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The Nature of Naive Explanations of Natural Selection

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Abstract

Unlike some pivotal ideas in the history of science, the basic notion of natural selection is remarkably simple and so one might expect most students to easily grasp the basic principles of the Darwinian theory; yet many students nevertheless have difficulty understanding Darwinian evolution. We suggest that misconceptions about natural selection arise from mistaken categorization. Our thesis for explaining students' failure to understand this concept, or evolution in general, is not that they necessarily fail to understand individual Darwinian principles; rather, they often fail to understand the ontological features of equilibration processes, of which evolution is one instance. They thus attribute the evolutionary process in general, and natural selection in particular, with event-like properties. For example, naive students appear to focus on the idea of *survival of the fittest*, but embed this idea within an event ontology that involves actors struggling to overcome obstacles and achieve goals. Results showed that most naive subjects' evolutionary explanations reflected an event ontology. Furthermore, event ontology attributes were positively correlated with Non-darwinian explanations; by contrast, equilibration attributes, when present, were positively correlated with key Darwinian principles. These findings suggest that students would greatly benefit from science instruction that emphasized the underlying ontology of modern evolutionary theory.

Empirical studies of students' conceptions about evolutionary biology have blossomed in the last decade (see Good et al., 1992), partly because such conceptions are foundational to studying a wide range of biological phenomena, and partly because they have been radically restructured in the history of science (Gould, 1996; Mayr, 1997; Samarapungavan & Wiers, 1997). Because evolutionary biology essentially involves one long verbal argument about how to interpret existing biological evidence (Darwin, 1996/1859; Mayr, 1988), one might expect most students to easily grasp the basic principles of the Darwinian theory. However, surprisingly, this is not always the case.

The Basic Darwinian Theory of Evolution

Unlike many other pivotal ideas in the history of science, Gould (1996; also Mayr, 1997) suggests that the basic notion of natural selection is remarkably simple—essentially three claims followed by an almost syllogistic conclusion: (1) All organisms tend to produce more offspring than can possibly survive, and yet populations remain stable. (2) Offspring are not perfect copies of some immutable type, but vary among themselves. (3) Some of this variation is passed down to future generations through inheritance (although Darwin was unsure of exactly how this might occur). These facts lead to the following inference about the mechanism of evolution, what Darwin called natural selection: If individual members of the species vary among themselves and many offspring must die (unable to survive in nature's limited ecology) then, on average, survivors will tend to be those individuals whose variations happen to be best suited to changing local environments. Given heredity, survivors' offspring will tend to resemble their successful parents; the accumulation of many favorable variants over time will produce evolutionary change.

Gould further (1996) notes that evolution rarely proceeds by the transformation of a single population from one stage to the next. For example, *Homo sapiens* did not evolve because our ancestors stood up straighter and began to speak. Such an evolutionary procedure (i.e., *anagenesis*)would permit one to use a linear metaphor like a ladder or chain to describe evolutionary change. Instead, evolution occurs through episodes of speciation, in which subpopulations branch off after becoming isolated from each other and eventually unable to interbreed (i.e., through *cladogenesis,* or branchmaking)—permitting Darwin's well-known metaphor of evolution as a branching tree).

Different descriptions and framing of these Darwinian principles are found in the literature (Bell, 1997; Mayr, 1997; Siegler, 1996; Ohlsson, 1991). Ohlsson (1991; see also Kitcher, 1993; Larreamendy-Joerns, 1996) provides an excellent summary of Darwin's theory in terms of five principles that essentially restate the points outlined above: (1) random intraspecies variability (individual variation); (2) heritability of certain traits (or genetic determination); (3) differential survival rate (local adaptation); (4) differential reproductive rate (reproductive advantage); and (5) accumulation of changes over many generations. Table 1 defines each of these principles briefly.

Insert Table 1 about here

We will exemplify these 5 principles using the classic case of the evolution of the peppered moth (*Biston betularia*). Around the middle of the nineteenth century, darker varieties of this moth, which had formerly been very rare, began to spread through the industrial regions of middle and north England. The reasons for this can be stated in terms of the five Darwinian principles. First, members of the species of moth varied in melanic pigmentation (*individual variation*) because of a single almost completely dominant mutation that had appeared in the population (Bell, 1997). Variability in coloring was thus the result of hereditary genetic differences (*heritability*). The spread of the darker moths followed the appearance of coal smoke over the newly industrialized towns that (when combined with rainwater) blackened walls and tree trunks, making the lighter, pepper-colored moths more easily visible to birds while the darker moths remained inconspicuous (*local inadaptation*). Bernard Kettlewell (1973), in a mark-release-recapture study of this species of moth, showed that birds prey on moths resting on tree trunks, eating the most conspicuous moths first (Note that, in the original lichen-covered trees before the soot, being darker may not have had any particular adaptive advantage.) Moths with a better chance of survival necessarily had a better chance to reproduce (*reproductive advantage*). Kettlewell (1973) showed that in the country side, the pepper colored variety increased in the course of a few days, whereas in polluted areas the melanic (darker) moths increased. Thus, the accumulation of random variability can lead to significant changes in the species in question (in this case, darker wing pigmentation) over many generations (*accumulation of changes*)—in fact, these changes are often statistically observable in a single new generation (Bell, 1997).

Although this basic explanation seems fairly straightforward, students nevertheless have difficulty understanding the concept of natural selection. This paper hopes to explain why.

<u>Misconceptions about evolution are extremely robust</u>

Although the complete details of basic evolutionary theory can be quite complex, especially if one considers the ‘new synthesis’—in which biologists began to appreciate how quantitative variation and the extensiveness of genetic variation within populations allowed Darwinian and Mendelian concepts to be integrated in a single framework (Mayr, 1997)—it is important to consider what a basic education in evolutionary theory might consist of. It seems reasonable to hope that students who are introduced to the theory of evolution should at least have a good grasp of the basic Darwinian principles (Ohlsson, 1991). Yet misconceptions about even the basic principles of Darwin’s theory of evolution are extremely robust, even after years of education in biology (Bishop &

Anderson, 1990; Demastes, Good, & Peebles, 1996; Demastes, Settlage, & Good, 1995; Jensen & Findley, 1996; Settlage, 1994; Zuzovsky, 1994).

Although their subjects are novices, Ohlsson and his associates (Ohlsson, 1991; Ohlsson & Bee, 1992; Larreamendy-Joerns & Ohlsson, 1994) provide several examples of the types of common misconceptions. For example, Ohlsson and Bee (1992) provide sample protocols of common errors students make when explaining how the tiger got its stripes. Students sometimes provided a Lamarckian response, in which they attributed the emergence of new species to the acquisition of individually-acquired traits (such as darker coloration), for example, "[...] Probably early tigers camouflaged themselves by rolling in the dirt and jungle and savannah plant life. Over generations the colors must have endured" or they maintain a teleological explanation, in which traits (such as the tiger's stripes) emerge for a reason, rather than due to selection, for example, "Tiger stripes are made for predatory purposes, without the stripes the tiger would not match his surroundings well (like camouflage), and enable him to kill his food. They are made for survival [...]" (see Ohlsson, 1991, for additional examples).

Not only are students' explanations incorrect, but their faulty explanations are extremely resistant to change, indicating that they truly hold deep misconceptions. Thus, we differentiate between false beliefs (e.g., knowledge that is incorrect, such as believing that no swans are black) and misconceptions (e.g., believing that electricity is like a liquid, which is a category mistake; to-be clarified below). We suggest that the former are more readily corrected from instruction whereas the latter are extremely difficult to remove (Chi, 1997). Possible reasons for students' misconception are discussed next.

Explanations for the misconceptions

Various hypotheses have been advanced to account for the existence of robust misconceptions about evolution and natural selection. One type of explanation focuses on the difficulty of understanding the *underlying concepts*, such as the concept of *populations* —students find it difficult to think in terms of populations of organisms, yet evolution involves changes in populations over many generations (Helenurm, 1992); the concept of *frequencies*—evolution is the result of changes in the frequencies of different types of individuals constituting a population; or the concept of *adaptation*—many students consider adaptation a theoretical primitive (like the notion of a point in mathematics) and see no reason to explain it (Ohlsson, 1991). A second type of explanation focuses on the difficulty students have in reconciling different levels of organization for such concepts as genes, individuals, populations, and species, not to mention those of genera and families (Mayr, 1997); and/or that some levels are imperceptible. A third type of explanation focuses on the dynamic nature, or the *time frame* of the concept of evolution (Samarapungavan & Wiers, 1997).

These three types of explanations can be used to explain why students have difficulty understanding a variety of concepts. For example, the same three types of explanations can be used to postulate why students find the concept of diffusion difficult to understand (Chi, In Press). Like natural selection, diffusion has many underlying concepts that students find hard to understand, such as those of density and concentration. Alternatively, diffusion may be hard to understand because it involves an imperceptible level of organization (e.g., the molecular level at which molecules move in random motion and the perceptual level at which concentrations vary), and/or an emergent level of organization. Finally, diffusion is also a time-dependent process, and its dynamic nature may pose a difficulty.

Such explanations of student misconceptions are reasonable and certainly account for some of the difficulties students face in understanding these concepts. However, the very fact that many concepts share analogous explanations suggests that they may share deeper conceptual similarities that underlie students' difficulties in understanding them. Chi and her associates (Chi, 1992, 1997; Chi, Slotta, & de Leeuw, 1994; Slotta & Chi, 1996) suggest that "category mistakes," in which students assign a concept to the wrong category, are a key reason why some science concepts engender deep misconceptions, even after extended instruction. As a result of such mistakes, students assign concepts to one category (often based on perceptual attributes) when it actually belongs to a different category. For example, many young children mistakenly think of whales as fish rather than as mammals, based on such characteristic attributes as whales living in the ocean, swimming like fish, and so on. Chi (1992, 1997; see also Chi, Slotta & de Leew, 1994; Slotta & Chi, 1996) theorizes that such initial incorrect categorization may hinder students' learning of the scientific theoretical understanding of certain concepts (such as natural selection in evolution, or diffusion in physics).

Category mistakes are extremely serious when students assign concepts to a category that is *ontologically distinct* from the true category to which it belongs. By ontologically distinct, we mean categories without any shared ontological attributes (as opposed to hierarchically distinct categories). For example, artifacts and animate objects may be considered to be ontologically distinct categories; artifacts support predicates such as "hand-made," whereas animate objects support such predicates as "grows." It will be very difficult to understand the true nature of an object if it is mistakenly classified, since the misclassified concept will inherit all the incorrect properties of its ontology—that is, if I am telling you a story about my child's stuffed toy dog and you think I am describing a live pet dog, you will make many false inferences about the dog in question and will find it hard to believe, for example, that it was not damaged when it fell out of our 5th story window. (For a brief discussion of the differences between ontological and other sorts of attributes—e.g., characteristic, definitional, and explanation-based attributes—see Chi, 1997.) An animate object such as a dog can never inherit the properties of artifacts, such as "finely crafted" or "old-fashioned" (except metaphorically) One could refer to the dog's look as old-fashioned, but not the dog itself. One cannot modify the concept of dog (or any particular dog, for that matter) by changing some of the dog's attributes, such as from being "pure bred" to being "finely crafted." Indeed, this is the power of such traditional stories as Pinocchio and Pygmalion, precisely because artifacts are transformed into living individuals, thus crossing impermeable barriers.

Of course, not all learning requires an ontological shift! One may gradually change the representation of an object through cognitive operations such as feature addition or deletion, the cumulative effect of which is a more well-defined or generalized concept, respectively. For example, one may discover that atoms are composed of several more basic particles, and that these particles are related to other physical forces like electricity and magnetism, and so on. All of these refinements of one's knowledge do not change the ontological category to which a concept belongs, and thus essentially represent what Chi (1992, 1997a) calls *belief revision*.

<u>Process ontologies</u>

One of the major ontological categories proposed by Chi (1992, 1997) concerns the nature of processes. Chi (1997) has proposed that processes can be differentiated into two basic ontological kinds: events and equilibration.

Insert Table 2 about here

Chi (1997) has identified 6 features that differentiate events from equilibration processes (see Table 2). First, events consist of components with *distinct* actions. Consider an individual game of baseball, which is commonly considered an event. In a baseball game, players perform several distinct functions, for example, at different points in the game the pitcher or a baseman becomes a batter against the other team. Second, the game is bounded: it has a clear *beginning* (the first pitch) and a clear *ending* (the last man out). Third, the actions of an event occur in a *sequential* order: The runner must get to first base before he can try for home. Fourth, the sequence of actions within the game are *contingent or causal*. The third base runner's try for home base is scored as a point only if the hitter’s ball was not caught. Fifth, an event is *goal-directed;* that is, it has an identifiable explicit goal (getting to home base) and the process of the event aims to achieve that goal. Finally, the event *is complete*, and terminates when the goal is achieved (three men are counted out in the bottom of the ninth inning).

Equilibration (or what we have labeled elsewhere as Constraint-Based Interaction) processes, by contrast, share properties that are diametrically opposed to these six “event-like” features—although they often also operate at a level that appears event-like. The process of diffusion is a good example. At the perceptual level, diffusion looks like an event, and standard textbook examples often even describe it as such (e.g., as the movement of gases from areas of greater concentration to areas of lesser concentration). However, at the molecular level, diffusion is not like this at all. Instead, it is a equilibration process that involves random molecular movement with the following six properties. First, diffusion has only *uniform* actions (all molecules participate in the same sort of random motion). Second, it is ongoing, without beginning or end, although an initiating agent external to the concept of diffusion may upset an existing equilibrium (e.g., placing a sugar cube in water). Third, instead of sequential ordering of the actions, the components of diffusion act *simultaneously* (all the molecules move simultaneously). Fourth, since the actions are uniform and act simultaneously, there can be no contingent, causal, and sequential ordering to them. Hence, diffusion is not the result of a particular molecule moving in a particular direction, it has meaning only in the context of a system of molecules moving *randomly* and *independently*. Fifth, diffusion is not goal-oriented: it does not aim to achieve the explicit goal of equilibrium. Rather, equilibrium is the *net effect* of the random movement of a system of molecules. Thus, equilibrium is an emergent property from the probabilistic effects of an accumulation of random movement. Finally (although this is not apparent at the perceptual level), unlike events, equilibration processes are in a *continuous dynamic* interaction and never terminate, even when there is no visible motion. Thus, at the molecular level, molecules are continually moving in the process of diffusing. A more easily visible example of this kind of process is the game of a tug of war. Even when an equilibrium has been reached and the rope being pulled by both sides does not appear to be moving, both sides must continue to pull in order to maintain equilibrium.

To sum up, an equilibration process is uniform, simultaneous, and ongoing; not distinct, sequential, or bounded, like an event. Furthermore, equilibration processes have no specific goal or end state; instead they involve continuous interaction whose net effect manifests alternative emergent properties. These contrasting set of attributes are summarized in Table 2. The previous example was taken from physics, but this sort of equilibration processes occur in the physical, biological, chemical, and social sciences.

<u>Evolution and equilibration</u>

We propose that the modern concept of evolution, and more specifically the mechanism of natural selection, is also an equilibration sort of concept. Consider how the example of the evolving pepper moth, mentioned earlier, can satisfy the six ontological properties of an equilibration process. First, the evolution of the peppered moth involves uniform action (each moth is either eaten or not eaten by predatory birds). Second, its evolution is ongoing; in each generation, the same sort of moth continues to be eaten. Third, evolution is simultaneous, not sequential; that is, predatory birds are eating the salt-and-pepper colored moths everywhere and all the time. Fourth, evolution is the result of multiple independent selections of organisms competing for resources (i.e., each moth is eaten independently by a different bird), with a certain degree of randomness; no sequence of contingent or causal subevents occurs. Fifth, evolution of a new dark species of moth happened as a result of multiple light moths being eaten, leaving the darker moths to reproduce; it is a net effect that reflects the probabilistic outcome of phenotypic (and genetic) selection. Finally, although this is not immediately apparent, nothing terminates. Birds continue to eat the lighter-colored moths that they can see, thus darker-colored moths (and their genes) are continually being selected among those present in the moth population, even if the birds and moths end-up in a dynamic equilibrium that produces no apparent change (i.e., if all moths come to appear dark-colored, the lightest among them will still be selected out of the population—or some other trait may become associated with the likelihood of being eaten).

Our thesis for explaining students' failure to understand natural selection or evolution is not that they necessarily fail to understand individual Darwinian principles. Rather, they fail to understand the ontological features of an equilibration process, of which evolution is one instance. They thus attribute the evolutionary process in general, and natural selection in particular, with event-like properties.

If our hypothesis is valid, then students' explanations about evolution should be framed in terms of an event ontology and rarely in terms of an equilibration ontology. To support our theoretical claim, we will present an analysis that examines college students' naive explanations of evolution. We argue that while students may understand some individual principles of Darwin's theory of evolution, they may not understand the equilibration attributes that the theory implicitly embodies. We then show that students, in fact, do not understand the equilibration attributes of the Darwinian theory, and instead conceive of evolutionary process as an event-like process.

The data

The protocol data were collected in a study of the Peripheral Isolate model of speciation (Mayr, 1982; Larreamendy-Joerns, 1996 [see end note]). Before beginning the study, 40 native English-speaking college students with no prior college courses in biology or evolution were asked to solve five prediction-explanation problems. These problems were designed to assess their understanding of the five basic principles of the Darwinian explanatory pattern (intra-species variability, heritability, differential survival rate, differential reproductive rate, and accumulation of changes over many generations).

Students were given seven minutes to predict and explain the outcome of a hypothetical situation designed to target each of the five principles.

For example, the first problem probed students' understanding of *intraspecies variability* through the following scenario:

> Under laboratory conditions a researcher developed a new kind of berry tree. All berry trees in the researcher's lab are genetically identical, that is, they are all clones of each other. This means that all of the physical characteristics of any given tree are identical to the characteristics of all of the other trees. If these berry trees are planted in a field where the environmental conditions are different from those in the researcher's lab (e.g., less water, more parasites, climate changes, etc.), will this kind of berry tree evolve over time? Explain the reasons for your answer. Please try to be as explicit as you can.

The correct answer to such a problem must mention that individual members of species must necessarily vary among themselves in order for natural selection with modification through descent (i.e., evolution) to occur over time. We made no distinction between subjects who argued for or against whether the trees in the above example would be able to evolve. (All five problems and the suggested answers are included in Appendix A.)

Two coding schemes were developed to analyze subject's responses. The first was adapted from the work of Larreamendy-Joerns and Ohlsson (Ohlsson, 1991; Ohlsson & Bee, 1992; Larreamendy-Joerns, 1996; Larreamendy-Joerns & Ohlsson, 1995) and examined whether students' explanations reflected any of the 5 Darwinian principles or whether it reflected some sort of non-Darwinian theory (the criteria of a non-Darwinian explanation will be elaborated below). The second coding scheme was adapted from Chi (1997; see also Slotta, Chi, & Joram, 1995; Slotta & Chi, 1996) and looked at whether students' explanations contained ontological attributes of an equilibration category. Each of these coding schemes and their results is presented next.

Codings of responses as either Darwinian or Non-Darwinian

Explanation answers (or responses) were considered Darwinian when they involved weak or strong use of any one of the five Darwinian principles as shown in Table 1. (Unlike Larreamendy-Joerns, 1996, who coded each answer only for the Darwinian principle targeted by that problem, we coded each explanation for any of the five Darwinian principles.) A *strong use* of the principle is one in which the subject clearly states the principle involved; for example, that individual members of a species necessarily vary among themselves, for intraspecies variation. A *weak use* of the principle involves an allusion to the principle without stating it clearly, for example, saying that 'some of the trees will be different from the others' alludes to intraspecies variability. Appendix A contains examples of strong and weak uses of the principles for all 5 problems. For example, the explanation below, in response to Problem 1, has a weak use of principle 5 (accumulation of change over time), and a strong use of principle 1 (intraspecies variation):

> "The chances of this berry tree surviving the real world are slim but possible. The natural elements that the tree would be exposed to in the world are likely to alter the genetic code slightly (n.b.,*virtually always false*). However, this change may be slow to take place and the regression may take many years (n.b.,*weak reference to accumulation of change over time*). It is impossible, however, for identically cloned trees to create another clone (A tree cannot have a seed that is guaranteed to be a clone of the original.) (n.b., *strong reference to intraspecies variability*). Because of things such as parasites, temperature, soil, and other plants and animals, each tree is going to be different from the next (n.b.,*slight confusion between population and individual trees*). And, just as DNA varies from person to person, it varies from berry tree to berry tree (n.b., *strong reference to intraspecies variability*)" (Subject 38).

Darwinian answers

A response, even if it refers to two Darwinian principles, or when it refers to the same Darwinian principle more than once, is counted as a single Darwinian answer. A response is counted as more than one answer only when it refers to both a Darwinian and a non-Darwinian ideas or when it refers to two distinct non-Darwinian alternatives (as will be described shortly). When different principles of a Darwinian or different non-Darwinian ideas are given in the same answer, it is often signaled by distinguishing linguistic markers such as “Not only that”, or “On the other hand”. By this criterion, the above response was scored as a single Darwinian answer, albeit one that referred to two distinct Darwinian principles (individual variation and accumulation of changes). Most students gave a single type of Darwinian or non-Darwinian answer for each of the five questions. Of the 198 student responses generated in the study (i.e., 40 students x 5 questions, with 2 missing cases) only 11 responses contained two types of answers and only 1 contained three (for a total of 211 coded answers) .

Interrater reliability was established by using two independent coders who were trained on the first half of the protocols and who then scored the second half of the protocols independently. Overall reliability for Darwinian and Non-Darwinian answers was 91.6% (high 100%, low 82%); overall reliability for the 5 Darwinian Principles was 83% (high 88%, low 79%).[1] Decisions of the main coder were used in all analyses.

A total of 78 answers (or 37%, 78 out of 211) refer to Darwinian principles. In contrast, 133 answers (or 63%) refer to non-Darwinian ideas.

Understanding of the appropriate Darwinian principle. Because an explanation answer can refer to more than one Darwinian principles, the 78 Darwinian answers referred to a total of 154 principles. (Note that when an explanation answer refers to a principle more than once, such repetition is not scored as a separate use of the principle. Thus, in the example above the principle of intraspecies variability is scored only once.) We next examined which of the five Darwinian principles was alluded to in response to each

[1] Larreamendy-Joerns’ (1996) reliability involved an overall correlation of 83% with an independent judge (high 100%, low 69%)

question.   Problem 5 elicited the greatest number of Darwinian explanations (25), and Problem 1 elicited the fewest (7). Furthermore, for each of the five Darwinian principles, we examined whether subjects: (a) made a strong (clear) statement of the principle, or (b) a weak (vague) statement of the principle. (See Appendix A for examples).

Table 3 shows the number of Darwinian principles mentioned in each of the five prediction problems. The bold numbers indicate the Darwinian principles specifically targeted by each problem. The bottom of Table 3 shows the overall use of each principle. Counting both a clear mention of the principle as well as an implicit mention of it, we see that like the students in Ohlsson's (1991) study, students here best understood the notion of *survival advantage* (Principles 3); this was identified in 62 out of the 154 explanations (40%) across all 5 problems. Only 21 out of 154 explanations mentioned intraspecies variability, and 18 mentioned heritability, 30 mentioned reproductive advantage, and 23 mentioned accumulation of changes. A contrast analysis shows that survival advantage is mentioned significantly more often than are any of the other principles, $F(1,197)=62.3$, $p < .001$.

Now, although 154 reference were made to one of the Darwinian principles, it is clear from Table 3 that only in very few cases was the appropriate principle explicitly mentioned for a given problem (the frequency of clear mention of principles ranged from 2 to 13). Note further that Table 3 only indicates that <u>one</u> of the 5 Darwinian principle was mentioned in the explanation, not necessarily that principle was well-understood or specifically targeted by the problem scenarios.

Note that a very similar analysis was conducted by Larreamendy-Joerns (1996); however, he only looked at clear mention and allusion to Darwinian principles for the specific question targeted (our bold numbers in Table 3). Larreamendy-Joerns gave a score of 2 for a clear mention of the Darwinian principle and a score of 1 for alluding to the principle. If one averages the scores reported by Larreamendy-Joerns for his example-based and theory-based groups, one sees that subjects obtained the following overall scores: Intraspecies variability (.25); Heritability (.58); Survival advantage (1.28); Reproductive advantage (.83); and Accumulation of change (.20).

In our re-analysis, if we also scored subjects according to this same system, we would obtain the following results: Intraspecies variability (.20); heritability (.53); survival advantage (.88); reproductive advantage (.58); and accumulation of change (.23). Our scores, when not virtually identical, have the same pattern in that survival advantage is the most prominent one. Our scores tend to be somewhat lower, most probably because we scored some student's references to these principles as being Non-Darwinian.

Insert Table 3 about here

Non-Darwinian Answers. Sixty-three percent (or 133 out of 211) of the students' answers were classified as non-Darwinian**.** Following Mayr (1997), we have identified two main non-Darwinian conceptions of evolution: Transmutational and Transformational , each with three subcategories (as shown in Columns 1 & 2 of Table 4 and in Appendix B). Furthermore, some explanations are either ambiguous (e.g., "As long as the butterflies remain in the same environment, I don't think that the color pattern of their wings will cause evolution") or consist of odd remarks, such as "No, obviously the butterflies are brightly colored for predators to attack them. No, if their color pattern doesn't change then they will continue to be attacked and would not be able to produce more". These miscellaneous non-Darwinian types of explanations were coded as either Ambiguous or Other, as shown in Column 3 of Table 4. Descriptions of these types and examples are shown in Appendix B and Table 4.

Insert Table 4 about here

The most common type of non-Darwinian explanations are the Lamarckian ones (69 cases, or 52%). Basically, the idea here is that changes arise from deliberate acts on the part of either parents or the species as a whole (such as the giraffe getting a long neck by stretching to reach higher and handing down this change to future generations). However, students also believe that change emerges spontaneously in response new or existing environmental conditions, as if the environment caused it to happen. For example, "Yes these Berry trees will evolve over time. They will adapt to their surroundings—maybe by becoming resistant to types of bugs or disease, or even adapting the amount of water and sun that it is exposed to."

In all, 62% of the students' non-Darwinian explanations refer to one of the two theories mentioned above (transmutation and transformation). The remaining NonDarwinian explanations were either too *ambiguous* to classify (29 explanations) or were <u>other</u> statements that were not explanations of any kind (22 explanations).

<u>Equilibration and event attributes in student explanations</u>

Our second coding scheme assessed whether students' explanation answers reflected a commitment to an event-like or a equilibration process. In order to explore this question, we adapted the verbal content analysis technique developed by Slotta, Chi, and Joram (1995) for analyzing explanations in terms of a particular set of conceptual attributes. Specifically, we isolated certain key phrases, determined *a priori* to indicate a commitment to either event or equilibration ontologies (e.g., saying "x *because of* y" shows a commitment to a causal connection between subevents) (see Table 5). Because some students were more talkative than others, we did not include multiple mentions of the same attribute in any given explanation (in other words, if one subject made three statements that referred to causal connections, they were given only one point for that attribute for that question). To better understand how this was done, consider the response we saw earlier:

"*The chances of this berry tree surviving the real world are slim but possible* (Claim/Other). The *natural elements* that the tree would be exposed to in the world *are likely to alter* (Event attribute—causal connection) the *genetic code* slightly (Dubious coordination of levels). *However, this change may be slow to take place and the regression may take many years* (Claim/Other). It is impossible, however, for identically cloned trees to create another clone. *(A tree cannot have a seed that is guaranteed to be a clone of the original*.)(Equilibration attribute—Randomness) *Because of* (Event attribute—causal connection) things such as parasites, temperature, soil, and other plants and animals, each tree is going to be different from the next. And, just as *DNA* varies from person to person, it *varies from berry tree to berry tree.* (Coordination of levels)" (Subject 38).

This coding allowed us to examine what proportion of student verbalizations reflected a commitment to an event ontology and what proportion reflected a commitment to an equilibration ontology. In the example above, one Event attribute was identified (even though it was mentioned twice), one Equilibration attribute was identified, and four Other attributes were identified (2 Claims and 2 Coordination of levels). It is important to note that we did not rely merely on the words students used in their explanations, but on the ideas behind them. Thus, for example, a subject who stated that "mutation enabled the species to survive" is considering mutation as a cause of survival and one of a sequence of events; however, a subject who stated that "random mutations will occur that make one or more trees better adapted" is considering mutation as systemic variable, consistent with an equilibration ontology.

In the 198 responses (40 subjects X 5 problems, minus 2 missing cases), 545 segments were identified as units codable into one of the three categories (Events, Equilibration, and Other).

Virtually all responses mentioned more than one event attribute with an average mention of 1.73 attributes per response. As the above example shows, students sometimes mentioned a given attribute several times in the same answer, however, in these cases the student was given only a single point for that attribute. Table 5 shows how students' ontological commitments were distributed across event attributes, equilibration attributes, and other verbalizations. (These classes of verbalization are explained in detail below.)

Insert Table 5 about here

Coding of the entire set of protocols was completed by two judges. Interrater reliability for the ontology coding again involved using an independent coder who was trained on the first half of the protocols and completed the second half of the protocols independently. Overall reliability was 87.5%. This overall score was based on the following subscores: equilibration attributes 94.6% (high 99%, low 85%), event attributes 86.5% (high 93%, low 80%), coordination of levels 85%, and other attributes 81% (high 97%, low 77%). Decisions of the main coder were used in all analyses.

<u>Evolution as an event</u>. Our fine-grained analysis showed that, of the 545 units coded, 342 (or 63%) referred to one of the event attributes. Seven units considered evolution in terms of distinct component actions (e.g., "Less water means that their [the berry trees'] roots will have to go deeper and spread more to accommodate the water loss. Cold weather might cause problems in survival and in the output of berries that the tree blooms") . As regards the second attribute, 56 units considered evolution to be bounded, with a clear beginning or ending (e.g., "The species must adapt, or it will *die out (or become extinct)*."). For the third attribute, 29 units reflected the idea that evolution involve sequences of subevents, "episodes," or steps (e.g., "*First,* many trees will die. *And* only a few new trees will adapt to the new climate, *and finally* a whole new species may evolve"). A third of the units (179 units, or 32.8%) framed evolution in terms of contingent or causal occurrences within the main evolutionary event itself (fourth

attribute): of these occurrences, 105 units (19.3%) refer to the conditions under which evolution occurs as *contingent* subevents (e.g., "*If* the new berry trees were planted in a new environment, many things could happen, *depending on* the change"); 74 units (13.6%) refer to *causal* subevents in evolutionary change (e.g., "Chances are that the berry tree will die out *due to* parasites, less water, climate changes, maybe even animal/human manipulation"). Note that over three quarters of the ontology units coded make some reference to this fourth event-attribute. Regarding the fifth feature of the event ontology, 51 units (9.4%) considered evolution goal-directed (e.g., "If the tree is to survive in the environment of the field, *it will have to develop traits* that are conducive to the amount of sunlight, water, parasites, etc., so it can continue to flourish.") Finally, 20 units (3.7%) referred to evolution as something that terminates (i.e., that is complete and finished). Here the attribute of termination often involved readjusting the relationship between individual traits and the environment so that evolution is no longer needed (e.g., "It would become used to the weather, and build up defenses, and just become an outside tree.) All of these ways of explaining evolutionary change are very different from considering evolution as an equilibration process.

Evolution as an Equilibration Process**.** As mentioned earlier, evolution considered as a equilibration process has attributes that are diametrically opposed to those of evolution seen as an event. Student explanations contained few examples of the equilibration attributes. A very liberal coding found 45 references to equilibration attributes among the ontology units we identified, or .23 equilibration attributes per question for each subject.

Students had some appreciation of the first equilibration attribute, which considers evolution to contain components that perform uniform action; 8 units (1.5%) were found of this attribute (e.g., "If the birds suddenly started to prefer one sort of butterfly, then that color would die out."). The implication is that "eating butterflies" is an action that all birds do. Five units (0.1%) referred to the second equilibration attribute in which evolution is an ongoing process (e.g., "Darwin believed that *evolution is always occurring*. Therefore, *the ducks would still be changing now*, not simply in the same form which they were thousands of years ago when the change first took place."). Some units (18, or 3.3%) showed some appreciation of the third equilibration attribute that *evolution is simultaneous*, with no sequence of causal subevents (e.g., "if one of the trees that was planted in a more parasitic environment had genes that protected it better, it would survive and reproduce while the other trees died."). Students made little reference to the fourth equilibration attribute, in which evolution is thought to involve *independent and random* actions. Only 8 units (1.5%) reflected the randomness of evolution (e.g., "These outside [i.e., environmental] factors will affect different trees in different ways, thereby giving us different berry trees.") and only 1 unit (0.02%) saw evolution as the result of many minor (independent) subevents (e.g., "In this scenario, the fittest ducks would be the one with the webbed feet since they couldn't paddle as fast as the webbed ducks, *thereby being prone to attacks by predators, as well as starvation and disease*."). No unit explicitly referred to evolution as a *net effect* of the independent selection of many organisms competing for resources simultaneously (the fifth equilibration attribute). Finally, 5 units (0.9%) viewed evolution as reflecting a dynamic equilibrium (e.g., "a change in the climate again *would shift the percentages back* in favor of the non-webbed ducks").

Other explanations. Other aspects of students' explanations that were not a verbatim repetition of the questions or of an earlier statement by the subject were coded as "other" verbalizations. Most student explanations included: (a) claims and supporting examples (114 units, or 20.9%) (e.g., "Darwin had many ideas about this."); (b) don't know (12 units, or 2.2%) (e.g., "I can't really answer this question because I am not really familiar with Darwin's theory of evolution.") ; and (c) uninterpretable comments (9 units, or 1.7%) (e.g., "...thereby no longer relative to the original, less active, less muscular, parent generation."), or *coordinating levels of evolutionary explanation*.

Indeed, students had some appreciation of the fact that evolution has subcomponents that operate at distinct levels of organization: 23 units (4.2%) referred to concepts at more than one level of systemic organization (e.g., "I don't think that protein affects the mice's *genes*, therefore it will not affect the *children of mice* raised on high protein."). A total of 28.9% of the units were thus classified as Other.

Summing up the number of units coded in all three categories shows that students generated 545 distinct attribute units across all five questions for all categories combined. Of these units, 62.8% referred to event-attributes. By contrast, only 8.3% of units referred to equilibration attributes. A t-test shows that this difference is statistically significant, $t(198)=14.2$ $p< .001$.

Correlations between explanations of evolution and ontological commitment

Given that the correct conception of evolution involves equilibration attributes and not Event-like causal attributes, if there is any validity to our coding one would expect a positive correlation between Darwinian explanations and equilibration attributes and a positive correlation of non-Darwinian explanations with Event attributes. Table 6 shows the actual correlations between the Darwinian and Non-Darwinian explanations and the event and equilibration attributes. Notice that the correlations have exactly the pattern that one would predict. That is, Darwinian explanations show a high positive correlation with equilibration and a negative correlation with event attributes, whereas the Non-Darwinian explanations show a high positive correlation with event and no correlation with equilibration attributes. It is also worth noting that Event attributes are significantly correlated with Other Attributes, whereas equilibration attributes are not significantly correlated with any other measures. This finding suggests that students use event attributes to construct non-Darwinian explanations of evolution, and equilibration attributes to construct Darwinian explanations. Moreover, when Other explanations were constructed, they tended to include Event-like attributes.

Insert Table 6 about here

Discussion

The present study follows upon and adds further support to a series of studies that Chi and her associates have been conducting to explore students' ontological commitments about foundational ideas in science. The basic notion is that many science concepts are difficult to learn because students naively conceive of them as one kind of concept, when in fact they are another. Students initially conceive of physical science concepts, such as heat, electrical current, and light, as a kind of substance (Chi, 1992, 1997; Chi, Slotta & de Leeuw, 1994) and/or they conceive of them (or concepts such as diffusion) as a kind of event, when in fact all of these concepts are kinds of equilibration processes. In this paper, we argue that the mechanism of natural selection, a process in which random variation first provides the raw material of change and in which selection (which generates nothing on its own) then acts to eliminate all but the best adapted variations to changing local environments, thus can be characterized by all the attributes of an equilibration process.

When students give non-Darwinian explanations, they tend to give primarily a Lamarkian account, in which organisms determine (implicitly or explicitly) what features they need to adapt, develop these features, and pass them on to their offspring in the form of altered heredity, thus gradually transforming the species over time. Lamarckian notions are prevalent and are consistent with a causal, intentional, event-like process. This latter Lamarckian notion may seem more intuitive perhaps because humans have a predisposition to perceive all processes as *events*, and to tell interpretative stories in which agents act to overcome obstacles in the pursuit of goals (Bruner, 1990). Such a predisposition would explain why it is so difficult to overcome our initial misconceptions.

It is important to note that, although 78 (or 37%) of the answers can be considered to be Darwinian because they refer to one or more of the Darwinian principles, nevertheless, the overall framework to which the explanation is embedded is still incorrect, and contain causal and/or intentional type of reasoning. For example, in the following answer, the student (Subject 25), in response to the intra-species variability problem, had the correct understanding of the Intraspecies Variability principle, but nevertheless, had an incorrect overall explanatory framework:

> "If the new berry trees were planted in a new environment, many things could happen, depending on the change. Most likely, *many of the trees would die off in the early stages of entering the new environment.* (correct notion of intraspecies variability). *Some new trees, however, would begin reproducing a new species which would be adaptable to the new environment.* (this is an notion of intentional reproduction for the purpose of adapting to an environment)."

Thus, as the example above shows, the student has the correct conception of the intraspecies principle, but his explanatory framework is incorrect. Thus, students' piecemeal understanding of the individual Darwinian principles leave them with the illusion of having understood Darwinism when in fact they harbor essential misconceptions about the Darwinian mechanism for explaining evolution.These misapplications of parts of the Darwinian principles are particularly pernicious for naive students learning about evolution. This point reinforces the notion that overcoming robust misconceptions of this type cannot be accomplished by merely teaching students the Darwinian principles. Rather, students must understand the attributes of an equilibration process.

Notice that the three principles that students did understand to some degree—heredity, survival advantage, and reproductive advantage—are clearly biological concepts that are not particularly hard to understand. The ones that they do have difficulty with (intraspecies variability and accumulation of changes) refer to equilibration attributes of randomness and independence (not causal and contingent events), and of net effect (not goal-directedness).

Our theory suggests that instruction for equilibration concepts should proceed by alerting and instructing students regarding the nature of a equilibration category. For example, Slotta & Chi (1996) isolated four equilibration attributes on which subjects were subsequently trained. The training focused on four main ideas: (1) equilibration processes have no clear cause and effect explanation; (2) equilibration processes involve a system of interacting components seeking equilibration among several constraints; (3) an equilibration process reflects the combined effect of several smaller processes occurring simultaneously and independently within the system; finally, (4) equilibration processes are without beginning or end, even if they achieve equilibrium. Results showed that students trained in equilibration attributes not only acquired a deeper understanding of a physics text about electricity, they were also able to transfer this understanding to an understanding of one of the key concepts in evolutionary theory: predator-prey relations.

The results of our present data analysis also show that college students who have no special training in evolutionary theory or biology largely consider natural selection as a complex event (especially one that is bounded and influenced by causal and contingent relations between subevents), and not in terms of constraint-based interactions occurring as complex systems reach equilibrium. As Larreamendy-Joerns (1996) points out, equilibrium seeking systems are uncommon at the level of everyday explanation, and are thus not obvious to naive explainers. Thus, even when students introduce equilibration attributes (such as the idea of *survival of the fittest*) into their explanations, they tend to embed them within a causal and goal-directed narrative that does not rely on equilibration as an equilibrium-seeking system. Instead, students appear to embed this idea (the survival of the fittest) within an event ontology that involves actors struggling to overcome obstacles and achieve goals. Like the college students examined by Slotta and

Chi (1996), the students in our study would greatly benefit from science instruction that introduced the underlying ontology of modern evolutionary theory, before learning about specific details about the evolution of particular species.

While student's underlying ontological commitment is central to their understanding of evolutionary theory, unlike many other basic science concepts, promoting conceptual change in understanding evolution may sometimes be especially difficult because beliefs about evolution are tied to students' cherished beliefs in other areas of life. Thus, even when some students understand the mechanism of natural selection perfectly well, they may choose not to believe it because they use different standards of evidence or refuse to abandon alternative core beliefs such as those of their religious community (Dagher & BouJaoude, 1997; Jackson, Doster, Meadows, & Wood, 1995). In such cases, Cobern (1996) suggests science teachers must open a dialogue about the nature of science and its place in students' personal and cultural world view.

Furthermore, conceptual change is not merely a matter of cold, rational reassessment of knowledge; students' motivations and the general classroom context will also influence how easily and thoroughly student will learn about natural selection. Thus, classrooms that encourage a mastery orientation to learning may help foster radical conceptual change students' views by promoting a climate that values mastery of scientific concepts—as opposed to mere test performance , which often inadvertently leads students to fear failure (Pintrich, Marx, & Boyle, 1993). So science teaching must also go beyond cold conceptual change to address affective and motivational influences on students conceptual change.

Only by addressing evolutionary theory on such deeply meaningful levels will students come, not only to understand that natural selection is an equilibration process, but also to believe it. Otherwise, these students are in danger of framing all of their exposure to natural selection in terms of a misconceived event ontology, or alternative belief systems, that will be very difficult—we would argue impossible—to alter.

End Note

1. The Larreamendy-Joerns (1996) study aimed to answer two main research questions: (1) Do students learn about evolution any differently from example-based and theory-based texts? And (2) did these differences depend on differences in concurrent verbalizations during reading? Two randomly assigned groups of students (n=20 per group) were given a pretest that involved (a) a general speciation task, and (b) five prediction-explanation problems about the 5 Darwinian principles (analyzed in our text). Each group was then assigned an example-based or theory-based version of a text about Mayr’s (1982) Peripheral Isolate Model of speciation. Finally students were each given a 2-part posttest that included both a general explanation task and a prediction-explanation task about speciation.

All students in the study significantly improved their understanding of speciation from pretest to posttest. The example group performed significantly better than the theory-text group on the open-ended task, although effect sizes were small. No difference was found on the final prediction-explanation problem. In all cases, students used ideas from the Peripheral Isolate model more and alternative ideas less on the posttest, although they continued to have the most difficulty with the idea of gene biasing within isolated founder subpopulations. Part of the explanation for these differences may be that the prediction examples cued students to access the appropriate information in what they had read. The content analysis of students explanations also showed that the theory group were more likely to include “law-like theoretical statements” while the example group tended to include more exemplar information (resembling narrative accounts) tailored to the problem at hand. Both groups did similar amounts of paraphrasing and annotating; but students given the example-text did more explaining and hypothesizing about the text, whereas the those given the theory-text did more monitoring and exemplifying. (The example-text might have been less complex and used more familiar vocabulary.)

Students' accounts of speciation fell into two broad groups: (1) those who defined what they meant by processes such as adaptation and survival of the fittest, and how those processes might operate in the cases they were explaining and (2) those who referred to these same processes without explaining how they might work. The explanations of students from the first group are closer to scientific explanations as they are about both causal relationships and causal mechanisms. Without any explanation of how processes work, it is impossible to know whether students mean very different things from scientists, even if they use the same terminology. Overall, this study has important implications for teaching about evolution and suggests the quality of explanations that students can provide are influenced by whether instructional texts provide worked out examples.

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Table 1.Five Darwinian principles with brief definitions (adapted from Ohlsson, 1991)

(1) Random intraspecies variability (individual variation). Individuals in one generation of a particular species differ from each other along a number of dimensions, including *physical* characteristics (size, color) *mental* characteristics (perception, memory, intelligence), and *behavioral* patterns (child-rearing, feeding).

(2) Heritability of certain traits (genetic determination). Some dimensions of variation are *genetically determined* (i.e. individual values on them are inherited), other dimensions of variation are *acquired* (i.e. individual values reflect experience and lifestyle). Only genetically determined characteristics are relevant for evolution.

(3) Differential survival rate (local adaptation). Different species-characteristics are more or less likely to assist survival in a given environment. Those with characteristics better suited to the environment will be selected from among the others by their increased chance for survival in that environment.

(4) Differential reproduction rate (reproductive advantage). Differential survival rate translates into differential likelihood to reproduce. Individuals who reproduce more are more likely to pass on their genes to the next generation.

(5) Accumulation of changes over many generations. Only small evolutionary changes occur within a single generation; but because the process is repeated over many generations, the accumulated changes can lead to substantial differences among isolated subpopulations and even to the emergence of a new species.

Table 2. Event and equilibration attributes (adapted from Chi, 1997a).

Event		Equilibration
Distinct actions	vs	Uniform actions
Bounded (begins and ends)	vs	Unbounded (ongoing)
Sequential	vs	Simultaneous
Contingent and causal	vs	Independent and random
Goal-directed	vs	Net effect
Terminates	vs	Continuous

Table 3. References to the five Darwinian principles in students' 78 Darwinian explanations (N=154)

	Five Darwinian Principles				
	Intraspecies Variability (A)	**Heredity (B)**	**Survival Advantage (C)**	**Reproductive Advantage (D)**	**Accum. of Changes (E)**
Questions					
Question 1 (A)					
Clear Mention of Principle	**2**	0	4	0	0
Alludes to Principle	**4**	0	3	4	13
Question 2 (B)					
Clear Mention of Principle	0	**7**	0	0	0
Alludes to Principle	0	**7**	0	2	1
Question 3 (C)					
Clear Mention of Principle	1	0	**13**	0	0
Alludes to Principle	2	0	**9**	4	3
Question 4 (D)					
Clear Mention of Principle	0	0	0	**9**	0
Alludes to Principle	3	4	6	**5**	0
Question 5 (E)					
Clear Mention of Principle	0	0	10	2	**3**
Alludes to Principle	9	2	17	4	**3**
Total Clear Mention of Principle	3	7	27	11	3
Total Allusions to Principle	18	11	35	19	20
Overall Sum	21	18	62	30	23

Note: Bold highlights the Darwinian principle specifically targeted by each question.

Table 4. Types of non-Darwinian explanations of evolution (N=133)

<table>
<tr><th>Non-Darwinian I.
Transmutational
Evolution

(13 explanations, 9.8%)</th><th>Non-Darwinian II.
Transformational
(Lamarckian)
Evolution

(69 explanations, 51.9%)</th><th>Non-Darwinian III.
Miscellaneous

(51 explanations, 38.3%)</th></tr>
<tr><td>1. <u>Hopeful monster</u>
(Sudden change)
(7 explanations)

“[Huntington’s disease] could get passed to a child with a mutation for an immunity for the disease. This child passes it on and soon everyone has an immunity for the disease and the disease gets wiped out.”</td><td>1. <u>Alters Phenotype</u>

a. Spontaneous environmental fit
(37 explanations)

“the distant relative compared to the first generation who started the protein will be weaker as a whole, because your body gets used to the protein.”

b. Deliberate environmental fit
(19 explanations)
“If the parent mice keep eating a lot of protein, then the young will be born with strong muscles.”</td><td>1. <u>Ambiguous</u>
(29 explanations)

“As long as the butterflies remain in the same environment, I don’t think that the color pattern of their wings will cause evolution.”</td></tr>
<tr><td>2. <u>Hybridization</u>
a. Amalgamate (mix)
(4 explanations)

“there is the potential for them to evolve into separate species if they mated with a different species of butterfly.”

b. Enhance
(2 explanations)

“mice that are produced as descendants are born of two strong, hyperactive parents [...]. The descendant mice, then, may be genetically more apt to have stronger muscles, etc.”</td><td>2. <u>Alters Genotype</u>
(13 explanations)

“The natural elements that the tree would be exposed to in the world are likely to alter the genetic code of the tree slightly.”</td><td>2. <u>Other</u>
(22 explanations)

“No, obviously the butterflies are brightly colored for predators to attack them. No, if their color pattern doesn’t change then they will continue to be attacked and would not be able to produce more.”</td></tr>
</table>

Table 5. Percentage of Event, equilibrations and other attributes coded in students' explanations, with examples (N=545).

Event **(342 units, 62.8%)**	**EQUILIBRATION** **(45 units, 8.3%)**	**Other** **(158 units, 28.9%)**
1. Distinct actions "Less water means that their roots will have to go deeper and spread more to accommodate the water loss. Cold weather might cause problems ... in the output of berries" (7 units)	1. Uniform Actions "If the birds suddenly started to prefer one sort of butterfly, then that color would die out." (8 units)	A. Coordination of Levels "...webbed feet, probably caused by a defective gene." (23 units)
2.Bounded: A) Beginning "*...a whole new species* might evolve" (22 units) B) End "The species must adapt, or it will *die out (or become extinct)*." (34 units)	2. Unbounded ('ongoing') Other predators may come along as well; *that is why evolution is continuous*. (5 units)	B. Claim/Example "Darwin had many ideas about this." (114 units)
3. Sequential "The traits of hyperactivity might get *passed on* to the baby mice." (29 units)	3. Simultaneous "nonweb-footed ducks were weaker, since they were more prone to attacks by predators *as well as* starvation *and* disease." (18 unit)	C.Don't Know "I can't really answer this question because I am not really familiar with Darwin's theory of evolution." (12 units)
4. A) Contingent "*If* the new berry trees were planted in a new environment, many things could happen, *depending on* the change" (105 units) B) Causal. "Chances are that the berry tree will die out *due to* parasites, less water, climate changes, maybe even animal/human manipulation" (74 units)	4. A) Random "*random mutations* will occur that make one or more trees better adapted." (8 units) B) Multiple Independent. Events "The color pattern of animals *can also serve for other important factors* such as sexual markers and for health" (1 unit)	D. Uninterpretable "thereby no longer relative to the original, less active, less muscular, parent generation." (9 units)
5. Goal-directed "If the tree is to survive in the environment of the field, *it will have to develop traits* that are conducive to the amount of sunlight, water, parasites, etc., so it can continue to flourish." (51 units)	5. Net effect (no examples) (0 units)	
6. Terminates "It would build up defenses and just become an outside tree." (20 units)	6. Continues "a change in the climate again *would shift the percentages back* in favor of the non-webbed ducks." (5 units)	

Table 6. Correlations between student' evolutionary explanations and ontological commitment (N=198).

	EQUILIBRATION	EVENT
Overall		
EQUILIBRATION	1.00	-0.06
EVENT	-0.06	1.00
OTHER	-0.04	0.19**
Darwinian	0.36**	-0.16*
Non-Darwinian	0.06	0.35**

* Signif. P ≤ 0.05, ** Signif. P ≤ .01 (two-tailed)

Appendix A. Scenario-Problems Addressing the Five Darwinian Principles with examples of student responses

1. *Intra-species variability problem*, which assessed students' knowledge of the role of intraspecies variability in evolutionary change.

> Under laboratory conditions a researcher developed a new kind of berry tree. All berry trees in the researcher's lab are genetically identical, that is, they are all clones of each other. This means that all of the physical characteristics of any given tree are identical to the characteristics of all of the other trees. If these berry trees are planted in a field where the environmental conditions are different from those in the researcher's lab (e.g., less water, more parasites, climate changes, etc.), will this kind of berry tree evolve over time? Explain the reasons for your answer. Please try to be as explicit as you possibly can.

Intra-species variability answer. The best answer to this question should state that the individuals in one generation of a particular species differ from each other in terms of physical characteristics (height, weight) mental characteristics (visual acuity, awareness), or behavioral patterns (nesting, foraging).

Strong Darwinian: Subject 38,"A tree cannot have a seed that is guaranteed to be a clone of the original."

Weak Darwinian: Subject 18, "If they are all exactly alike (clones), how are they going to compete for adaptation?"

Non-Darwinian: (Transmutation: Amalgamation) Subject 15, "A seed from the berry tree could drop and [mesh] together creating a whole new tree."

2. *Genetic determination problem,* which explored students' knowledge of the relation between genetic characteristics and evolutionary change.

> A scientist is interested in the effects of high protein food in mice. In her lab, she has a population of mice which she feeds with food containing high amounts of protein. As a consequence, after a few weeks on this diet, mice develop stronger muscles and become hyperactive. If this researcher keeps

> feeding entire generations of mice with the high protein food, will the distant descendants of this population of mice become stronger relative to the first generation of mice who feed from the high protein food? Explain the reasons for your answer. Please try to be as explicit as you possibly can.

Genetic determination answer. The best answer to this question should state that only *genetically determined* characteristics are relevant for evolution (i.e., individual values on them are inherited), not *ontologically acquired* dimensions of variation (i.e., individual values reflect experience and lifestyle).

Strong Darwinian: Subject 1, "The mice will be exactly the same because muscle strength is not an inherited trait. You've got to work hard for it."

Weak Darwinian: Subject 30, "I know that if my brother buys lots of weight gainer and other such GNC products, he may make himself stronger, but it won't have any effect on his children's strength. The same thing would most likely occur in the mice."

Non-Darwinian: (Transformation: Alters genotype) Subject 3, "The muscles and hyperactivity may become inherent in the mouse gene pool."

3. *Differential survival rate problem*, which looked at the role of differential survival rate (i.e., natural selection) in promoting evolutionary change.

> In the tropical rain forest in Panama there is a species of butterfly known as *Anartia fatima*. This species of butterfly has variable color patters in its wings. Some butterflies have wing stripes, others have only one color. Biologists have discovered that butterflies with wing stripes and those with plain wings show similar levels of wing damage (produced by unsuccessful levels of bird attacks); both types survive equally well. Will the color patterns of their wings lead these butterflies to evolve over generations? Explain the reasons for your answer. Please try to be as explicit as you possibly can.

Differential survival rate answer. The best answer to this question must state that some species' characteristics are more likely to help species survival in a given environment. Those individuals with characteristics better suited to the environment will most likely to survive in that environment.

Strong Darwinian: Subject 9, "There seems to be no reason for the butterflies to evolve. I would say no because neither wing is at a disadvantage; neither the wing stripes or the plain wings have a higher survival value."

Weak Darwinian: Subject 2, "if birds suddenly start to prefer one color over another the butterflies with the less preferred wing color will survive."

Non-Darwinian: (Transformation: Spontaneously Alters Phenotype) Subject 7, "The butterflies with wings of varying colors would slowly develop striped and plain wings to ensure itself optimal survival."

4. *Differential reproduction rate problem*, which examined the effect of differential reproduction rate on evolutionary change.

> Huntington's disease is a genetic condition caused by a dominant gene. The brain deteriorates, and the victim loses control over both mental and motor patterns. A period of insanity accompanied by jerky movements of the face and limbs is finally followed by death. This condition usually does not set in until the victim's 30s or 40s. Generally by then he or she has produced children, half of whom will also have inherited the gene and are therefore doomed to suffering the disease. What would the effect of natural selection be on the occurrence of Huntington's disease in a human population? Explain the reasons for your answer. Please try to be as explicit as you possibly can.

Differential reproduction rate answer. The best answer to this question must state that increased survival rate translates into a better chance to reproduce. Individuals who reproduce less are less likely to pass their genes on to the next generation.

Strong Darwinian: Subject 6, "Since it [Huntington's disease] does not show itself until after the person has had a chance to reproduce, it would not really be affected by natural selection."

Weak Darwinian: Subject 16, "In natural selection those people who do not have the disease or whose parents did not have the disease would survive the longest."

Non-Darwinian: (Transmutation: Hopeful monster) Subject 15, "So many people would end up getting Huntington's disease that no Homo sapiens would exist any more. Possibly time for a new species; maybe one in which Huntington's doesn't affect it."

5. *Accumulation of changes problem*, which looked at student's views on the importance of accumulated change over time in promoting evolutionary change.

> Attempting to account for the evolution of ducks, a biologist provides the following hypothetical scenario: Thousands of years ago, the ancestors of the current ducks lived mostly in dry lands. They had physical characteristics similar to those of certain varieties of pigeons. However, global warming increased the average amount of rain, and as a result, the pigeon-like proto-ducks were forced to live in mostly flooded areas. They were on the brink of extinction since these proto-ducks were not very good swimmers since they did not have webbed feet. As a result they could not find enough food in the lakes and ponds to survive. Then, by mutation, a few web-footed ducks were born and natural selection favored them. Web-footed ducks survived and non-webbed ducks perished. Assuming the facts to be correct, does this explanation conform to Darwin's theory of evolution? Explain the reasons for your answer. Please try to be as explicit as you possibly can.

Accumulation of changes answer. The best answer to this question must state that only small evolutionary changes occur within a single generation, but that substantial differences among isolated subpopulations and even the emergence of a new species, becomes possible since the process is repeated over many generations and changes accumulate.

Strong Darwinian: Subject 38, "According to Darwin, minor changes took place in an animal, then another minor change, then another. He did not see one major change taking place and nothing else."

Weak Darwinian: Subject 1, "Webbed-footed ducks survived and nonwebbed-footed ducks went extinct."

Non-Darwinian: (Transformation: Deliberate Alteration of Phenotype) Subject 4, "Say one duck tried to survive, and kicked its feet, and started slowly/badly at first, but did it. Over time his leg muscles became stronger and his feet more apt for water than land."

Appendix B. Students' Non-Darwinian Explanations for the Five Scenario-Problems

1. Transmutational evolution refers to a major mutation or saltation (jump) that produces a new type of individual. We found two main types of transmutational evolution in students' 211 explanations.

(a) *Hopeful monsters*. According to this explanation, current members of a species all have particular traits that are no longer well-adapted to a changed environment. A new type of individual is born that proves to be superior to the existing members of the species. This individual founds a new species (while those in the original species die out) (e.g., "[Huntington's disease] could get passed to a child with a mutation for an immunity for the disease. This child passes it on and soon everyone has an immunity for the disease and the disease gets wiped out.")—7 explanations, or 3.3%.

(b) *Hybridization*. According to this explanation, the individual members of a species all have particular traits. Through mating they pass these on to their offspring in one of two ways: (i) they *amalgamate* (blend) the characteristics of both parents (e.g., "I do feel that there is a potential for [these butterflies] to evolve into a separate species if they mated with a different species of butterfly.")—4 explanations, or 1.9%; or (ii) *enhance* the characteristic by giving children a "double dose" or by allowing the *recessive genes* of both parents to become dominant—2 explanations, or 1%.

A total of only 13 explanations (6.2%) explained evolution in terms of *transmutation*. These percentages are shown in parentheses in Table 3.

2. Transformational evolution (Lamarckism) refers to evolution as the gradual spontaneous or deliberate change of organisms into those of a superior species through either phenotypic or genotypic change. We found two main types of Lamarckism in students' explanations.

(a) *Phenotypic transformation* to generate needed variation. There are two main variants of this explanation: (i) *spontaneous environmental fit,* in which evolution occurs when a new trait spontaneously emerges (without selection) in response to new or existing environmental conditions—a trait that improves a species' fit with the new environment (if not, the species will died out) (e.g., "the distant relative compared to the first generation who started the protein will be weaker as a whole, because your body gets used to the protein.") This is the most popular Non-Darwinian explanation—37 explanations, or 17.5%; (ii) *deliberate environmental fit* (Activity driven generation of needed variation), in which evolution again occurs when the environment causes problems for members of the species. This time, however, the individual members, or the species, decide (discover, learn) that a particular activity helps them overcome or solve the problem, causing them to develop a certain trait (if not, they die out) (e.g., the giraffe got a long neck by stretching to reach higher leaves). This is also one of the most popular Non-Darwinian explanations of evolution given by the subjects in our study—19 explanations, or 9%, although it is sometimes difficult to tell from the protocols whether students are using notion of deliberate effort figuratively or literally (e.g., "The plant will grow longer roots in order to survive").

(b) *Genotypic transformation*, in which individual or group effort alters the genotype. For example, students suggest that parents' activities may alter their genes, perhaps through selection over many generations, and these altered genes produce children who are born with the new trait (e.g., "The muscles and hyperactivity may become inherent in the mouse gene pool."). Although less common, these sorts of explanation are found in a fair number of responses—13 explanations, or 6.2%.