CURRICULUM ARTICLE

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The Alien Ecosystem Project: An Integrative and Creative Assignment for Biology Classes

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ABSTRACT

Nonmajors biology courses are often taught as less detailed versions of the majors courses. There is often a heavy emphasis on memorizing structures and pathways. This approach can result in low engagement of more creative thinkers. In three community college courses I included a two-week capstone project in which students built the biosphere of an Earthlike alien planet. Students first created alien species to fill specific niches, documenting them through life histories and drawings. Then, working in groups, they hierarchically nested their aliens into food webs and linked ecosystems. In the final iteration of the project, they also grouped their species into evolutionary lineages based on the similarity of their drawings. Students were thus able to directly demonstrate their understanding of key concepts of biology without relying on technical jargon.

KEYWORDS

Astrobiology, Formative Assessment, Inquiry-Based Learning, Biology Education, STEAM

INTRODUCTION/BACKGROUND

This article concerns an effort to reform undergraduate nonmajors biology education. It illustrates the difficulties inherent in such a project -- which involve all of the participants, at all levels of organization --and possible ways of circumventing some of those difficulties.

Students can be motivated partially by grades, but they learn better and more easily when they are engaged by an authentic problem. Several pedagogical approaches are based on this idea: problem-based learning (PBL) and process-oriented guided inquiry learning (POGIL) are only two of the many acronyms that represent a similar constructivist teaching philosophy. They have consistently been shown to increase engagement and learning (Eberlein *et al.,* 2008).

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Why have these approaches not been more widely adopted? First, despite some high-level discussions, we as scientists and teachers honestly do not agree on what defines the least common denominator of biological literacy, either for citizens or for pre-professionals (Klymkowsky, 2010). The American Association for the Advancement of Science has issued guidelines for middle school and high school (AAAS, 2012), but these systematic efforts have not yet been extended to the college level. Generally, individual experts fall into emphasizing skills (Wright, 2005) vs. emphasizing fundamental knowledge and concepts (Klymkowsky, 2005). There are additional disagreements about whether specialized vocabulary is necessary for understanding of biological concepts, or whether the terms are simply shorthand, labels of convenience best used between experts.

Second are reasons less appreciated by the literature, reasons which fall into a single conceptual category called *suboptimization* by systems theorists (Meadows, 2008, p85). At several levels of organization, emergent social interactions lead to selfish, short-term minimizing/maximizing behaviors that benefit the individual in the short term but are counterproductive for the entire system (including the individual engaging in the selfish behavior) in the long term. Evolutionary science predicts that one path to maximizing an individual organism's fitness is to be efficient, to minimize investment of resources. However, this can have consequences for the society as a whole, which can be regarded as a super-organism (Wilson and Vugt and O'Gorman, 2008). One can easily see examples of suboptimization in any biology department, from faculty re-using last year's tests, to students "cramming" the night before the test, despite its proven failure as a long-term memory strategy (Kornell, 2009), to departments choosing cheaper and less experienced adjunct instructors or graduate TAs, particularly for nonmajors courses (American Association of University Professors, 1997).

These two sets of reasons collide in the syllabi of nonmajors courses, which are often condensed versions of those for first-semester majors courses. They have the same emphasis on biochemistry and cell biology at the expense of ecology and evolution, which are arguably more relevant to current societal concerns. The assumption in both kinds of courses appears to be that *starting simple, at the level of molecules, is the most efficient way to transfer information.* Research on conceptual change suggests that this intuition is partially right, but that the process cannot be summarized so simply (Berkeley Education & Assessment Research Center, 2005). Other factors such as student attitudes may come into play. According to the National Academy of Sciences, there is little research into the effects of student attitudes on their learning in biology courses (Dirks, 2011), but in my personal experience, attitudes mattered a great deal, perhaps more than the logical clarity of the presentation. Motivated majors may pick up higher-level concepts in later courses through sheer repetition, but nonmajors typically take only a single course. As a result, they may be alienated from biology and even science in general by the emphasis on chemical processes that they find too remote from their own experiences. They say things like "*Why are we studying all this chemistry stuff?*" or "*This isn't biology. Biology is about rain forests*."

I taught for two years at community college where I was given a syllabus that followed the typical progression of macromolecules, DNA replication, cell division, cellular respiration, photosynthesis, Punnet-square genetics, etc. (see Online

Materials). My students, most of whom had no intention of becoming scientists or medical professionals, were rarely engaged by the earlier topics, as evidenced by the common quotes above. Low engagement led to low motivation for homework or studying. On the other hand, they *were* interested by genetics, as it related to humans in a way that was obvious to them, and they clearly enjoyed drawing portraits of "children" they generated randomly from tables of dominant/recessive allele pairs.

I speculated that teaching in reverse order, starting with organisms and delving into cellular and molecular details later, would be more engaging, but as an adjunct, I was not allowed to change the syllabus. Instead, I decided to develop a short capstone experience that would tie together all of the semester's mandated topics in an different way, one that would allow students to create, rather than simply to memorize. I also hoped it would reactivate memories of topics covered earlier in the semester in a more effective way than a review lecture would do.

My design process for the Alien Ecosystem Project (AEP) was itself evolutionary. I cast about, somewhat randomly, for examples whose genetic elements I could recombine into a new configuration that would meet the constraints of my current environment. I was inspired by the enthusiasm my student "parents" showed for drawing their randomly generated imaginary "children." That observation, guided by my predilection for science fiction media and nature documentaries, led me to examine a series of projects (Adams, 2002; Barlow and Summers and Meacham, 1979; Crabbe and Eder and Espinois, 2005), two of which I will describe in further detail as the parents of the AEP (Funaro, 1994; Viau, 2004). These direct influences are summarized in Table 1.

Table 1: Inspirations for the Alien Ecosystem Project

Contact Conference	***World Builders***	***Alien Ecosystem Project***
Three day exercise	10 week course	Three lab sessions
Face to face, performance aspects	Hybrid, work mostly written as web pages	Homework and face-to-face, alternating
Teams of 2-10, bolstered by expert advisors	Groups of 2-3 student	24 students per laboratory section
Single species focus	**Ecosystem focus**	Ecosystem focus

Inspirations 1: Cultures of the Imagination

This project was inspired by an exercise called Cultures of the Imagination (COTI), run more than 25 times by the Contact Consortium at their annual (now biennial) meeting. That exercise consists of two teams, isolated from one another, each of which builds a future civilization. Often there is a human team and an alien team, but not always. Each team is given a planet, which has conditions that are often quite different from those on Earth.

The exercise runs for three days, during which the conference attendees are briefed daily on the progress of the two teams. By common agreement, the teams are kept in ignorance of one another's activities. During the briefings, the audience members ask questions and offer suggestions from their own disciplinary expertise. On the first day, the players tell the story from the dawn of life on their planet or moon through the evolution of an "intelligent animal," something that has the potential to develop culture but hasn't done so yet. The Earth example they usually use is *Australopithecus*, although a dolphin might be roughly the same level of intelligence, without hands for manipulating tools. The second day the players are responsible for reaching the beginnings of civilization, the Earth analogue usually being the city-states of the Fertile Crescent or one of the other early river-valley agricultural systems. The third morning, at least one team must achieve technology capable of space flight, and during the afternoon of the third day, the two teams meet for a first contact, which is role-played live in front of the conference attendees.

The Alien Ecosystem Project was different from COTI in several respects. First, there was no competition. Everyone was on the same team, although there were three different laboratory sections working in semi-isolation. Second COTI was designed by anthropologists, science fiction writers, and space enthusiasts; the AEP was designed by a biologist for a biology class. Therefore the focus was not on the detailed history of a single species as it develops culture and technology, but on the overall structure of the ecosystem. In this way the AEP more resembled its other parent.

Inspirations 2: WorldBuilders

AEP's other major influence was a semester-long course called World Builders, created by Elizabeth Viau for education students at California State University (Viau, 2004; Viau, 2006). The focus of World Builders was on small groups of two or three students, and it ran for ten lessons, involving, in order: 1) astronomy; 2) geology; 3) meteorology; 4) microbiology; 5) water plants; 6) water animals; 7) water ecology; 8) land plants; 9) land animals; and 10) land ecology.

The AEP likewise differed from World Builders in several respects. The AEP was a larger group project, designed to engage an entire laboratory section of 24 students, and it emphasized these larger group dynamics. For instance, in World Builders each student created several species across different biomes, and then each team member was assigned one biome, collected all species for that biome from other team members, and individually integrated them into larger ecological structures like food webs. In the AEP, there were self- or class-appointed leaders who stood at the white board, drafting the food web with dry-erase markers, while the creators of individual species came up to the board individually with their drawings and descriptions. Creators suggested links, while the audience critiqued, made other suggestions, and voted on those links when necessary. The AEP was different, too, in that the students were simply given a planet, rather than designing one on their own, and in that it condensed the work of the last seven World Builders lessons into two weeks. Finally, the AEP emphasized different aspects of evolution than World Builders, by requiring students to connect every species in their laboratory section into an integrated Tree of Life diagram, rather than by drawing intermediate evolutionary stages for individual species.

CURRICULUM COMPONENTS

Table 2 lists the component assignments for the AEP. The amount of paperwork grew over the course of three semesters, in an attempt (largely unsuccessful) to provide more detailed feedback and improve the quality of the submitted packages. The Review Checklists also served as the basic grading rubric for the assignments. Forms and student examples are included in the Online Materials.

Table 2: Assignments for the Alien Ecosystem Project

First	Second	Third
Individual Work	***Individual Work***	***Individual Work***
3 Drawings + life histories (draft)	3 Drawings + life histories (draft)	3 Drawings + life histories (draft)
Group Work	***Group Work***	***Group Work***
Lab Section-Wide Food Web	Lab Section-Wide Food Web	Lab Section-Wide Food Web
	Planet-Wide Food Web (extra credit)	
	Lab Section-Wide Tree of Life	Lab Section-Wide Tree of Life
		Planet-Wide Tree of Life (extra credit)
Individual Work	***Individual Work***	***Individual Work***
3 Drawings + life histories	3 Drawings + life histories	3 Drawings + life histories
	Answers to Design Questions	Answers to Design Questions
	3 Review Checklists	3 Review Checklists

"Lakeworld"

Unlike either COTI or World Builders, we used the same alien planet for all three iterations of the Alien Ecosystem Project. It was generated by Fractal Terrains™ Pro Demo 2.2 (ProFantasy Software Ltd., 2011). Fractal Terrains, now updated to version 3, is a commercial mapping program used to supplement fantasy or science fiction role-playing games. The demonstration version of this software is free, and sufficient for our purposes, as we used one of the default sample worlds (slightly modified) and did not need to export or print out the results at high resolution. The full version of the software is more capable, and could be used to generate any sort of terrain. Although the choice of which world to use was somewhat arbitrary on my part, and not central to the design of the project, the version of Lakeworld that we used can be found in the Online Materials as an example.

Lakeworld was named not for the large central sea, but for the many freshwater lakes that dot the single donut-shaped continent, most of which can only be seen with the Zoom functions. It was quite a lot like Earth, but with a higher carbon dioxide level in its atmosphere, so surface temperatures were warmer (temperature is directly adjustable in Fractal Terrains). We had discussed global warming in class, and I wanted students to review that aspect of the course in the simulation. The smaller land mass meant that most of Lakeworld also had considerably higher average rainfall than Earth. Lakeworld was also more noticeably cratered than Earth, indicating some large impacts in the not-too-distant past, and possibly mass extinctions.

PROCEDURES

First Week

Many of the previously existing laboratory exercises did not require all three hours of the laboratory class, and students often finished and left early. In the third hour of the third-to-last laboratory session, students were instead introduced to the planet. In this first session, teams of 2 students loaded the file Lakeworld.ftw onto a station in the departmental computer laboratory and simply explored. I showed them the interface, which allowed them to shift views, emphasizing altitude, temperature, rainfall, or the integrated "climate" view, which color-coded the landforms based on the Earth biomes they most resembled. Students rarely used the other views, suggesting that I should have had a question set or an Earth comparison enrichment activity. The first goal of this activity was to generate some curiosity and enthusiasm at the end of a long semester. The second goal was more obviously practical, namely to get students to choose a single favorite environment in which to place their creations, to generate questions and ideas for their creatures.

Between sessions, as homework, each student created three species, which might be related to one another, ecologically or evolutionarily, or be unique. They were to bring in drafts of a natural history and a portrait of each of their species, including any life stages and male-female differences. I provided examples in the form of short verbal descriptions, but no drawings of my own, as I knew from previous experience that many students are anxious about their perceived lack of drawing skills, and I wanted to encourage them to be more creative than correct in this first stage. Instead I showed them my 4-year-old son's drawing of the "Lobster-Pig," which originally inspired the example creatures. My descriptions, included in the Online Materials, emphasized the environmental niches into which these species fit, and their evolutionary history.

Second Week

During the second three-hour laboratory session, students brought in their species and presented them to the class, who criticized them for scientific validity based on the concepts covered throughout the semester. Again, I encouraged them to be playful and creative, to introduce as much variation into the population of creatures as possible, and then to be selective about the scientific details, mimicking at some intellectual or social level the process of evolution. With 24 students per laboratory section and three species per student, each species could only receive an average of 2 minutes of critique (24x3x2 = 154 minutes). In the first iteration (Fall 2006), these were verbal discussions, and given the time constraints, they were necessarily shallow, but energetic. In the second iteration (Spring 2007), I added a set of Design Questions, available in the Online Materials, to which I responded with written feedback before the final draft of the three species. This considerably increased my time investment and slowed their feedback. Many students simply skipped questions they didn't know how to answer, and for the final draft, I added a Peer Review checklist, also available in the Online Materials. Students were responsible for collecting three peer reviews of their work before submitting it to me.

Students in both the second and third iterations of the project (Spring 2007 and 2008) followed this version of the project. Surprisingly, this did not substantially improve the feedback that students received, as most of them waited until the day they were turning it in to gather the reviews; in other words, they were minimizing effort rather than maximizing quality. The reviewers contributed to this dynamic by minimizing their own effort, checking off the boxes without being particularly critical. Thus my attempts to deepen the experience outside of class did not help, and may have actually damaged the exercise by making it more like work (checking little boxes) and less like fun. Much more successful were the interactive whiteboard classroom sessions described below.

Third Week

Between sessions, the students revised their species, in some cases starting over. During the final three-hour laboratory session, up to 24 students in each laboratory section assembled their species into food webs. As described above, the work in this session consisted of the students drafting networks of species on a white board with dry-erase markers, arguing productively the entire time, while the instructor sat in the back of the laboratory room (1st and 2nd iterations), or in his office (3rd iteration), ready to answer questions or mediate disputes. After about an hour, the students had to settle on a final network that they transferred to paper and placed on the wall in the hallway for other classes to inspect at their leisure. Examples of these food webs are included in the Online Materials. During the second iteration (Spring 2007), the three labs were also given the opportunity to integrate their work into one large planet-wide food web of 216 species for extra credit, outside of class.

During the second and third iterations of the project (Spring 2007-8), students also did an additional mapping of their species into an evolutionary tree. This stage involved each laboratory section, as a group, comparing their drawings and looking for common features of shape and color that could support a hypothetical tree. They had practiced a similar task before, using Jon Herron's PhyloStrat program (Herron, 2005), which creates a distribution of lizard phenotypes that the players have to solve for a most parsimonious tree. This AEP task was much more difficult than PhyloStrat, both because there were many more species in the tree and because only a few of the students had built their species with evolutionary relationships in mind. The situation was more like early natural philosophy, when Linnaeus and others had to impose categories on a huge and buzzing confusion of species, without any clear idea of evolution. Again, as an extra credit opportunity, a subset of students from all three sections integrated the three evolutionary trees into a single planet-wide Tree of Life. The result is also shown in the Online Materials.

EXAMPLES

Examples of all three types of student creations can be found in the Online Materials.

Table 3: Examples of Individual Student Work

Iteration	Mash-Ups	Earth Niche Analogues	Truly Creative
1. Fall 2006	Gizzard Lizzard; Shelled Rabbit; Batcat; Beetle Worm, Ant-Crawfhish, & Slipper-Sneak; Cornish Shrub; Meaty-Fly, Bug-Yummy Shroom, & Shelled Hare	Pink Wassler,Ringer Insect, & Briar Plant; Flying Peeze & Musket; Allgerous, RocoCoral, & Mitty Leaf	Splooge; Plastiwhale
2. Spring 2007	Elisa; Cat Butterfly & Flyrat; Sharkopus, Nemio, & Stunnia	Alienus Bacterius, Grandius Amoebius, & Bacterius Muertius; Worleytron & Squish; Aero, Cronk, & Lurky;	Hydro, Electro; Lilly Bet & Wriggle Rod;
3. Spring 2008	Wizard, Elephopter, & Pandaroo; Whalego, Beavotter, & Frogeleon; Octkey; Blowshrimp	Great Moss & Nitroalgae;	Glowjule, Shimmer Moss, & Sparkleberry

Table 3. Commas (,) divide species created by the same student. Semicolons (;) divide species created by different students. Photographs of original student work can be found in the Online Materials, except for the Plastiwhale, which is a recreation by the author from memory, as the student asked to have his drawings back at the end of the semester. Column headings are explained in the text.

Figure 1: Schematic Examples of Collective Student Work

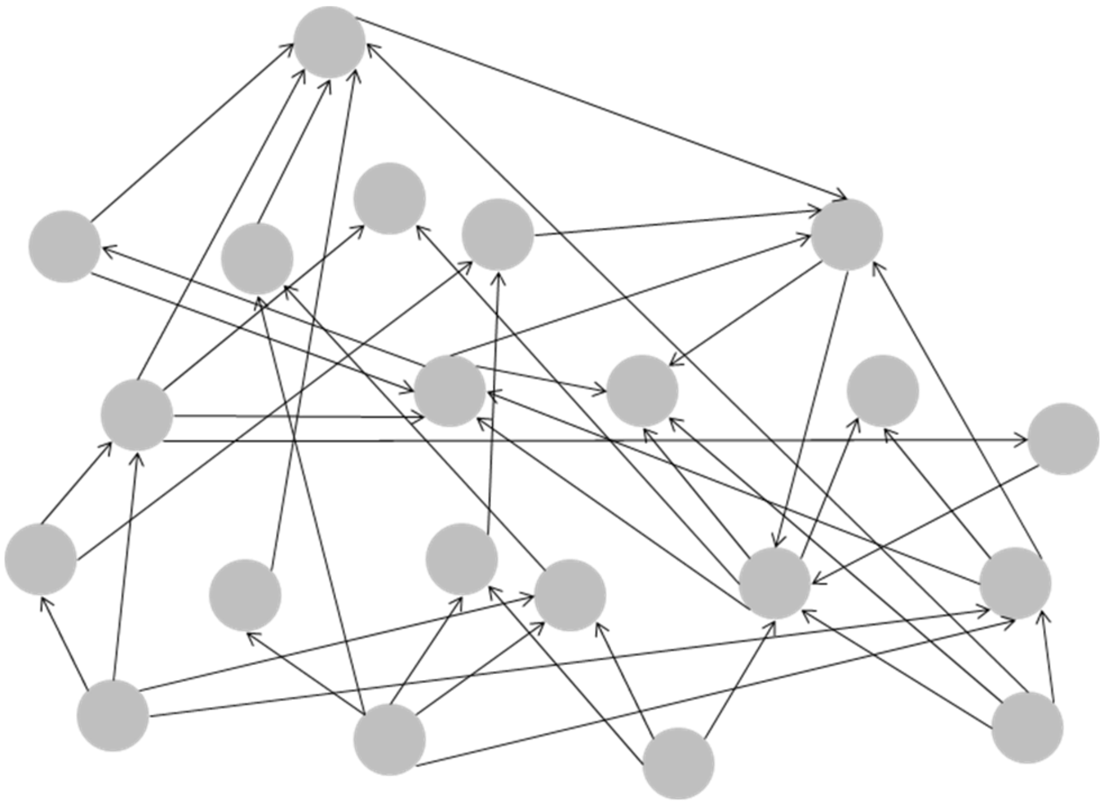

Figure 1A. Simplified schematic version of the food web designed during Iteration 1 of the Alien Ecosystem Project, organized roughly by trophic level, with producers at the bottom. Nodes are left blank to emphasize the relationships. Some of the arrows that are pointed downwards, in the "wrong" direction, are for early life stages of high-level consumers (eggs, larvae). Compare with the original drawing in the Online Materials.

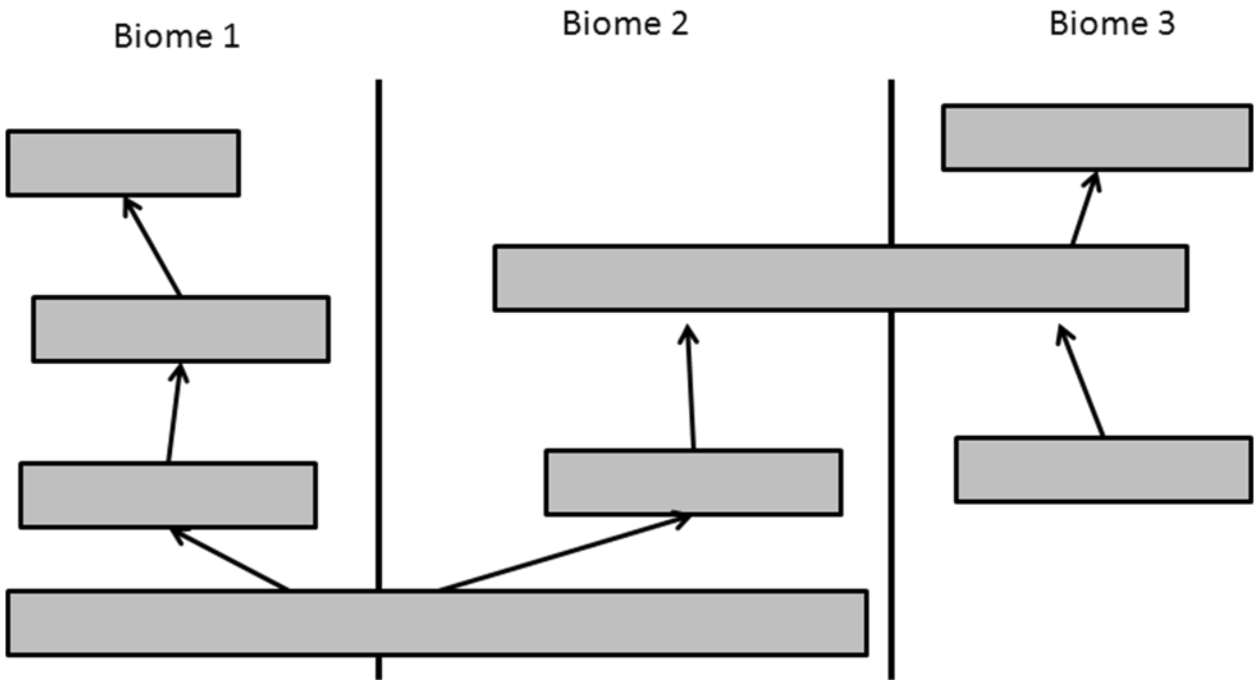

Figure 1B. Simplified schematic food web, organized by trophic level and by geographically adjacent biomes. Nodes are left blank to emphasize relationships. This increase in hierarchical structure and clarity represents an advance for the students in conceptualizing and presenting their food webs. Compare to the more detailed original drawings in the Online Materials.

RESULTS

Formative Assessment for Feedback

There are many possible ways to sort these examples into general patterns. I preliminarily used two. The first way was to look at artifacts and to imagine the amount of time and effort an individual student put into the project, based on how long it would take me to recreate what they had done. These rough, overlapping, subjective categories are shown in Table 3 above and detailed below. The second way was to look for understanding of specific concepts covered earlier in the semester. Here I used a Review Checklist as a grading rubric.

Type One: Mash-Ups (~60%)

The most common student creation was a simple mixing of two Earth animals, feature by anatomical feature. This could be because the model animal, the Lobster-Pig, had such a composite name, although the description of the animal provided went well beyond the name. The number of mash-ups might also be due to students taking "the easy way out." Creatures in this category were less likely to be drawn and more likely to be based on pictures taken from the Internet, which supports this interpretation. The historical examples below in Figure 2, however, suggest something more complicated and fundamental.

Figure 2. Distortions by Analogy.

Moconerous, *Aberdeen Bestiary*, 1542

Cameleopard, *Historia Animalium*, 1551

Figure 2 shows early artists' conceptions of the monoceros (unicorn), based on the real-world rhinoceros, and the cameleopard, based on the real-world giraffe. The artists, who had not seen the animals for themselves, apparently relied on verbal or written descriptions from people who had.

When people encounter new creatures, they seem to describe them qualitatively, by analogy to things they already know (Aberdeen University Library, 2010; National Library of Medicine, 2012). The number of mash-up projects may be a genuine reflection of this cognitive bias. The two explanations are not mutually exclusive, of course – the bias towards analogy with familiar creatures, shared across humanity, would lead to a reliable shortcut in description.

Type Two: Earth Niche Analogues (~30%)

The second most common student solution was to create Lakeworld species that were not anatomically matched to earth species, but which filled identical ecosystem niches. Their creations were almost always neatly divided into "plants", "animals", and "fungi" or, less often, into "producers" and "consumers" the way they are on Earth. This strategy may have been encouraged by the way the Fractal Terrains program's Climate Viewer labels each ecosystem using Earth terms (ie., tropical forest). Students were reluctant to use the other views, which show altitude, temperature, and rainfall separately. A more involved version of the AEP might require use of the separate views, so that the students have to do the work of integrating them internally.

Type Three: Truly Creative (~10%)

A small minority of students, often those with an artistic background, approached the project with more enthusiasm. These students made up some unique creatures which did not respect Earth category boundaries. Often, they also did not respect the laws of physics, but that was to be expected to some extent, since they were not simply copying an existing Earth creature. For instance, the Plastiwhale from Fall 2006 was a very large, flat sheet of cells that floated on top of the ocean and dredged the ocean bottom for organics and minerals through a very long mouthpiece.

This subjective approach was not used for grading purposes, but as a formative assessment (Black and Wiliam, 2009), to decide how detailed any time-consuming feedback to the student should be. Students who put more effort into the project got more feedback. The number of students in each effort category was also my only metric for how well the project managed to engage students on an individual level. During the group sessions, my observations were that at least half of the students were actively engaged in the main discussion at any given time, with roughly another quarter engaged in smaller side discussions. Having three quarters of the students on-task for three lab periods was an improvement over having them rush through an experiment as quickly as possible and then leave.

Qualitative Assessment of Specific Topics

I hoped that students would use this Alien Ecosystem assignment as an opportunity to integrate concepts learned throughout the semester. The pictures below (Figures 3 and 4) represent two examples of higher-level concepts, for which students might memorize the definition, but which they might understand at varying levels of depth – qualitatively or even quantitatively. For instance, the relative lack of energy at higher levels of a food pyramid contributes to the differences in the reproductive strategies of organisms at those levels. Top-level predators, who are energy-limited, tend to have small populations, and small numbers of offspring individually, in which they invest heavily. This level of parental care leads to late-loss survivorship curves, as opposed to the early-loss survivorship curves characteristic of the lower levels of the food pyramid.

Figure 3: Food Pyramid

Figure 3 represents the 10% rule for food pyramids. Producers may capture 1000 calories of energy, but only 10% of that energy is available to Primary Consumers (10% of 1000 = 100). This pattern continues upwards through the levels of the food pyramid (10% of 100 = 10). A tertiary consumer (not shown) would receive only 1 calorie.

A second major cluster of concepts centers around how the various nutrient cycles set limits on how much of the available solar energy can be captured by producers in a particular ecosystem. This concept of the limiting nutrient ties together elemental chemistry, macromolecules, and photosynthesis, all of which received extensive treatment early in the semester. Each ecosystem has a signature mix of nutrients. On Earth, nitrogen and phosphorus are often limiting on land and in shallow water, while it is light that is in short supply in the deep ocean. Water is also a common limiting resource in deserts or on mountaintops. Oxygen supply can also be limiting in certain environments, but as this element was never addressed in our textbook, I did not include it.

Figure 4: Limiting Nutrients

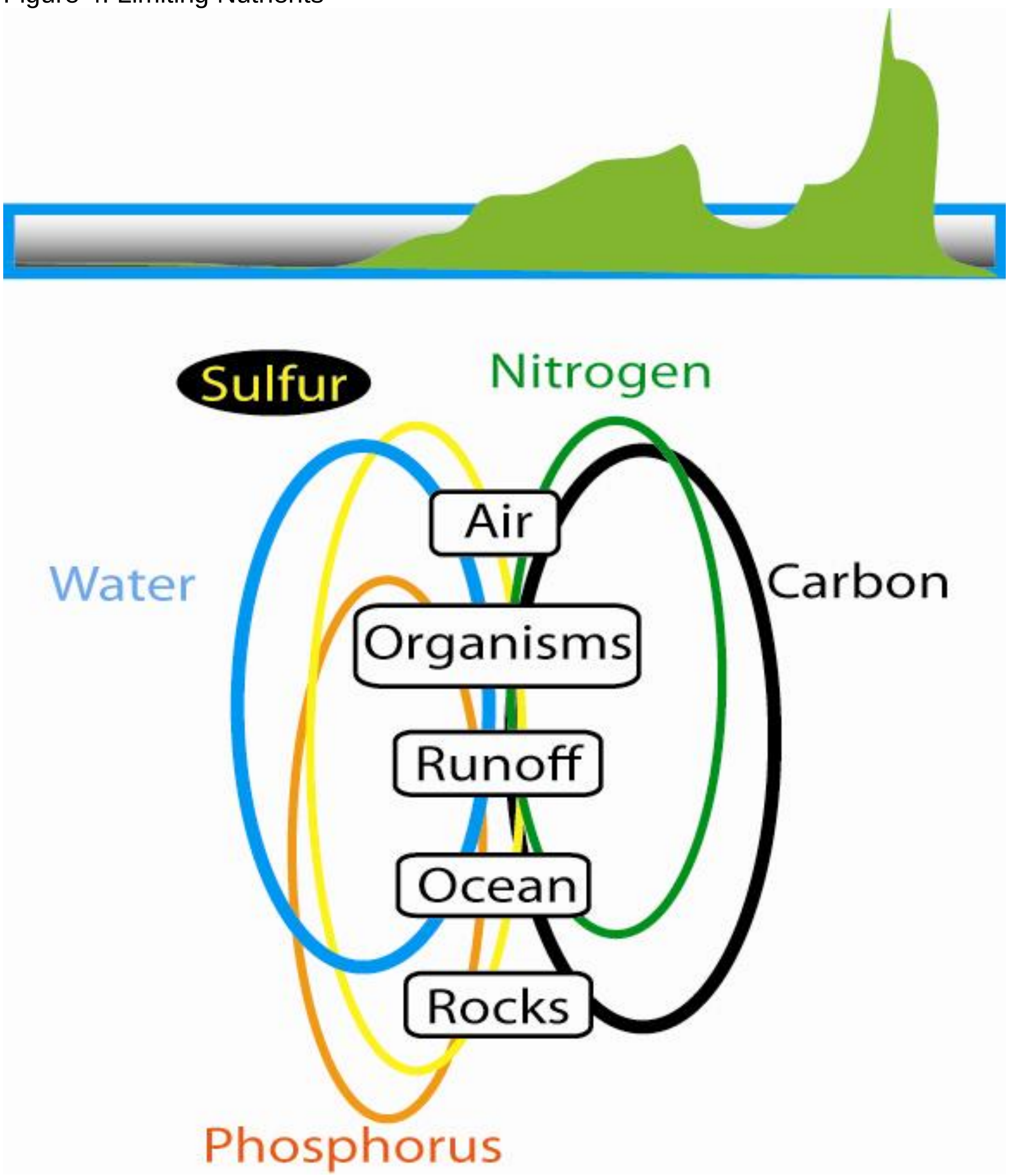

Figure 4 integrates the information for five nutrient cycles into a single picture. Each colored line passes through several compartments. For instance the hydrological cycle passes through four compartments, but is not chemically captured in rocks (it does of course pass through as groundwater). This is the kind of integrated picture I hoped students would develop as they built their ecosystems.

Quantitative misconceptions

Breeding population sizes were consistently underestimated: 7,700 for an insect, for instance. Brood sizes for individual organisms were also consistently underestimated. The relationships between population size and trophic level were usually qualitatively correct at the levels of predator/prey pairs (individual links in Figure 1A), but the students did not integrate that information across every species in a level of the food pyramid, or across levels of the food pyramid. The idea that only 10% of the total energy and biomass in one level is available to the next level did not induce students to check their estimates. Animals (or trees) of wildly different sizes required exactly 1,000 calories of energy per day.

Figure 5: Trophic Level vs. Population Size (Fall 2006 only)

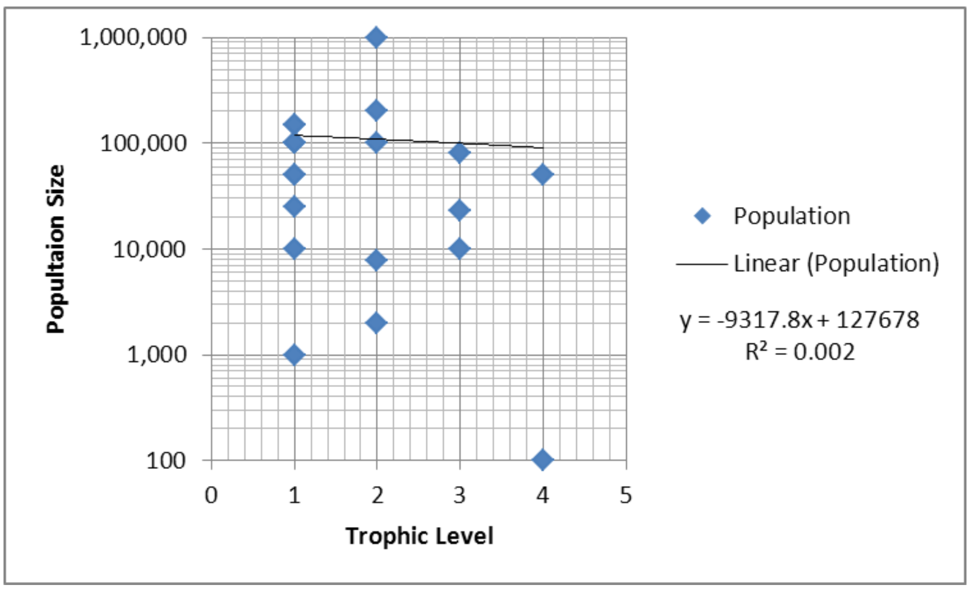

Figure 5 shows that students qualitatively understood that predator numbers cannot exceed their prey, but this idea did not seem to extend to primary producers (trophic level 1), and the scatter for individual populations was very high. The linear fit was poor (R^2=0.002).

Many of their other mistakes fall into this same category. For instance, the Batcat is a 180-pound carnivore that flies on a 6-foot wingspan. Quantitatively this is ridiculous, given the amount of force required to lift a creature that size in near-Earth gravity, but the qualitative comparison with the Catphish makes more sense:

> *"The Batcat can't fly well in areas with lots of trees, because it is so large. . . The Catphish is smaller so it is able to fly faster and maneuver around trees."*

Nonscientists (nonmajors, particularly) clearly had a different conception of what is required for their creatures to make "scientific sense." Numbers and mathematics figured little into their conceptions. In designing exams since this project, I have successfully used ordinal rankings to allow students to display qualitative conceptual knowledge, without having to perform calculations. Of course, there are other questions that do require calculation, but separating biological concepts from mathematical skills allows for a more accurate and precise diagnosis of a student's current capabilities.

Qualitative misconceptions

Other misconceptions had less to do with mathematics. Students generally did not understand the idea of limiting nutrients. Most of them, across all three iterations of the project, apparently picked one at random, because their choices had no relation to the environment in which the organism lived. Others in the first iteration apparently agreed among themselves that their planet had little to no sulfur, and therefore that every environment on the planet was sulfur-limited. Every class did include producers, consumers, and decomposers, demonstrating some understanding of the carbon cycle.

Surprisingly, many students did not understand the cycling of chromosome number that sexual reproduction requires. Can this also be explained away by math-phobia? Can college students really not do multiplication and division by twos? It seems more likely that in trying to memorize the welter of vocabulary (prophase, metaphase, etc.), they had not grasped the logical concepts underlying the differences between mitosis and meiosis, namely that mitosis evolved to minimize mistakes within an individual body and that meiosis evolved to shuffle genes across generations.

These two convenient categories of qualitative and quantitative misconceptions can overlap. For instance, many students said that their species was density-dependent or density-independent. These labels properly apply to the individual environmental factors that limit population size. Further, some even said that nothing limited their population size, even though the population sizes were generally quite small. This implies that they did not understand the implications of geometric growth rates at even a qualitative level – that "there must be some limit to growth, even if I don't know what that number is, and that organisms do not **choose** to limit their population sizes; they grow until some external factor stops them."

Bright Spots on Qualitative Understanding

Students had relatively good qualitative understanding of several types of ecological relationships between species. Predator-prey, commensal, and mutualistic relations were common; for some reason, parasitism was rare. This is ironic, considering that perhaps 40% of all species are at least partially parasitic during at least part of their life cycle, and that as many as 75% of links in Earth food webs involve at least one parasite, as many parasites have parasites of their own (Dobson, *et. al*., 2008). Also, carnivorous plants and top carnivores were overrepresented, presumably because they are "cooler" or more dramatic than plants and herbivores.

Evolutionary trees based on anatomy also showed the proper qualitative patterns of branching for life on Earth, at least at the multicellular level. Ancestors always branched into two daughter species, not three or four, and did not merge again once they had separated. No class ever considered the possibility that a different planet might have more loosely defined species boundaries. One class (Spring 2007) did have multiple origins for life on Lakeworld, with one group of microbes arriving on the planet inside meteors.

DISCUSSION

One of the most valuable aspects of the exercise for me as a teacher was that it revealed the dazzling variety of misconceptions that my students held, in a way that a multiple-choice test designed by an expert, from that expert's point of view, would rarely do. I have begun to use an evolutionary metaphor for this situation, namely that all possible misconceptions potentially exist somewhere in the student population. In fact, individual students can even hold multiple, mutually contradictory positions in their heads, much like the multiple alleles contained in their cells. Most multiple-choice exams do not allow for the expression of these misconceptions, so they remain hidden and uncorrected. The AEP succeeded at eliciting these misconceptions in a fun and engaging way.

The other insight this exercise crystallized for me is what I have come to call "the teacher's dilemma," in which the instructor continually demands more of the students, and the students continually resist those demands. Without clear and agreed-upon standards of biological literacy, we are left with the nagging feeling that students simply need to do more. This anxiety leads to stuffing more and more content into our courses, to the detriment of learning. After the first iteration of the AEP, my response was to require the students to spend more time on the project outside of class, when it was the social interaction inside of class that was the most effective driver of their engagement.

Since the time that I designed the AEP, so-called STEAM (STEM + Arts) approaches to teaching science have received much media attention (Pomeroy, 2012; The Conference Board, 2007) and some funding (Stem to Steam, 2012). Other papers by Rohrbacher and by Walker in this volume will cover this movement in more detail. Here, I will say only that the AEP could fit under the STEAM umbrella as easily as it fit under an inquiry umbrella.

Current Applications and Future Development of the Alien Ecosystem Project

The AEP was designed as a capstone experience for the semester, but in its current state, it would likely be even more useful as a formative assessment project at the beginning of a course. Forcing intensive group interaction during the first two weeks of class would be valuable for formative assessment of group work skills, which are currently being emphasized in many curricula (Cohen, 1994; Michaelson and Knight and Fink, 2002). The first two weeks of the semester is also a time when many students are still waiting for their financial aid checks and therefore don't even have books, a time many instructors spend doing icebreaker exercises or "covering the syllabus." The AEP could serve as an engaging icebreaker exercise, one with the added benefit of being related to the content of the course. One could then use the misconceptions revealed during this exercise to drive lessons throughout the semester, drawing on examples of student work at the beginning of each misconception lesson. At the end of the semester, the same examples could be used in summative assessments, in which the students have to find the mistakes of the earlier versions and correct them. Alternately, other examples could be drawn from the same pool, or even from the work of earlier classes. This use of the AEP would require no more time than the original -- perhaps less, as the feedback would be during class discussion and not written to individual students.

As shown above, the AEP was quite effective at revealing student misconceptions, about evolution and many other biological concepts. However, as a capstone project, it did not allow much time for correcting those misconceptions. As a different way to extend the AEP, I am currently developing a semester-long interdisciplinary exercise based on this three-session project. In that exercise, which will supplement rather than replace existing laboratory sessions, students will begin with the best estimates of conditions on a real alien planet or moon. There are currently 77 confirmed planets to choose from (National Aeronautics & Space Administration, 2012). Rather than simply creating alien species from whole cloth, students will work in groups to evolve them using a series of computational models that will link physics, chemistry, and biology into a seamless sequence (which, importantly, will not conflict with the organization of existing textbooks). Changes made to physical parameters, such as the amount and color of light coming from the local star, will propagate upwards and constrain developments at the higher levels. Each repetition of the course will tweak different parameters, and the results will be archived in a series of web pages. Eventually we may be able to make general predictions about evolutionary solutions to the problems of survival under different environments. Importantly, we will have fun doing it.

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