We have chosen to emphasize the above concept for several reasons. First, we believe this concept is absolutely essential in order for students to make sense of evolution. Second, this concept is difficult for students to understand. Simply explaining it to students is not enough no matter how skillful the explanation is. Third, most textbooks and courses fail to treat this concept adequately, forcing students to grapple with more advanced and difficult treatments before they have mastered this fundamental idea.

Critical Barriers to Understanding Natural Selection

The concept of evolution by natural selection as presented in the previous section appears easy to understand. Actually the concept and the ideas embodied within *are* fairly simple, but *only after one understands and accepts them.* Such understanding and acceptance may not be easily gained by beginning biology students. The students in our college nonmajors biology course have taken and passed an average of 1.5 years of previous high school and college biology courses. Yet their answers to test questions reveal a surprising lack of understanding. Consider the following examples:

> "When the salamanders started living in caves, their eyesight was no longer important. The new generations of salamanders, through natural selection, were born with nonfunctional eyes."
>
> "The theory of natural selection states that if an organism requires a special adaptation, over the years they will slowly acquire it."

The above statements were taken from student responses to questions on tests taken *after* these students had received instruction in natural selection. We know that these students had both listened to and read clear explanations of the process of evolution through natural selection, yet they still gave responses like those above.

Why do these ideas pose such a problem for students? How can they complete instruction in evolution and still misunderstand? This module is based on one kind of answer to these questions. The answer arises from extensive research comparing inexperienced students with scientific experts as both deal with scientific problems. In general, this research shows that the students think and act in ways that make sense to them, but that are incompatible with scientific thought.

The presence of these alternate ways of thinking makes the learning of science a far more complicated process that scientists normally imagine. Students cannot simply absorb or memorize scientific content. They must reassess and restructure their intuitive knowledge of the world. Furthermore, they must abandon misconceptions or habits of thought that have served them well all their lives in favor of new and unfamiliar ideas.

The old habits of thought can be amazingly resistant to change through instruction. They persist even after students have apparently learned the scientific alternatives. Many students become quite good at learning what is expected of them to pass science tests while continuing to use their old ideas in "real world" situations. We have adopted a phrase from David Hawkins and describe these enduring habits of thought that interfere with scientific

thinking as "critical barriers" to the learning of science. Hawkins defines these as "irretrievably elementary stumbling blocks" that prevent students from fully understanding scientific concepts and principles. This module is the product of a research and development project in which we have tried to understand the critical barriers to student learning in a nonmajors' biology course, then design materials and activities that will help students overcome those barriers.

There seem to be several critical barriers that prevent many of our students from attaining a scientific understanding of the process of evolution by natural selection. In general students enter our course believing that they already understand the process fairly well. Unfortunately, they are usually wrong. Figure 1: A & B, on the next page, contrasts the process as it is typically understood by our students with the process as scientists understand it. These conceptions of evolution by natural selection are different in many respects, the most important of which are the following three issues:

1. Students fail to make a distinction between the separate processes responsible for (a) the appearance of traits in a population and (b) the survival of such traits in the population over time.
2. Students fail to recognize that the process of natural selection is dependent on differences (in genetic traits and in breeding success) among individual members of a population.
3. Students misinterpret the nature of evolutionary change in populations, believing that *all* individuals change slowly over time.

The following sections contain a detailed discussion of the misconceptions held by students with respect to each issue. Although, in reality, correct scientific understanding of evolution by means of natural selection is achieved only by integrating the separate issues into a coherent whole, they are discussed separately below for ease of organization. Examples in each section are taken from responses to pretest and posttest questions our students gave and are included because they are representative of misconceptions students hold with respect to the issue discussed.

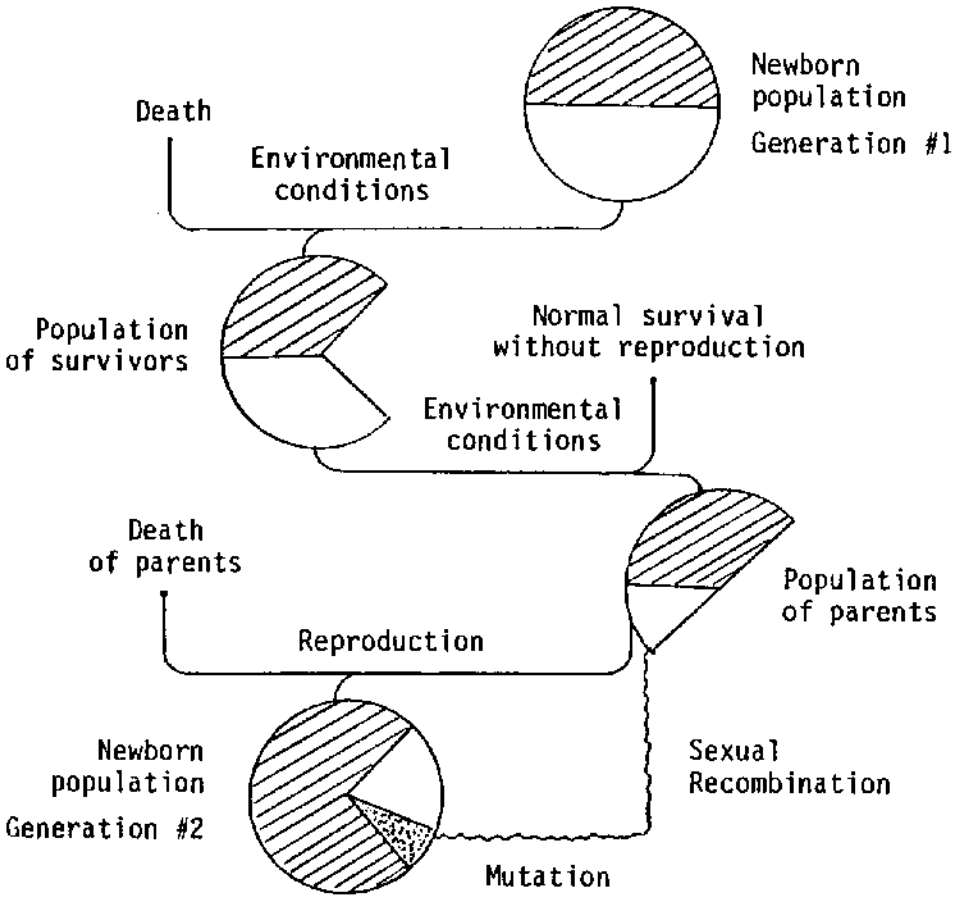
Origin and survival of new traits in populations. Biologists recognize that two distinct processes, fundamentally different in cause and effect, affect traits exhibited by populations. New traits originate by random changes in genetic material (mutation, sexual recombination), and then survive or disappear due to selection by environmental factors (thus affecting the composition of the population as a whole).

In contrast, students possessing naive conceptions do not recognize the existence of two processes affecting the population. The sole process seen to affect traits (often called by students "natural selection" or "adaptation") is viewed as affecting only the quality and/or appearance of traits.

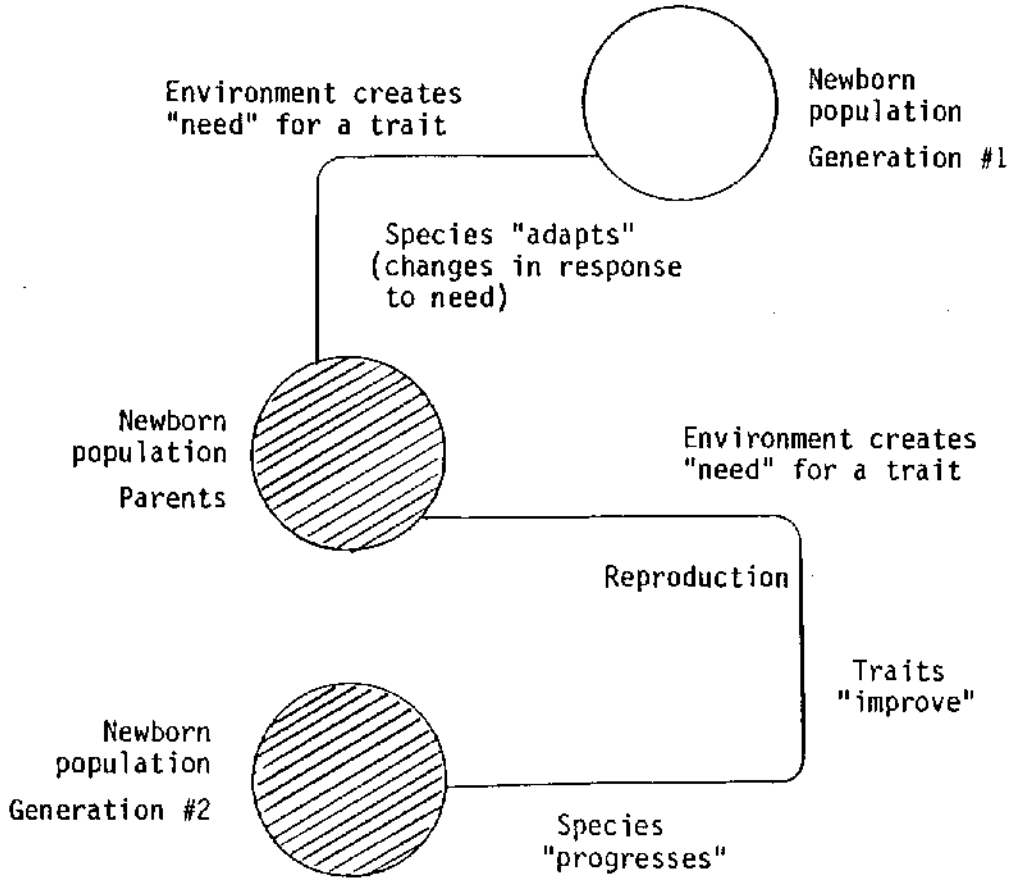
Furthermore, many students believe that environmental conditions are directly responsible for changes in traits.

Example: "Because with each generation the cheetah became more developed. The body began adjusting to the environment in order to survive."

A. Conception of Evolution by Means of Natural Selection



B. A Generalization of Students' Naive Conceptions



NONRANDOM CHANGES in population composition

RANDOM CHANGES in traits possessed by individuals

NONRANDOM (environmentally induced and directed) changes in traits

-Individuals with adaptive trait

-Individuals lacking adaptive trait

-Individuals with new traits changes in traits

-Partially adapted individuals

There is much variation in this particular naive conception concerning the details of students' belief. As far as when (in the reproductive cycle) the environment exerts its effect, two beliefs are common. Students may believe that the environment acts directly on living organisms, which alter their traits in response to environmental conditions and subsequently pass on all or part of these alterations to offspring. Alternately, students may believe that the environment (somehow) affects the genes as they are passed to offspring. Inherent in this later belief is a conception of "progressive evolution," whereby the genes of each successive generation "improve" or "fit" more closely to the environment.

With regard to the *mechanism* of environmentally induced change in traits, students' beliefs are various and often unclear. The most often stated effect of the environment on traits is creating *need* or *purpose*.

Examples: "Eventually the animal [cave salamanders] didn't need the sight and through the genes it was eliminated."

"Modifications for another essential need [then] evolved."

Some students are satisfied with this explanation as is: that *need* determines the appearance and modification of traits without explaining how it does so. Others incorporate, into their conception, an explanation of how need affects traits. The two most commonly used explanations are "use-disuse" and "adaptation."

The use-disuse explanation is classic Larmarckianism. Use (or disuse) of body parts results in development or deterioration of those parts. While this point is fairly easy to disprove to students in the short run (i.e., building muscles will not result in stronger children), it is difficult to convince them that long-term use or disuse will have no effect. They may believe that long-term use or disuse of body parts (for example, the cultural practice of binding the feet of young females in Oriental countries) will ultimately result in genetic modification of that body part (i.e., females born with smaller feet). But the influence is only believed to work over long time periods (i.e., hundreds or thousands of years) instead of at each generation.

Examples: "Eventually over the years they [cave salamanders] became blind because of not using their eyes."

"Therefore, they were meant to see, but since they no longer used a limb of their body, it lost its function."

With students who use the "adaptation" explanation of environmental effects, naive beliefs are often difficult to detect. These students are using a legitimate evolutionary term, but it is clear from their statements that they are *not* using the evolutionary definition of the word. Instead, they are using the word in reference to an individual (and/or collective) response to a "need."

Examples: "Their legs could have adapted by growing longer."

"Adaptation--for survival purposes the anatomy changed to enable cheetahs to catch their prey."

This issue as a whole is perhaps the most difficult one for our students. The idea that the environment directs the appearance and development of traits is very logical and appealing. To achieve proper understanding students must accept not only the idea that random processes cause the appearance and modification of a given trait, but also that the environment in no way influences this. In order for students to understand evolution they must accept that the environment affects *only* the survival and spread of traits, *after* their appearance in the population.

The role of variation within populations. Biologists understand that variation within populations is a prerequisite for evolutionary change. Differences among individuals with respect to genetic traits result in differences in reproductive success due to selection pressures imposed by the environment. This within-population variability is clearly depicted in Figure 1-A.

Students possessing naive conceptions often do not consider this variability as relevant, viewing selection as a process occurring to the species (or population) as a whole (see Figure 1-B).

Examples: "They [cheetahs] might have had to run fast to escape predators and gradually their muscles and bones changed to adapt to this."

"The cat [cheetah] was in an area where the environment changed and he had to adapt by learning to increase his speed."

While these students may understand that organisms differ from one another, they view this difference as irrelevant to evolution.

As in the previous issue, correct scientific understanding is achieved not only by recognition of the importance of variability to differential reproduction (rather easily achieved), but also by *rejection* of the naive conception, that selection involves a collective response on the part of the species or population.

Evolution as changing proportions of individuals with discrete traits. Biologists recognize that changes in traits appear sporadically and at random. Gradual progression in evolutionary change has to do with the spread of given traits through the population over the course of many successive generations. This is depicted in Figure 1-A by the increase in the percent of shading (proportion of individuals possessing adaptive traits) in the population circle.

In contrast, many students view evolution as consisting of the gradual, progressive, "improvement" or deterioration of traits over the course of successive generations. This is depicted in Figure 1-B by an increase in the degree of shading in the circle as a whole.

Example: "As sight was not needed, these salamanders in the cave passed down genes with less ability to see until they had evolved to the blind ones."

Again, correct student understanding of this issue involves not only acceptance of the scientific conception, but also rejection of the naive notion of gradual improvement in traits. If this rejection does not occur, students may believe that evolution involves not only the spread of traits through populations, but also an improvement of trait quality as it is passed from one generation to the next.

Terms that are confusing to students. Another stumbling block to correct learning of the theory of natural selection is the confusion in terms used in connection with it. Two such terms--"fitness" and "adapt"--can cause extreme difficulty, since their meaning, in everyday language, is very different from their usage in evolutionary terms.

1. Adapt/Adaptation. When one hears, in everyday conversation, that an individual adapts, one understands that individuals respond to environmental conditions by altering their form, function, and/or behavior. When one hears, in evolutionary terminology, that organisms adapt, one understands that the composition of the population changes over a period of several generations. These two definitions are quite different, and students, hearing this word used, often construct meanings in terms of the former familiar definition.

   Using the everyday definition for the process of adaptation in the evolutionary sense also tends to be reinforced by the misconception explained in the previous section, that is, that environmental conditions influence appearance and modification of traits.

2. Fitness. Biologists use the term "fitness" to express the capability of individuals (or genes) to produce surviving offspring. But, in the everyday sense, this word means, "big, strong and healthy." This discrepency in definitions can confuse students. The confusion may be amplified by inaccurate popularizations of evolution which state, "Only the strong survive."

Summary. The major contrasts between the scientific conception of the process of evolution through natural selection and our students' conceptions are summarized in Table 1. The naive conceptions described in Figure 1-B and in Table 1 are the critical barriers to understanding that this module is designed to overcome.

Table 1

Contrasts between Scientific Conception and Naive Conceptions of Natural Selection

Issue	Scientific Conception	Naive Conceptions
Major Issues		
Origin and survival of new traits in populations	Two separate processes: 1. Random genetic events affect the appearance and quality of the trait itself. 2. Environmental conditions affect only the survival and spread of existing traits.	Only one process is recognized. Environmental conditions are seen to affect the development of traits over time by causing: 1. Need or purpose 2. Adaptation 3. Use/disuse Environmental effects are understood to influence individuals and/or genes. No distinction is made between appearance of a trait and its survival in the population.
The role of variation within populations	Individual differences recognized as essential. 1. Differences in traits 2. Differences in breeding success related to environmental conditions	Individual differences are not seen as relevant. The species (as a collective) is seen to change over time.
Evolution as changing proportions of individuals with discrete traits	Evolution consists of a change in the *proportion* of individuals in a population exhibiting a given trait over several generations.	Evolution seen as consisting of a change in the *quality* of traits possessed by individuals over several generations.
Confusing Terminology		
1. Adaptation	Passive process in which the composition of traits exhibited by a population changes over several generations.	Active process in which individual organisms respond to environmental conditions by altering their form, function, or behavior.
2. Fitness	Ability of organism to produce offspring which survive to maturity.	Possession by an organism of "desirable" characteristics such as size, strength and intelligence.