Addressing Misconceptions in Evolution at the High School Level

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Introduction

Evolution is a core concept that unifies the entire field of biology, and is woven through the life science strands of the National Science Education Standards (NRC, 1996). This makes it an important area of study for high school students, but there are several challenges in teaching evolution. One challenge is the acceptance of evolution by American adults and students. In national samples, approximately one-third of American adults strongly rejected evolution, and only fourteen percent thought that evolution is "definitely true" (Miller et al., 2006). In this cultural context, teachers find that students may or may not accept the theory of evolution because of the personal religious and /or social beliefs that they bring to the classroom. One study found that thirty-one percent of students in the study did not accept any part of evolution, thirty-five percent accepted evolution, six percent accepted the theory with conditions, and twenty-one percent did not have sufficient information to accept or reject the theory (Woods & Scharmann, 2001). And there is evidence that people in the general public, including students, have little scientific understanding of the processes of evolution. This may be in part due to the personal reservations they have about the acceptance of evolution (Cavallo & McCall, 2008). Another study of natural history museum visitors found novice reasoners who use intuitive explanations that are also present in childhood used goal-directedness as the mechanism of evolutionary change instead of natural selection (Evans et al., 2009). Another challenge is that many teachers do not emphasize evolution as a topic of study in their classrooms (Beardsley, 2004).

Further, evolution is an area where students hold a variety of misconceptions and lack conceptual understanding because some of the key concepts in evolution are non-intuitive. For example, students hold misconceptions about the role of variation of traits within a population, and the difference in reproductive success. They attribute changes in traits to a need-driven or intentional process rather than random genetic mutation and sexual reproduction (Bishop & Anderson, 2006; University of California Museum of Paleontology). Driver et al. report that a persistent and common misconception is that variation within a species is a response to the environment (Driver et al., 1994). Students also lack the skills to properly understand and interpret evolutionary trees, which are the tools scientists use to construct and evaluate hypotheses about evolutionary ancestry and relationships. One prominent misconception is that students read meaning in the order of the terminal nodes or tips of a tree rather than the branching patterns of ancestry that connect the tips (Gregory, 2008). Many students think that species that are located closer together at the tips of the tree are more closely related to one another than those that are further apart. Students think that the number of nodes along the path between two species on a tree indicates how closely related they are. And, when given the species and sets of traits for each on a tree, many students are unable to correctly identify the most likely traits shared by the common ancestor (Meir et al., 2007).

Science and Global Issues (SGI) Project Overview

To address the challenges of teaching about evolution, the Science Education for Public Understanding Program (SEPUP) at the Lawrence Hall of Science is developing an evolution unit that uses an issues and inquiry-based approach for learning the process and outcomes of natural selection. Throughout the unit, students learn how to use evidence and reasoning to make claims and formulate scientific arguments, use the tools for studying evolutionary ancestry and patterns of descent, and examine the process for natural selection. SEPUP curricula use issues and inquiry to engage all students in the study of science. Students learn how to evaluate and base an argument on scientific evidence, and learn how science and society interact.

The evolution unit described in this study is part of *Science and Global Issues,* a two-year high school science program that uses sustainability as the unifying context for studying scientific concepts related to national and state science standards. One year of the course includes a two-week introductory unit on sustainability and four nine-week biology units: ecology, cell biology, genetics, and evolution. The units are based on SEPUP's issue-oriented science model in which students investigate scientific concepts and apply science content to personal, societal, and global issues. Students learn to use evidence in the decision-making process about the issues. To facilitate student engagement, success, and ability to apply what they learn, the units include inquiry-based embedded literacy strategies. The program includes the research-based SEPUP/BEAR embedded assessment system which is based on nine key progress variables and associated scoring guides for formative and summative assessment of higher-order learning outcomes (Wilson & Sloane, 2000).

The *Science and Global Issues* curriculum was produced through a backward design model after a thorough review of the National Science Education Standards and major state standards. The evolution unit is comprised of a series of diverse activities, including investigations, models, and readings. After a review of the standards and the literature on evolution education, the key topics and concepts that were decided on for the unit include speciation, the mechanism of natural selection, the development of the theory of natural selection and evolution by Darwin, phylogeny, the genetic basis of adaptation, fossil evidence for evolution, whale and human macroevolution, and the outcomes of evolution including adaptation. In this unit, more emphasis than is typical for high school evolution programs was placed on evolutionary trees that are used as tools for interpreting and understanding evolutionary evidence. This emphasis was based on recommendations from scientists and experts in evolution education (Catley, 2006; Padian, 2008).

This paper provides a summary of student learning for all four biology units and focuses in detail on the evolution unit. The *Science and Global Issues* curriculum provides assessment items aligned with the major learning objectives for each unit. Three major learning objectives based on the review of the national and state standards were used to organize assessment goals for the evolution unit:

1. Organisms [species] are classified into a hierarchy of groups and subgroups based on similarities, which reflect their evolutionary relationships.
    - Similarities are based on physical characteristics, genetics, fossil evidence, and embryology.
    - Models of evolutionary relationships include evolutionary trees.
2. Evolution is a consequence of natural selection, which takes place at the population level.
3. Outcomes of evolution include adaptation, speciation, and extinction.

Procedure

This paper, a formative evaluation of the 2008-2009 SGI national field test of the evolution unit, measures student learning by unit pre-test/post-test change. The assessment items on the pre- and post-tests consisted of multiple choice and constructed response items that aligned with the three unit assessment goals described in the previous section of this paper. A breakdown of these items according to assessment goal is included in Appendix 1. Each constructed response item was scored using a criterion-referenced rubric based on a scoring system with levels that ranged from 0–2 to 0–4. Curriculum developers used the items on the pretest to determine how much students knew prior to instruction, and the items on the posttest to determine each student's individual achievement at the end of the unit.

Participants

A call for application to participate in the 2008-2009 national field test was sent to teachers from rural, urban, and suburban populations nationwide who were interested in teaching an issues and inquiry-based curriculum. Applicants were chosen to maximize the diversity of teaching experience, size and location of districts, and socioeconomics of student populations. Experienced teachers who demonstrated an understanding of and commitment to teach the genetics and evolution units were selected by the curriculum design team. In this second field test of two, the majority of teachers taught all four of the biology units.

Test Administration and Collection

Participating teachers received pre- and post-tests to administer for each unit. Teachers were instructed to administer each test within one class period. For analysis, three populations of students: underrepresented STEM, Caucasian, and English Language Learner students were selected at random from classrooms that reported a 90% or better completion rate of the curriculum. In order to represent a wide variety of papers and ensure sufficient statistical power, matched pre- and post-tests from each of the three populations were randomly selected for analysis.

Test Scoring and Analysis

The tests were scanned using an optical scanner for the dichotomous multiple-choice questions. The assessment specialist designed a rubric for the constructed response items in conjunction with the SEPUP unit lead author. Undergraduate science majors were trained to apply the rubric and moderated students' papers in order to achieve a 90% or greater reliability rating with the assessment specialist and SEPUP unit lead author prior to scoring. One scorer scored each item in order to alleviate intra-scorer variability.

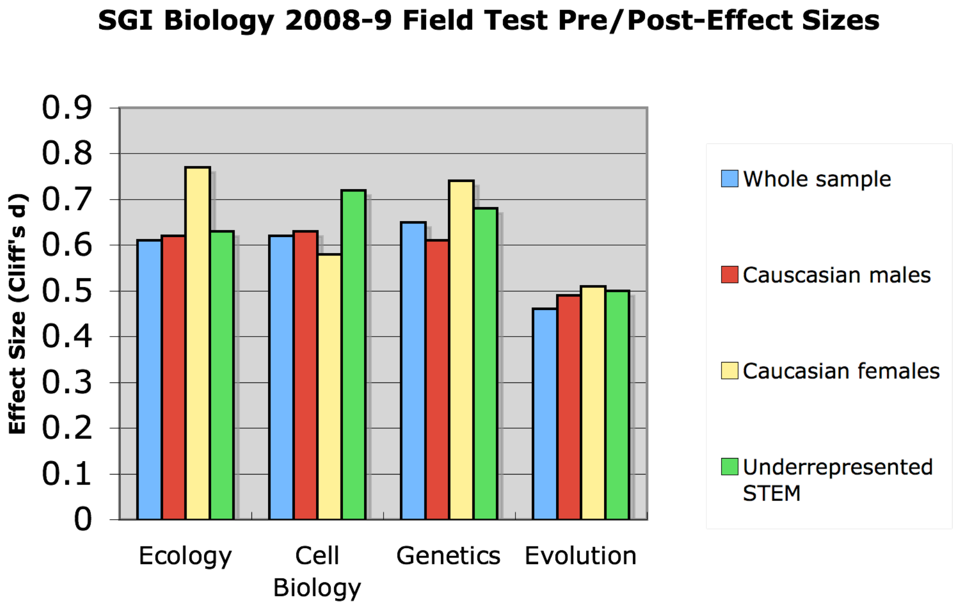
This unit uses alternate forms on pre and post with linked items. To equate the forms, we used concurrent validation to set the item difficulties to a common scale on the post-test and estimated student proficiencies on pre- and post-test based on those item difficulties. The maximum likelihood estimates were used for calculations of effect size. Raw score percentages were calculated as well for comparison.

In some cases, the distribution of the variables significantly departed from normal (median, skewness statistics, and results of Shapiro-Wilk tests are presented). In these cases, both mean and median scores and Cohen’s D and Cliff’s D (a non-parametric estimate of effect size) are presented.

Overall Findings

As shown in Figure 1 below, the effect sizes were high for all of the biology units except the evolution unit, which showed effect sizes at the upper end of the moderate range. A closer examination of the pre- and post-test items for the evolution unit along with the evolution education literature helps to identify some of the challenges students encounter when learning about evolution.

Figure 1



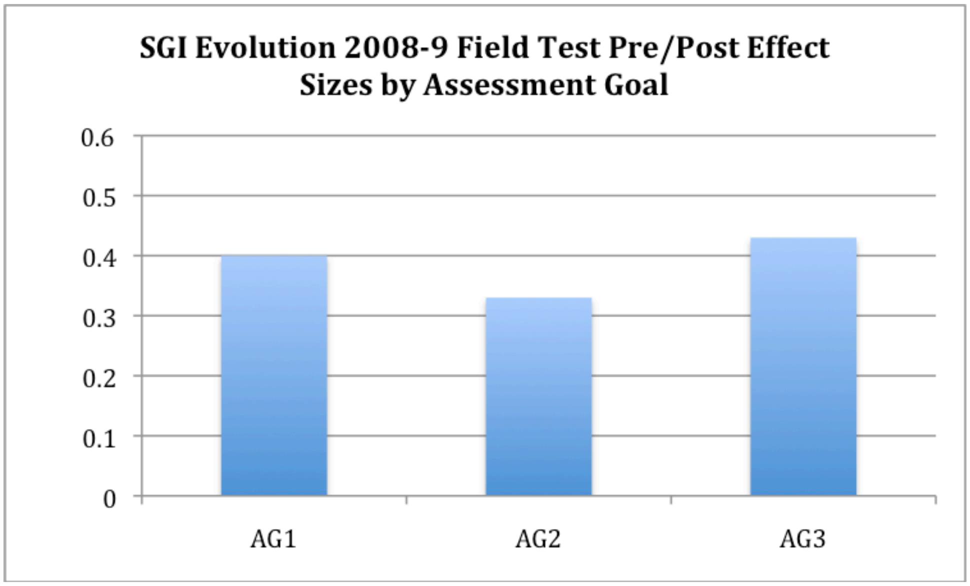
Evolution Findings

In order to better understand how to address challenges in student learning of concepts related to Evolution, we examined pre-post changes in student learning broken out by the 3 major conceptual areas (Assessment Goals) detailed earlier in this paper. Each assessment goal contained Multiple Choice and Constructed Response Items. From there, we examined student responses on sub-ideas and items within each assessment goal in an effort hone in on where student misconceptions were changed and where misconceptions were most difficult to change. These item-by-item results must be tempered by the fact that some of the items were linked items that were found on both forms of the test while other items were non-linked items found on only one form of the test. The examination of the responses will inform the development of the revised version of the unit.

Pre-Post Change Overall and by Assessment Goal

As seen in Figure 2, students showed stronger gains in their understanding of concepts related to how organisms are classified into hierarchies that reflect their evolutionary relationships (Assessment Goal 1) and the outcomes of evolution (Assessment Goal 3) than in their understanding of the relationship between natural selection and evolution (Assessment Goal 2).

Figure 2



Looking more closely at student scores from pre- to post in Table 1, we see that student gains in ability estimates (MLE estimates) were weaker for Assessment Goal 2, with an average gain of .78 logits, than for Assessment Goals 1 and 3, where average gains were 1.06 and 1.13 respectively. In examining the raw score percentages, we see that students showed the same total amount of gain from pre- to post (14%) for all 3 Assessment Goals, but that students began with lower scores on Assessment Goal 2, and demonstrated greater variability in their scores both at pre-test and post-test.

Table 1: Student Pre-Post Gains for Evolution Unit (n=236 students)

	Whole Test	Assessment Goal 1	Assessment Goal 2	Assessment Goal 3
Pre Post Change Using MLE Estimates				
Effect Size (Cliff'sd)	.46	.40	.33	.43
Mean (SD) Pre	-.93 (1.14)	-1.03 (1.59)	-.75 (1.09)	-1.05 (1.29)
Mean (SD) Post	.03 (1.13)	.05 (1.47)	.03 (1.31)	.08 (1.46)
Change	.96	1.06	.78	1.13
Pre Post Change Using Raw Scores (% possible)				
Effect Size (Cliff'sd)	.46	.40	.32	.43
Mean (SD) Pre	.50 (.17)	.56 (.21)	.38 (.20)	.51 (.17)
Mean (SD) Post	.65 (.17)	.70 (.18)	.52 (.24)	.65 (.17)
Change	.15	.14	.14	.14

Analysis of Individual Items or Sub-Constructs within Assessment Goals

In order to understand where student misconceptions were addressed and where they were resistant to change, student achievement on individual items representing sub-constructs were examined from pre-test to post-test. For multiple-choice items, this was represented by % of students in each group who provided a correct response. For the constructed response items, this was represented by the % of students in each group who scored at least a 2 or higher, representing an at least partially correct response. For the purposes of this discussion, items that showed increases of 10% or more were treated as areas of strong improvement. Items that fell below this were treated as areas where misconceptions persisted.

Assessment Goal 1:

This assessment goal has two sub-ideas about the classification of organisms: one is based on the organisms themselves and the other is about evolutionary trees that are used to classify organisms.

- **Similarities are based on physical characteristics, genetics, fossil evidence, and embryology.**

Themes that emerge:

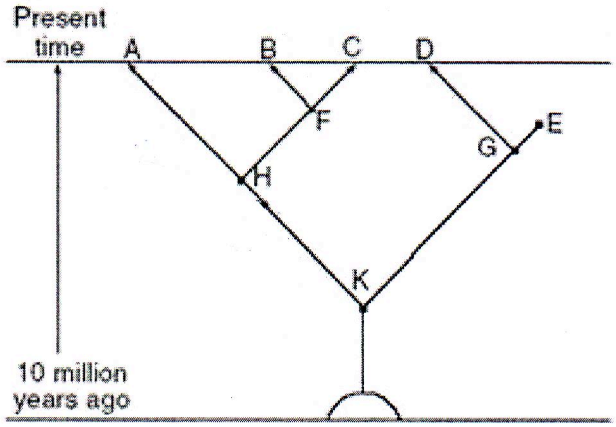
1. Students exhibited a varied amount of growth for the idea that structural similarities indicate common ancestry, with greater change in some items than others. Both of the items in this category were linked items. Subsequently, the variation seemed to be a characteristic of the item. For example, students could identify that structural similarities in the bones of vertebrate forelimbs suggest that they share a common ancestor. However, students showed less growth in explaining how the beak depths of individuals compare in two populations living on two different islands.

Models of evolutionary relationships include evolutionary trees.

The gains on all four of the tree items ranged from 11.9% more having a score of 2 on the post-test to 29.2% more having a score of 2 on the post-test. The average gain on these four items was 21.0%. All of the tree items were linked items.

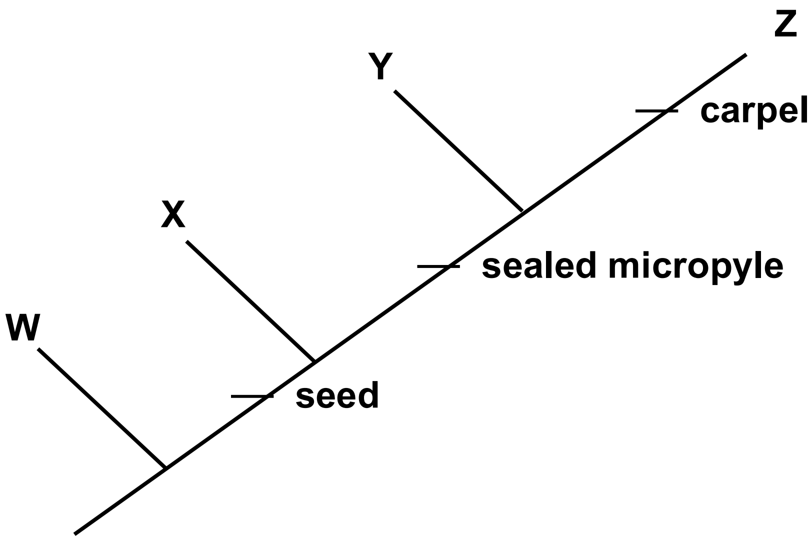
Themes that emerge:

1. Students exhibited strong growth in determining how closely related species are on an evolutionary tree. For example, in the tree shown below, students showed growth in responding that B and C are more closely related than A and C.

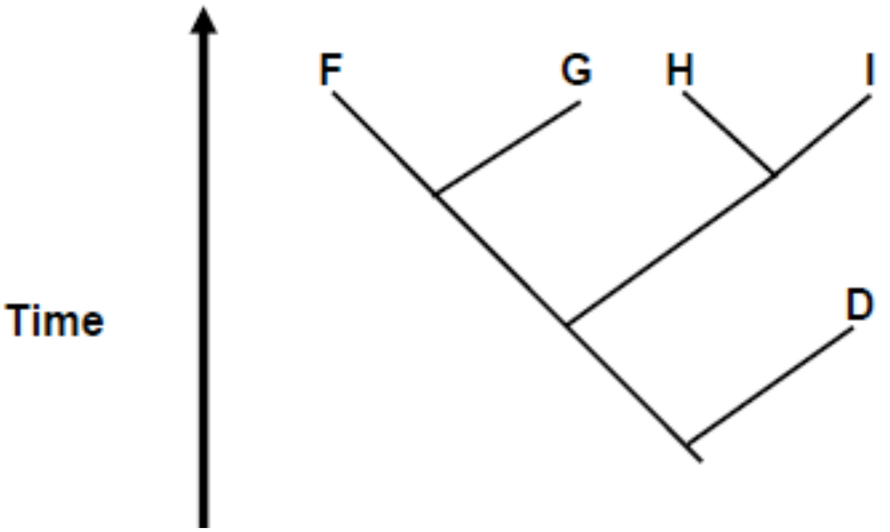


2. Students showed strong growth in determining common ancestry on an evolutionary tree. For example, students showed growth in naming that node "K" in the tree shown above is the most recent common ancestor of "B" and "D."

3. Students demonstrated strong growth in determining shared characters on an evolutionary tree. In the item shown below, students showed growth in stating that group "Z" shares the sealed micropyle with only group "Y."



4. Students displayed strong growth in determining where extinction occurs on an evolutionary tree. In the tree shown below, students could state that "D" was the first group to go extinct.



Assessment Goal 2:

It is important to note that none of the items in assessment goal 2 are linked. They are all non-linked items that appear only on one form of the test. Themes that emerged when looking at the student results for assessment goal 2:

1. Students displayed variable growth in their ability to identify that variation in populations exists, and that variation gets passed on/inherited. Students demonstrated growth in identifying how variation in a population arises, but not explaining the mechanism for how it arises. These three items ranged from gains of only 2.2% on a multiple choice item up to 31.1% more having a response scored a 2 or more.

2. Students exhibit strong improvement in understanding that there is competition for limited resources such as food. For these items, the gains ranged from 9.1% up to 21.6% gain from pre to post. The average of the gains for these items is 16.1% gain.

3. Students continue to hold the misconception that environment induces the changes acted on by natural selection.

Assessment Goal 3:

Themes that emerged when analyzing the results for assessment goal 3:

1. Students generally are able to define and identify examples of adaptation. There was a large variation in student gains for the adaptation items depending on the specific item. These items were a mix of linked and non-linked items.

2. There was a modest reduction in the misconception that evolution gives organisms what they need or that organisms adapt intentionally, but this growth was not associated with a complete understanding of the role of mutation and natural variation as source of traits on which natural selection acts.

3. Students showed strong improvement in the concept that speciation often results from geographic isolation. For these items, there was an average of 27.2% gain from pre to post-test. However, these are non-linked items, which tempers the conclusions that can be drawn.

4. Students showed strong improvement on the extinction item with 17.6% more students having a score of 2 or 3 on the post-test as compared to the pre-test. Again, this is a non-linked item, which limits the conclusions that can be drawn.

5. Students were able to make general statements about evolution, adaptation, and natural selection but cannot describe the mechanisms in detail accurately.

Summary

To summarize, the quantitative and qualitative findings suggest certain areas that showed improvement as well as areas that will be strengthened in the curricular revisions that are currently taking place prior to the publication of the materials. Areas of strong improvement included the idea that there is competition in populations for limited resources. Students also exhibited strong growth in understanding that variation exists in populations, that variation is inherited, and that speciation can result from variation and inheritance in a population that is introduced to a new food source. Students demonstrated strong growth in their understanding that speciation often results from geographic isolation.

Another area of strong student growth was using and interpreting evolutionary trees, including determining common ancestry and how closely related species are, and identifying shared characters and where extinction occurs. The literature suggests that misunderstandings about evolutionary trees and how to interpret them are common among students. One prominent misconception is that students read meaning in the order of the terminal nodes or tips of a tree rather than the branching patterns of ancestry that connect the tips (Gregory, 2008). This leads to misinterpretations about how closely related species are. For example, students incorrectly use the proximity of the tips to each other to represent more closely related species. The specific items that addressed this issue provide evidence of learning of this difficult concept from pre to post. Another misconception is that some students think that the number of nodes in the path between two species indicates how closely related they are (Meir et al., 2007). This was another area of strong growth for the study students who showed marked improvement from pre to post in reading and interpreting the trees.

Areas to be strengthened in the revised unit are that evolution acts on the natural variation that exists in any population, and that this variation results from random mutations and sexual recombination. The misconception that the environment induces change persisted. Another concept that will be strengthened in the unit is that the traits that an organism acquires during its lifetime are not inherited. This concept is associated with a common Lamarckian misconception that acquired characteristics can be inherited (Lawson, A.E. & Thompson, L.D., 1988). These concepts were developed in the field test versions of the curriculum, yet it is clear that students' existing ideas remained resistant to instruction. An understanding of these concepts is crucial to an accurate scientific understanding of the processes of evolution and natural selection.

It is interesting to note that genetic literacy has a moderately positive relationship to the acceptance of evolution in the United States and Europe (Miller et al., 2006). This suggests that adults who have some understanding of modern genetics are more likely to accept evolution. Yet many studies confirm that high school and college students do not understand genetic concepts such as the interaction of genes and the environment, and that acquired characteristics cannot be inherited (Driver, et al., 1994). In light of such studies, it is not surprising that students' misconceptions persist about variation, its role in natural selection, and the Lamarkian view of evolution. A deeper understanding of genetics and the interactions of genes and the environment is likely key to a deeper understanding and acceptance of the mechanism of evolution by high school students. Although most students in this field test studied genetics before studying evolution, and student outcomes for the genetics unit showed large effect sizes, further work must be done to emphasize the origins of population variation and to link key understandings about genetics to the role of genetic variation in evolution.

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Appendix 1

Assessment Goals Evolution Field Test #2

* Note: The items that are in bold are linked items and were found on both versions of the test.

1. Organisms [species] are classified into a hierarchy of groups and subgroups based on similarities, which reflect their evolutionary relationships.
    - Similarities are based on physical characteristics, genetics, fossil evidence, and embryology.
    - Models of evolutionary relationships include evolutionary trees.

Form A: **3, 4, 5, 9, 15, 16**, 22, 23

Form B: **1, 4, 5, 9, 15, 16**, 22, 23

<u>Further breakdown of AG1</u>

Structural Similarities: **3/1, 4**
Trees: **5, 9, 15, 16**
Trees & Conservation: 22, 23

2. Evolution is a consequence of natural selection, which takes place at the population level.

Form A: 1, 8, 10, 11, 12, 13 , 20, 21

Form B: 3, 6, 8, 10, 11, 12, 13, 20

<u>Further breakdown of AG2</u>
Natural Selection Definition: 3
Evolution: 1
Darwin's Theory of Natural Selection: 20
Traits and Natural Selection: 6, 12, 13
Environmental Factors: 10, 11
Microevolution: 8

3. Outcomes of evolution include adaptation, speciation, and extinction

Form A: **2**, 14, 17, **18**, 19

Form B: **2**, 14, 17, **18,** 19, 21

Further breakdown of AG3
Speciation: 14, 19
Adaptation: **2**, 17, **18**
Extinction: 21