JET
The Journal of Effective Teaching
an online journal devoted to teaching excellence

Teaching Evolution: From SMART Objectives to Threshold Experience

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Abstract

Despite the centrality of evolution to the study of biology, the pedagogical methods employed to teach the subject are often instructor-centered and rarely embedded in every topic throughout the curriculum. In addition, students' prior beliefs about evolution are often dismissed rather than incorporated into the classroom. In this article we describe the use of SMART (specific, measurable, attainable, relevant and time-sensitive) guidelines to "flip" our classroom in order to create and maintain a supportive learning environment that addresses these concerns. This environment consisted of at-home learning modules deployed at specific times throughout the semester. We found that students responded well in the environment and generally achieved our benchmarks for performance. We observed that many students struggled both with conceptual understanding as well as their conflict between deeply held personal beliefs and evolutionary theory. Our observations also appear to support the view that evolution through natural selection is a threshold concept in biology.

Keywords: Evolution, natural selection, SMART guidelines, threshold concepts, flipped classroom.

Nothing in biology makes sense except in the light of evolution. (Dobzhansky, 1973)

As Dobzhansky's famous quote communicates, the concept of evolution through natural selection is perhaps *the* central theme in biology. Yet, multiple obstacles exist in the classroom that can create an environment in which its concepts can be difficult for students to grasp. First, evolution is often addressed as a separate principle and rarely embedded in every topic throughout a biology curriculum. In addition, evolutionary concepts are often taught using instructor-centered models of education, where content delivery is prioritized through methods such as the traditional lecture. This, despite the evidence that there are critical impediments to learning through traditional lecture and that student-centered instruction produces better learning outcomes (Armbruster, Patel, Johnson, & Weiss, 2009). Furthermore, evolutionary biology comprises concepts that students often find difficult, even in other contexts, such as the notions of equilibrium and change,

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complexity, scale, variability and hypothesis creation. These (as well as others) have been classified as threshold concepts within evolution (Taylor 2006), meaning these ideas present troublesome knowledge and that once mastered, can result in fundamental changes in understanding (Meyer and Land, 2006). Finally, confronting the commonly held belief that humans represent the pinnacle of a teleological evolutionary process as well as the influence of theological thinking in the classroom presents its own challenges.

In their seminal article detailing the challenges and solutions involved in teaching evolution in a higher education setting, Bruce Alters and Craig Nelson emphasize that the key to teaching evolutionary theory in the classroom is to adopt student-centered learning as opposed to the more traditional instructor-centered teaching methods (Alters & Nelson, 2002). In instructor-centered teaching, the focus is on the delivery of content with the students absorbing material to the best of their ability. Learning in this setting is often either *superficial* or *strategic*. Superficial learning is defined here as the student memorizing information without making any connections to prior knowledge, while strategic learning is characterized by an orientation towards getting a good grade with very few students actually applying the knowledge gained in the classroom to real world situations (Entwhistle, 1987). In contrast, student-centered learning is designed to promote deeper learning where students are able to understand, internalize, and then apply concepts learned to real world situations (Bender 2003; Blumberg, 2009; Carmean & Haefner, 2002). Properly implemented, this type of student-centered learning can lead to increased motivation to learn, greater retention of knowledge, deeper understanding, and more positive attitudes towards the subject being taught (Collins & O'Brien, 2003).

Yet, student-centered learning methods can also take a considerable amount of time on the instructor's part. SMART (Specific, Measurable, Attainable, Relevant, Time-oriented) objectives, routinely used in project management and education (Blumberg, 2009) can help ensure that critical content is being delivered in an efficient and effective manner, even in student-centered curricula.

This study employed and modified SMART objectives as a strategy to achieve a student-centered classroom that introduced and reinforced threshold concepts and built on students' prior beliefs. During the planning stage of the course development we constructed a set of *specific* learning outcomes using action verbs. The outcomes were designed to be *measurable* with specific benchmarks assigned and *attainable*; that is, they could be achieved in the course of a semester (or learning module) and were appropriate in scope.

The standard SMART guidelines call for designing *relevant* objectives in the sense that they are aligned with an overall goal or plan. We felt that this sense of the word was less applicable in our case as our learning objectives were clearly aligned with the overall goal of having students master the concepts of natural selection and evolution. Instead, we modified the SMART program by incorporating recent pedagogical theory focused on the importance of culturally relevant teaching (CRT). CRT is a term coined to describe "a pedagogy that empowers students intellectually, socially, emotionally, and politically by using cultural referents to impart knowledge, skills, and attitudes," (Ladson-Billings, 1994). In other words, curricula should be relevant to the students' lives (Osborne &

Cooms, 1987; Osborne & Sellars, 1987). Our student population is mostly of African-American, African or Latin American heritage and we chose topics that we anticipated our students would encounter in their daily experiences and would therefore resonate on a level that other topics might not. In short, the SMART guidelines were adapted here to mean relevant to students' lives, rather than relevant to an overall goal or plan.

Finally, our curriculum presented the material with specific *timing,* with assignments due at regular intervals. We introduced the topic at the beginning of the semester, reinforced it during the semester using real world examples, and assessed learning outcomes at the end of the semester.

Employing SMART objectives helps the instructor to engage in both student-centered teaching and good assessment practice (Blumberg, 2009; Suskie, 2009). In addition, this study found that SMART objectives can be used to effectively design what is now known as a flipped classroom. In this teaching style students access learning materials such as audio clips, videos, PowerPoint presentations, etc., customized for the topic and then typically take an on-line assessment to measure background knowledge and basic understanding. The advantage of this approach is that it allows instructors to devote more in-class time to the more challenging concepts that students typically struggle with and promotes a deeper understanding of the topic at hand (Bergmann, 2012).

An additional major aspect of teaching evolutionary theory is addressing prior beliefs. Personal belief systems play a significant role in learning (Hokayem & BouJaoude, 2008), best exemplified by a negative correlation found between acceptance of evolutionary theory and a strong belief in God and frequent prayer (Miller, Scott, & Okamoto, 2006)). One of the major tenets of cognitive psychology emphasizes addressing and building on students' prior knowledge (Murphy & Alexander, 2000). Therefore, to teach the science and ignore students' personal beliefs would result in failure to teach evolution effectively (Nelson 2007). In order to address prior beliefs, we provided our students with opportunities to freely express their views on issues relating to evolution.

This paper describes our approach to a flipped classroom, using modified SMART guidelines, which allowed us to generate a student-centered, supportive learning environment that introduced and reinforced threshold concepts, built on students' prior beliefs, and was successful as measured by student attainment of performance benchmarks.

Method

We conducted our study at Bronx Community College, a campus of the City University of New York, over the course of 4 semesters of an Introduction to General Biology course (n = 83 students, approximately 20 students per class). Students enrolled were a combination of biology and non-biology majors, 57 freshmen (68.7%) and 26 sophomores (31.3%). Two instructors conducted the study, each operating from the same set of specific and measureable learning outcomes. (Table 1)

Table 1. Student learning outcomes aligned with taxonomic level

Taxonomic Level	Student will be able to…	Terms
Recall	…define terms	Population Genetic variation Mutation Selection Pressure Allele Fitness Natural Selection
Comprehension	… distinguish between terms when applied to real-life situations	
Application	… apply terms in scenario-based questions	

While evolutionary theory includes other obvious important concepts – e.g., Hardy-Weinberg equilibrium, genetic drift, sexual selection, etc. – we felt that the objectives in Table 1 represent a good stable of knowledge for students who are being introduced to the concepts in the setting of a college biology course for the first time. The choice of these specific learning outcomes and the scaffolded structure of assignments combined to make the outcomes *attainable* by our students. We felt that these learning objectives were neither too difficult nor too easy for our population.

Throughout the curriculum we endeavored to incorporate *relevant* examples that students would not be considering for the first time and that would resonate in settings outside the classroom. By examining antibiotic resistance, lactose intolerance, skin color and sickle cell anemia (with malaria acting as the selective pressure) we were able to illustrate evolutionary concepts with topics that we anticipated held interest for students in other contexts. Antibiotic resistance has been a popular topic in both the scientific and mass media for the past decade or more (Desilva, Muskavitch, & Roche, 2004). Lactose intolerance is very likely commonplace in our student population, with 75% of African-Americans, 51% of Latino/Hispanics (Scrimshaw & Murray, 1988) and 70-90% of Africans (de Vrese et al., 2001) experiencing the condition. The significance of skin color and the concept of "race" are ever-present in our society. Given the sensitive nature of the topic, however, professors in a traditional instructor-centered classroom may choose to omit this topic. The potential for discussion to veer away from the strict evolutionary issues may cause professors to worry about having sufficient time for content delivery while simultaneously wanting to encourage discussion that students will find engaging and interesting, even if it strays from evolutionary theory. In contrast, the flipped classroom approach that we employed (described below) is an ideal paradigm for the consideration of the evolution of skin color. The biological concepts are delivered at home through completion of the assignment, including a formal assessment. Classroom time can then be devoted to reinforcement of the concepts while at the same time allowing students to confront troublesome knowledge along biological as well as sociological and political avenues. Finally, our institution has a relatively large population of students with African heritage, especially from Western Africa. The prevalence of sickle-cell anemia in this region is especially relevant to these students.

In order to satisfy the *time-oriented* element of the SMART guidelines, we provided learning opportunities via a natural selection learning module, assigned at regular intervals during the course of the semester. For each assignment, students were directed to access a folder, stored on our institution's Blackboard system, which contained necessary instruction and material for students to complete two tasks.

Task 1 – Complete a Natural Selection Learning Module followed by an on-line quiz

At regular intervals throughout the semester, students were instructed to open and view a short Microsoft PowerPoint presentation. These presentations contained a self-directed, culturally relevant lesson that illustrated one or more concepts in natural selection. Figure 1 shows a portion of the presentation that students completed for the antibiotic resistance module, along with some sample quiz questions for that module.

The student learning outcomes associated with these presentations (Table 1) were continuously assessed using on-line quizzes that the students were required to complete after viewing the presentation. The quizzes allowed us to place more emphasis on specific and attainable learning objectives, including recall of important terms, comprehension of evolutionary concepts and the application of these concepts (Bloom, 1956). Importantly, the same topics were found in multiple modules, giving students an opportunity to see and consider topics repeatedly, a known factor in improved retention and performance (Rock 1957).

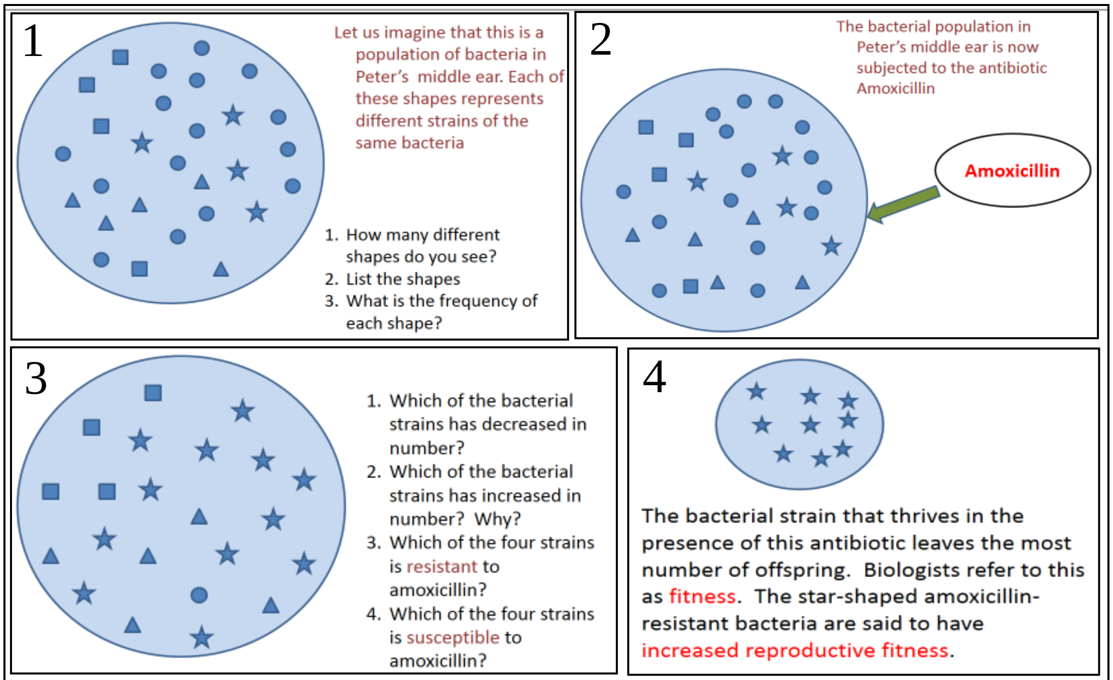
Task 2 – Watch a video clip and complete a reflective writing assignment

For each module, in addition to the presentation and quiz, students were instructed to watch one segment of a 7-part series, titled *Evolving Ideas*, available on the Public Broadcasting Service (PBS) website. Each segment provides a short, 7-10 minute presentation on a concept in evolution by natural selection (Table 2).

Associated with each video was a reflection question that asked students to consider one or more of the concepts presented and to write a response on our on-line Blackboard system. In some cases, the reflection was a purely subjective investigation of how the student felt about the topic. In other cases, students were asked to recall and summarize the primary concept of the video. The viewing of the video and reflective writing assignment were assessed only for completion. By providing students with a low-stakes environment in which to consider topics in evolutionary biology, we hoped to create a space where students could express prior beliefs and any challenges to those beliefs that the assignment may have provoked.

Final Exam

We also completed a summative assessment by including questions about evolution through natural selection on the cumulative lecture final. Out of the 75 questions on the final, we included 15 questions designed to probe students' recall, comprehension and application of the chosen concepts (Table 1).



<u>Sample quiz questions</u>

1. The triangle shaped strain was found to be most susceptible to amoxicillin (T/F)
2. A change made in the DNA sequence of an organism is called a ___________
3. A change made in the DNA sequence of an organism can convert an existing gene into an alternative form called a(n) ___________
4. The collection of bacteria in Peter's middle ear is called a ___________
5. The antibiotic amoxicillin imposes a (2 words) _________ ___________ on the bacterial population.

Figure 1. A sample of slides from the online presentation for antibiotic resistance module, along with representative quiz questions

Table 2. Video segments and associated student learning outcomes. Adapted from http://www.pbs.org/wgbh/evolution/educators/teachstuds/svideos.html

Video Segment:		Reflection Question:
1.	Isn't Evolution Just A Theory?	"Agree or disagree, and why: Once a theory has been proven to be true, scientists should forget about it and move on to other, more important subjects."
2.	Who Was Charles Darwin?	Charles Darwin was concerned about publishing data that suggested that every species had not been created by divine force, but had arisen from a common ancestor. Do you feel like there are any similarities today? Are there any scientific data that you would be worried about publishing because they would be considered controversial or taboo? If so, which ideas and why? If not, why not?
3.	How Do We Know Evolution Happens?	The video discusses "transitional forms" when talking about the evolution of whales from a wolf-like ancestor. Based on your understanding from the video, how are transitional forms, found in the fossil record, used to support the theory of evolution? Give an example, either from the video, or from another species, of a transitional form.
4.	How Does Evolution Really Work?	In your own words describe each of the 4 aspects of natural selection that are described in the video. Do not just list the four aspects, describe them.
5.	Did Humans Evolve?	For the following list of organisms, place them in order from those that are most closely related to humans to those that are more distantly related. Thinking back to the video, describe the number of "spelling mistakes" (the DNA differences) that are found as you go down the list and relate that to evolutionary distance from humans. Use http://www.timetree.org/ and the species names given to find the evolutionary distances. Norway Rat - *Rattus norvegicus* Baker's Yeast - *Saccharomyces cerevisiae* Horseshoe crab - *Carcinoscorpius rotundicauda* Chimpanzee - *Pan troglodytes* Blue Whale - *Balaenoptera musculus* Dog - *Canis familiaris*
6.	Why Is Evolution Controversial Anyway?	Do you agree or disagree with this statement? And why or why not? "Scientific explanations are based on empirical evidence. Science can explain the evolution of life on earth based on scientific evidence. But, it cannot supply the basis for ethical behavior or explain the existence of God or the human soul. On the other hand, religious discourse is based on metaphor and symbolism. Religion can supply the basis for ethical behavior and explain the nature of God and the human soul. But it cannot offer scientific explanations based on symbol and metaphor."

Results

Quizzes

Task 1 required the students to complete a Module on natural selection including an independent review of a PowerPoint presentation on a culturally relevant example of evolution, followed by an on-line quiz. We designed the questions so that they would be drawn from the first three categories from Bloom's taxonomic hierarchy (Recall, Comprehension and Application). Analysis of student performance over the semester revealed a general improvement trend for two of the three taxonomic levels. In both Recall and Application questions, student performance showed a general, though not statistically significant, improvement over the course of the semester (Figure 2). For the Recall questions, the performance was steady over the first two weeks (73.9±20.5%, 73.1±17.6%). In week three the average increased to 77.9±16.5% and in week four it peaked 85.3±10.5%. For our Application based questions, performance was 46.6%, 46.4±17.3%, 75.5% and 72±8.5%.

Interestingly, performance on the Comprehension questions was variable, showing no discernible trend over the course of the semester. As discussed below, the question design in this category may require refinement in order to accurately assess student knowledge.

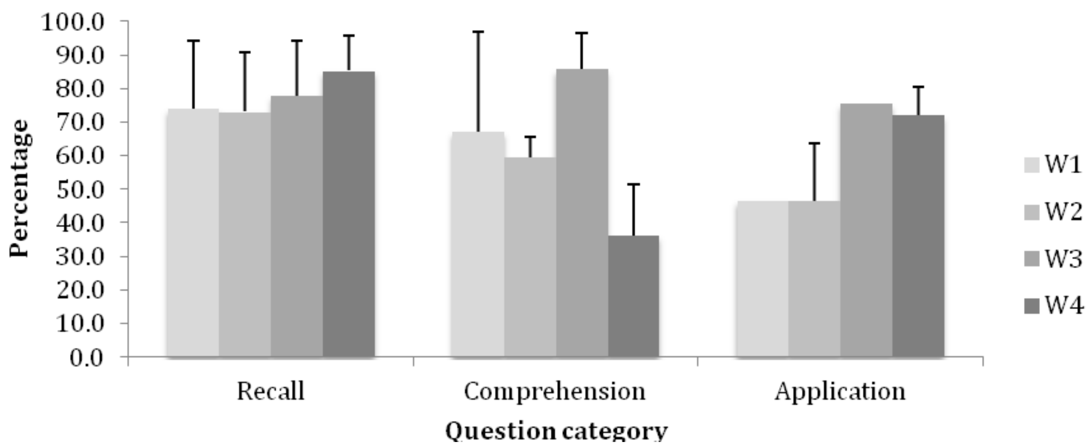


Figure 2. Performance on quiz questions, ordered according to the first three levels of Bloom's taxonomy, over the course of the semester. W1=Week 1, W2=Week 2, W3=Week 3, W4=Week 4.

Final exam

We completed a summative assessment through inclusion of 15 questions from the evolution curriculum on the final exam. For the final exam we continued to draw from the first three taxonomic levels and we also continued to use culturally relevant examples in our assessment.

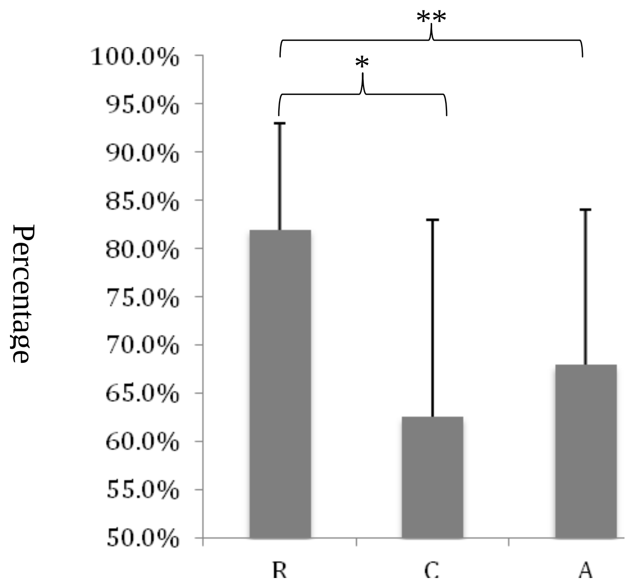


Figure 3. Performance on questions drawn from the first three levels of Bloom's taxonomy on summative exam. (R=Recall, C=Comprehension, A=Application) *, p < 0.02**

As expected, student performance was higher on the Recall questions (82%±11% correct) compared to the Comprehension (62.5±20.5% correct) and Application questions (67.9±16.2% correct) (Figure 3).

For each question on the final we anticipated that at least 70% of students would answer a question correctly, drawing on previously established standards for benchmarks (Suskie, 2009). Out of the four sections, students in three sections (74.7% of students) met or exceeded the benchmark (Figure 4). We also found an interesting, though not statistically significant, tendency for students to perform better on the final exam questions relating to evolution and natural selection than they did on the other topics. (72.6±5.6% on evolution questions versus 67.3±4.6% on the rest of the final, $p = 0.13$)

Participation in discussion board

We found rates of participation in the discussion board to be very high for the first assignment (96.6%) followed by a decrease during the remainder of the semester. (Figure 5). For every reflection at least 75% of the students participated. In addition, we found that 58% of the class had 100% compliance with the assignment, completing a reflection assignment for all 6 weeks. Together these data reflect an affinity for the assignment even though it was assessed only for completion and comprised a relatively small (less than 10%) portion of the overall course grade.

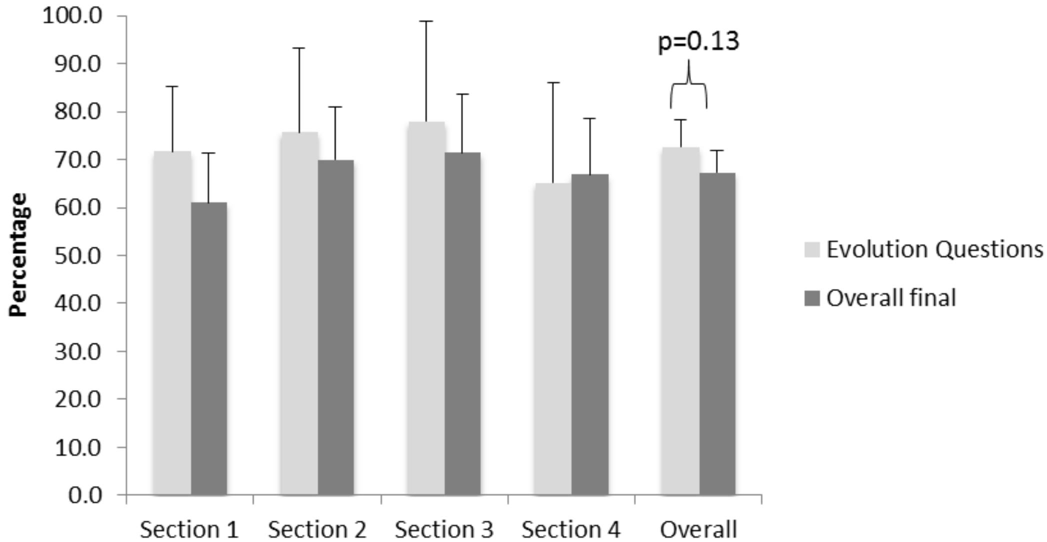


Figure 4. Section analysis for summative assessment. 75% of sections and students performed above the benchmark. Overall, performance on evolution questions suggestively exceeded performance on the questions from the remainder of the curriculum that comprised the final exam ($p = 0.13$).

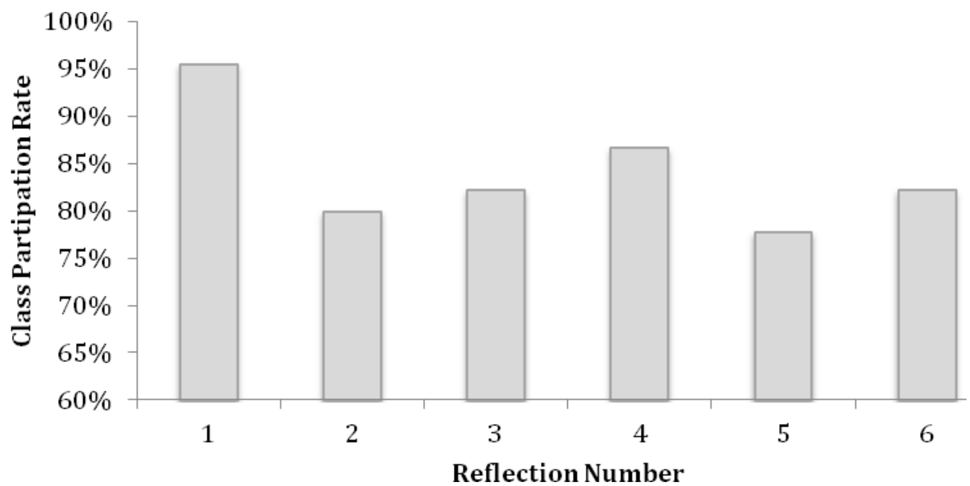


Figure 5. Participation rates for discussion board reflection questions.

Discussion

Our experience shows that the use of SMART guidelines to generate a curriculum for teaching evolution holds promise for overcoming the obstacles that stand in the way of student understanding. More generally, we believe that the use of SMART guidelines as a mechanism to create a flipped classroom allowed us to craft a learning environment that is student-centered and supportive.

Despite the generally positive results, we observed areas where students struggled or where the impact of our pedagogical strategy was unclear. For example, with our continuous assessment we found that student performance on questions designed to measure comprehension was highly variable. We realize that a contributing factor to explain this observation is our failure to make the concept of inheritance explicit in our learning modules. In particular, the performance on the final weekly quiz dropped dramatically. This quiz covered material presented in a module on sickle cell anemia and malaria, a topic we informally recognize as one of the more difficult. Malaria acting as a selective pressure causing the persistence of the sickle allele is an especially troublesome concept. Increasing the opportunities for students to identify selective pressures and their impact will be a focus of future efforts.

Based on the classic interpretation of Bloom's taxonomy we also expected that students' performance on Comprehension questions on the summative assessment would occupy a median position between Recall and Application questions. Our finding that student performance on Comprehension questions was similar to Application questions may reflect a similarity in the difficulty encompassed by our questions at these two levels of the taxonomy. We will analyze our assessment to determine if a greater distinction between the questions is required.

On the cumulative final we found a number of concepts for which students failed to meet the benchmark.

1. Gene mutation as the initial step in the evolution process when presented in context.
2. The spread of alleles through a population during the natural selection process.
3. Identifying a selection pressure
4. Role of Vitamin B6 in the evolution of human skin color

We plan to address 1 and 2 by modifying every module to include an activity that begins with a genetically homogenous population that experiences the introduction of a mutation followed by the generation of novel alleles. Making inheritance and its underlying mechanisms explicit in all of the modules will reinforce concepts 2 and 3.

For concept 4, the assessment tool may be the issue because this question was an outlier among the Application questions in terms of students' performance. A possible contributing factor is that the question that we included on the final was phrased as a negative, which has been shown to be problematic, especially for questions requiring higher levels of cognitive reasoning (Tamir, 1993). Breaking this question down into parts that leads the student step-wise from the broader evolutionary aspects of skin color to the finer details may help to improve student performance and pinpoint the problem areas. We feel that the evolution of skin color presents a challenge because it requires students to understand the basics of two unrelated physiological mechanisms, the synthesis of vitamin D and breakdown of vitamin B6 (Jablonski & Chaplin, 2003). Given its importance generally in society and specifically for our student population, we will retain this module despite the difficulty level. Our strategy to address this difficulty is to split this module into two parts, dealing with each mechanism separately, thereby providing ample opportunity for students to struggle with this troublesome knowledge.

The use of SMART guidelines appears to point to a neat and linear progression of learning from beginning to end. However, our experience showed that the process is far messier and hardly linear. Students struggled with both conceptual understanding of evolutionary theory and displayed reactions to various aspects of evolutionary theory that evidenced a conflict with deeply held personal beliefs. As opposed to dismissing our students' prior beliefs about evolution, we provided a platform for them to air their personal beliefs via the Blackboard discussion board or blog (Alters & Nelson, 2002). We found that even though students were simply being assessed for participation on the discussion board, often students did not post single-sentence or single-paragraph responses. Instead, a majority of the students posted meaningful and well developed responses to the posed questions, such as the two examples below:

> *"A lot of … religious believers grew up going to church and learned God created everything. At first I had difficulties in my science classes because they were teaching me something different from what I learned and believed in."*
>
> *"It never ceases to amaze me how organisms with similar physical features turn [out] to have different genetic characteristics. I would never in million years believe that whales are more closely related to wolves as opposed to sharks."*

The usefulness of this exercise is that it allowed students to occupy the liminal space (Meyer & Land, 2003). During a student's acquisition of threshold knowledge, there is a period of consideration and examination. Students often engage in both excursive and recursive thinking, where they will reach out toward a new concept or understanding and then retreat to a set of prior knowledge (Cousin, 2006). In our discussion board we found numerous examples that indicate students were struggling with the concepts of natural selection and evolution. In order to draw students into the liminal space of the threshold experience and get them to engage deeply, it is essential for the instructor to create and maintain a supportive learning environment (Meyer & Land, 2006). Here the role of the instructor becomes essential in presenting a series of carefully crafted challenges that would gently guide the struggling student as they traverse the liminal space (Taylor, 2006). For future classes we will refine our learning opportunities to allow for immediate incorporation of student struggles that are revealed in the low-stakes assignments.

Our overall strategy of using SMART objectives to design our flipped classroom has produced promising results. We found that, in general, students performed better on the questions related to evolution and natural selection than they did on the final exam overall. While this difference was not statistically significant, it is a suggestive result that indicates our curriculum is having the desired effect. As discussed, we have identified areas where the curriculum can be improved and refined suggesting that future sections may see a statistically significant effect. This also raises the question of whether this curriculum design could be applied to all course topics within General Biology courses, or indeed across multiple disciplines. Should instructors choose to adopt a flipped classroom approach, SMART guidelines could be particularly helpful in designing curricula.

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