isotope 16, then every one of these oxygen molecules is for all intents and purposes identical. Sure, there may be slight differences in energy states, but any one of these molecules can be put into essentially identical states with others. There is no variation that begins to approach the magnitude of what is seen in biological systems. The same is largely true of any chemical species (again ignoring the chance of different isotopes being used in different molecules). **Variation is the result of the incredible complexity of even the simplest biological entities**.

Many would say that the central role of biology is to understand the source, production, maintenance and meaning of variation.

When we see variation, we see evidence on the phenotypic level for possible genetic differences. We see differences that may well affect the ability of an organism to reproduce and may have important implications for evolution.

Wrap your mind around this -- a different take on phenotype and genotype: A well-known evolutionary biologist, Richard Dawkins, likes to think about organisms as being composed of an "eternal" (but changing) component that he calls the "**replicators**" and the "**survival machine**" -- the temporary structure they produce to enable them to replicate. Thus, the survival machine is the phenotype, produced by the replicators (the molecules upon which the genotype is written). Only the replicators are ultimately projected into the future – the survival machine (phenotype) is simply used like a lifeboat to get them from one moment in time into the future. And, although the idea is that the information contained in the replicating molecule is long lived (lasting more than the single generation of the survival machine) even it changes over time. Dawkins first wrote about these ideas to a mass audience in *The Selfish Gene*.

Biological Populations

A population is a collection of individuals, usually ones that are relatively similar in terms of genes. Perhaps the most important biological population is called the **deme** – it is a collection of individuals found in a particular location who are capable of

[3] The term "extended phenotype" is sometimes used to refer specifically to the effects of an organism's

reproducing with each other (species after often defined as consisting of one or more demes). Since **phenotypic variation** – the lack of identity between individuals -- is a central fact of biology, then descriptions of populations such as demes require a statistical approach. These approaches are essentially a formalized way of summarizing the aggregate characteristics of the members of a group. You will be introduced to some of the statistics used to describe populations in lab.

Changes that Occur In the Lifetime of an Individual vs. Those that Occur in a Population

Phenotypic changes that occur within one individual over time are referred to as **ontogenetic** (from the word ontogeny) – another term is **developmental**. On the other hand, if differences occur over several generations to members of a population at comparable ages, and if these differences are due to changes in the frequencies of genes in this population, then we say that these are **evolutionary** changes. So, evolution is a population phenomenon characterized by changes in the genetic makeup of the group over generational time whilst ontogenetic changes occur within individuals and are not accompanied by changes in the genes the individual carries (although they are related to changes in something called gene expression – we'll cover this later this semester).

More About the Phenotype: The Notion of Form and Function

A central theme of biology is the intimate association of the phenotype's **structure or form** and its **functions and activities**.

- **Form** refers to the shape and physical properties of some structure, whether it is a molecule, collection of large molecules, cell, limb or even the results of behavior (e.g., a nest). Put another way, when biologists talk about form, they talk about some material facet of the organism's phenotype – internal or external to the individual.

---

behavior. We will avoid this term and just talk about 'phenotype".

- **<u>Function</u>** refers to the *use of forms* -- what does a particular bone do (usually many things!), how does a particular behavior serve the individual that displays the behavior, *etc*. As with mechanical devices, for a particular function, certain shapes are better than others, others are more or less equivalent or offer other possibilities.

Clearly form and function are intimately inter-related and it is the role of much of biology to study these relationships.

Class Discussion Questions

Why are organisms not identical?

What are the sources of biological variation?

What are <u>traits</u> and what do they have to do with the concepts of phenotype, form and function?

Do individuals have variation with respect to form or function of one trait?

The Biological Hierarchy of Complexity

Humans love to categorize things. We find it useful to take objects and assign them to one group or another based on some sort of shared properties (a form of induction). Groups are to some degree the product of the mind and they are not necessarily perfect reflections of nature. For these man-made groupings to be useful in a practical sense, they need to be defined by meaningful differences and similarities.

We humans engage in group-making behavior every time we see something new. This includes things that we can sense without aids -- such as new types of animals, plants or rocks or new assemblages of the same and likewise, it applies to things that are totally new to us because we have extended out senses. Thus, with the invention of the microscope we see cells for the first time and begin to group them; and a similar process happens with telescopes and the discovery of nebulae, galaxies and far more exotic objects.

It seems that we next cannot resist the notion of grouping these groups according to similarity. One of the most common and useful ways of doing this is as a hierarchy –

an arrangement where the members of different "levels" become increasingly more inclusive (larger). Hierarchy based on size is the best example of this. In size hierarchy, groupings are arranged from smallest to large and generally at the same time from simplest to the most complex. Thus, the nature is divided by scientists into a hierarchy starting with subatomic particles, *e.g.*, quarks (or perhaps "strings"), to the universe as a whole (the cosmos).

Biologists study a limited portion of this spectrum: their interest begins with macromolecules and ends with ecosystems. Study of each level of this hierarchy is accomplished by specialists who have mastered certain tools that have proven to be most appropriate to a particular level.

Level	**Specialization**
Macromolecule	biochemistry, biophysics
Cell	cytology, cell biology
Tissue	histology, physiology, structural biology
Organ	physiology
Organ System	physiology, endocrinology
Organism	physiology, ethology (behavior)
Population	evolution, ecology
Community	community ecology (*e.g.* marine biology)
Ecosystem	limnology, oceanography

As you might suspect, given the complexity of life, <u>not all biological specializations can be so conveniently ordered because their subject matter encompasses more than one structural level.</u> **Genetics**, which explores the question of the hereditary basis of life, can be approached from the level of macromolecules (molecular genetics which studies the hereditary material itself - DNA), from the level of the individual (Mendelian genetics which studies the rules governing the transmission of traits from parent to offspring) and from the population level (population genetics which studies the amount of genetic variation in and between populations and serves as the basis for the study of evolution). Likewise, **developmental biology** follows the life history of a single individual from a single cell (the zygote) to its final appearance as an adult multicellular, multi-organed organism.

Reductionism, Holism and the Biological Hierarchy

The fact that nature can be usefully viewed as a hierarchy has more significance than simply providing a classification scheme for arranging biological specializations. It has given rise to a philosophical debate among scientists known as **holism** (or **antireductionism**) versus **reductionism**.

- **Holists** view each level as unique and ruled by processes that cannot be understood from a study of its component parts. In its most radical form holists believe that the whole is greater than the sum of its parts, because new properties **emerge** at each level. A less radical version of holism posits that complexity produces many possible interactions and it is not easy to predict which will dominate at higher levels of organization based on a knowledge of simpler, less inclusive levels. Thus, a knowledge of the property of cells found in a mammal could not be used to readily predict how a mammal regulates its temperature.

The Relationship Between Holism and Emergence

Note that the notion of holism is closely allied with a belief in emergence. **Holism** is simply the notion that some factors are best understood a particular level of complexity and not from its atoms (see reductionism below) and **emergence** goes along with this and states that some properties appear at higher levels of organization that were not evident at simpler levels.

- **Reductionists** take a different view of structural levels from holists. They argue that each level can be fully understood by analyzing its "atoms" or parts. For reductionists, **the whole is nothing but the sum of its parts**.

Reductionism is a basic strategy of scientists who attempt to explain nature in the simplest way possible and with the fewest laws or generalizations needed to achieve this task. The ideal reductionist goal is to explain the universe by means of a single equation that integrates the four known forces of nature (electromagnetism, weak nuclear force, strong nuclear force and gravity). As regards biology, the reductionist position would be that all of biology could be reduced to the laws of physics and chemistry; biology would then be the study of a subset of natural phenomena circumscribed by the limits of chemistry and physics, and biological laws could be written in terms of physiochemical laws.

Holists categorically deny this possibility and argue that the findings of biology, although describable to some extent in terms of physiochemical process, deal with a level of complexity that is a consequence of the interaction of its parts and so cannot be understood simply from analysis of its parts alone. During the history of life and its constituent parts, the phenomenon of **emergence** occurs whereby novelty is introduced through the interaction of parts. Emergence can be seen in both phylogeny (e.g., the origin of birds and their unique structural feature - feathers) and ontogeny (e.g., the development of organs from undifferentiated tissue).

You have probably been thoroughly introduced to reductionism in high school. So, although I consider myself primarily a reductionist, let's give holism its due. Consider the following question: could the properties of water be **predicted** from a knowledge of the laws governing the behavior of its constituent parts, *viz.*, hydrogen and oxygen? Reductionists would answer yes to this question because they view water as nothing but oxygen and hydrogen combined as represented in the formula H_2O. Holists would answer no because they view the properties of water as dependent upon the unique interaction of oxygen and hydrogen which is **not predictable** from a knowledge of the independent properties of oxygen and hydrogen studied by themselves. Which answer is correct? We will never know because we will never learn all there is to know about oxygen and hydrogen to test whether or not this knowledge is sufficient to **predict** the properties of water. The key word in this debate is "predict" because once the whole is known, it can be described in terms of the interaction of its parts. The debate centers on whether or not a knowledge of the parts alone is sufficient to **predict the interaction that emerges** from biological novelty at the next higher level of organization.

Study of the Hierarchy – The Notion of Disciplines and their Antidisciplines

The great evolutionary biologist and conservationist **E. O. Wilson** makes the distinction between **disciplines** and their **antidiscipline** in referring to the relationship between areas of science that study different levels of structural organization. Physics is the antidiscipline for chemistry that in turn is the antidiscipline for biology. **The antidiscipline describes the basic laws governing the structural units that form the parts of the whole studied by the discipline**.

Whether these laws are sufficient to reduce the discipline entirely to the terms of the antidiscipline is the subject of the holist-reductionist debate.

Wilson also notes that **a good scientist should be familiar with three different fields of study**:

- one's own discipline
- its antidiscipline and
- the field for which one's discipline serves as an antidiscipline.

For example, a good cell biologist should not only be well versed in the intricacies of cell structure and function (the discipline), but also understand how biochemistry (the antidiscipline) explains cell structure-function correlation, and how cells are organized to produce the structure and function of tissues and organs, which is the focus of histology or physiology for which cell biology serves as an antidiscipline.

How We Will Study the Biological Hierarchy: In this course I will use both reductionist and holist approaches in explaining biology. As much as possible I will attempt to explain higher-level units in terms of units previously described in discussion of the lower levels of organization. This will require that you keep up to date with the material covered since we will use this material later in the course. At the same time I will use the levels of organization approach as a pedagogical device by viewing the properties of each level as the result of **an interaction among the units of the next lower level**. I

The **big questions of modern biology** spring from the study of form and function:

- How form relates to function. This is the substance of physiology, anatomy and biochemistry.
- How genes and environment interact to determine the phenotype throughout an organism's life; this is the stuff of genetics and developmental biology
- How the environment and populations of organisms interact over time: the subjects of ecology and evolutionary biology.

In looking at the questions above, please realize that one can approach most of them two rather different ways:

- **Mechanistically** -- How did the structure or function arise during the developmental history of the individual (i.e., during its **ontogeny**). What sort of chemical and physical mechanisms are responsible for the phenotype. These types of questions are said to deal with **mechanism – sometimes, this is also termed proximate causation**.
- **Phylogenetically** -- How did the structure or function arise during the history of the species to which it belongs (i.e., during **phylogeny**)? What were environmental forces and chance events that determined the phylogeny. Such types of questions are sometimes said to deal with **ultimate causation** (know the term) but I will simply refer to them as **historical or phylogenetic approaches/questions**.

Taxonomic vs. Conceptual Approaches to Biology

Compared to the other natural sciences, biology is an enormously complicated field fragmented into a myriad of sub-areas or specializations. The reason is that biology studies the process of life, its intrinsic enabling structures, and its diversity in the form of species. Consequently, each specialized area of biology concentrates on one aspect of life for the purpose of making the complexity of biology intellectually digestible. For instance:

- some biological specializations involve **taxonomic approaches** since they focus on species diversity and so are restricted to the study of particular taxonomic groups, *e.g.*, <u>ornithology</u> (the study of birds) or <u>entomology</u> (the study of insects).
- Others, *e.g.,* genetics, physiology and ecology, ask basic questions about life and so represent **conceptual approaches** to biology.

We will adopt the conceptual rather than the taxonomic approach in this course. Nevertheless, the subject matter of conceptual biology is very broad and so we will have to restrict our discussion further to a limited set of topics and approaches.

STUDY AND REVIEW QUESTIONS

1. Describe the hierarchical arrangement of structural units studied by biologists and discuss the significance of this hierarchy in terms of reductionist and holist approaches to biology. Explain how Wilson's discipline-antidiscipline distinction (last set of notes) can organize the sciences and biological subdivisions.

2. Explain the basis for believing that biology is a unified science despite its many subdivisions.

3. Distinguish between (among) each of the following:
   - a. taxonomic and conceptual approaches to biology
   - b. holism, reductionism and emergence
   - c. discipline and antidiscipline
   - d. cell theory, theory of biogenesis, and the theory of evolution
   - e. the theory of evolution and Darwin's theory of natural selection
   - f. structure and function
   - g. biochemistry, cytology, histology & physiology
   - h. ethology, ecology and genetics
   - i. central dogma, regulation
   - j. proximate and ultimate causation

4. Identify each of the following:
   - a. macromolecule
   - b. cell
   - c. tissue
   - d. organ
   - e. organ system
   - f. organism
   - g. population
   - h. community
   - i. ecosystem
   - j. Virchow
   - k. Darwin
   - l. E. O. Wilson

5. Why is the notion that life must be consistent with thermodynamics so important and what does this have to do with notions of vitalism and materialism?