

Thinking Critically in Undergraduate Biology: Flipping the Classroom and Problem-Based Learning

Tracie Marcella Addy
Yale University

Catherine LePrevost
North Carolina State University

Maura Stevenson
Quinnipiac University

Introduction

Critical thinking is a desired learning outcome in undergraduate biology. However, there is frequently ambiguity associated with how this term is defined. Ennis (1991) defined critical thinking as “reasonable and reflective thinking focused on deciding what to believe or do” (p. 6). The American Association of Colleges and Universities (2013) indicated that critical thinking is “a habit of mind characterized by the comprehensive exploration of issues, ideas, artifacts, and events before accepting or formulating an opinion or conclusion” (p. 5). In this report, we take elements from each of these definitions and define critical thinking as higher order thinking skills (Bloom, 1956) developed by a trained mind. We support the notion that critical thinking is context-dependent, can become habitual (a patterned way of thinking), and can be developed and nurtured in the disciplinary classroom.

In undergraduate biology, the development of students’ critical thinking is important, as its usage is integral to the nature of science. Through inquiry, scientists make observations about the world around them, formulate hypotheses as to why phenomena occur, design experiments to test predictions, and draw conclusions based upon the outcomes of research. The process of drawing experimental conclusions relies heavily upon *deductive* reasoning, which involves using evidence to ascertain why a particular result is observed. Additionally, scientists form theories through *inductive* reasoning in which they frame very general conclusions based upon specific data. Deductive and inductive reasoning are among the higher order thinking skills important in science, along with synthesizing information from a variety of sources, evaluating the quality of evidence, transferring scientific knowledge to other contexts, and problem-solving, all of which fall within Bloom’s Taxonomy (Anderson et al., 2001).

Thus, because critical thinking is integral to the sciences, biology students who do not improve upon these skills during their schooling may not be able to acquire a basic competency needed to perform successfully in the discipline. Critical thinking is also important outside of the sciences; studies suggest that many students do not gain this important aptitude in their early collegiate years, and those with lower order thinking skills have worse employment and financial outcomes post-graduation (Arum et al., 2012; Arum & Roska, 2011).

Although development of critical thinking is much desired, understanding how it plays a role in student achievement and how to foster such skills can be elusive. A common goal for students is to gain discipline-specific, foundational knowledge while enrolled in a course. However, if teachers reward students solely for memorizing and recalling basic facts through testing, students may fail to fully develop higher order thinking skills. Based upon our

experiences, as instructors of biology, we find that designing learning environments that aid students in practicing higher order thinking skills enables them to develop critical thinking. While the development of critical thinking may appear simple, it often poses a challenge to many faculty. Instructors who were themselves taught in classrooms that did not involve much critical thinking may teach in the same manner, arguably leading to generational patterns that may not necessarily foster these skills. Even the most well-intentioned instructors may not know, or have the time and space to figure out, how to transform their classrooms to encourage critical thinking. Moreover, there is no proven teaching strategy that will facilitate learning for all students, and even students taught in more traditional learning environments where critical thinking was deemphasized may nevertheless have developed these skills. Still, designing learning environments where all students practice higher order thinking skills may foster the development of critical thinking for many of them.

Reflecting upon our own teaching experiences with biology students, as well as the outcomes of institutional review board-approved investigations conducted in general biology courses for majors, and the literature in this area, we describe in this report several reasons why critical thinking is important in undergraduate biology as it relates to student achievement and attrition in science. Our investigations were conducted at a small private university in the northeastern United States. We also describe how particular learning environments have the potential to further enable students to develop their critical thinking through writing (AAAS, 2011).

High School Preparatory Experiences; Achievement and Critical Thinking in College Biology

Undergraduate students' backgrounds and prior experiences impact academic achievement when they arrive at the university. Such factors as academic behaviors during high school; the extent to which students were exposed to violence; available resources; and the infrastructure, support, and quality of their high school each seemingly plays a role in the level of achievement during a student's first year of college (Wolniak & Engberg, 2010). This finding suggests that students who have more college-level preparatory experiences and less adverse high school cultures are at an academic advantage.

Examples of high school preparatory coursework associated with college achievement include Advanced Placement (AP)–level classes. We see the positive influence that having taken AP Biology has for our students. These students often achieve higher grades in our courses. Results of a basic demographics survey of one of our first-semester General Biology I classes showed that final course grades were positively correlated to whether or not they had taken AP Biology in high school (Spearman's Rho $r = 0.44$; $p = 0.0053$; $n = 38$). These findings corroborate a matched comparison study of students who took AP Biology and those who did not. Those who took AP Biology and received college credit via high AP exam scores had higher first-year and subject area GPAs than non-AP students and AP students who did not receive college credit due to lower scores on their AP exams (College Board, 2009).

These results raise the question of why students achieve higher grades in college biology after having taken AP Biology. Anecdotal evidence from several of our students suggests that taking this high school preparatory class pre-exposed them to the material and ways of thinking that helped them succeed in our general biology courses. AP Biology introduces certain fundamental concepts and also helps students prepare for the level of critical thinking required at the university level. For instance, the free response portion (approximately 40%) of the AP

Biology exam prior to the Fall of 2012 (taken by our students described here) assessed students' capabilities to analyze and interpret information through writing (AP College Board, 2013). The newer version of the exam (Fall 2012 and beyond) shifts emphasis even more heavily from the coverage of content to skill development. Students are now required to a greater degree than before to evaluate data and form conclusions in the writing portion, which now accounts for 50% of the exam. Focusing more on skill acquisition and less on content may impact many students' seemingly pervasive high school beliefs that biology involves only the memorization of facts. Such insidious belief systems can ultimately set them up for failure if they do not discover until college that critical thinking is essential to science.

Because taking AP Biology courses can thereby aid students in practicing higher order thinking skills (Anderson et al., 2001), students who have already practiced these skills in high school likely have an advantage in our general biology courses. Indeed, we find that there is a relationship between students' incoming critical thinking and final course grades. When we administered the Cornell Critical Thinking Test Level Z (CCTT-Z) to assess the critical thinking of first-semester freshmen enrolled in a general biology course section for majors, we found a significant positive correlation between students' scores on the test and final grades in the course ($r = 0.57$; $p = 0.0002$; $n = 38$). The CCTT-Z is an established standardized multiple choice test that assesses students' abilities to perform deductive and inductive reasoning, as well as to identify fallacies, meanings, and assumptions (Ennis, 1996, 2005). Students took this test online at the beginning of the course. Even among a range of variables also surveyed—including gender, race, parents' education levels, completion of AP Biology in high school, deep and surface study process skills through the revised two-factor Study Process Questionnaire: R-SPQ-2F (Biggs, Kember, & Leung, 2001), and epistemologies toward teaching and learning (Luft & Roehrig, 2007)—students' critical thinking scores were the best predictors of their final course grades.

This finding regarding the relationship between critical thinking and achievement is perhaps not unexpected and may inform an important issue in the biological sciences and STEM (science, technology, engineering and mathematics) fields in general, namely, the attrition of students along the “pipeline.” If students perform poorly in their introductory biology courses, they typically will not advance to the next course. Although a combination of many factors, including prior academic experiences, the discovery of other interests and talents, and poor study habits, could contribute to this attrition, devising ways to enhance critical thinking from the start of students' college experiences may, nevertheless, help bridge the divide between strong and weak skills to encourage the achievement and understanding of science by all students (AAAS, 1990).

Improving Biology Students' Critical Thinking Through Writing

One way to foster students' critical thinking is through writing, which can be carried out in various forms in biology (see Table 1). Proposal writing for an experiment to be conducted encourages students to practice the process of science. Laboratory reports, a specific example of Writing in the Disciplines (WID) (Carter, Ferzli, & Wiebe, 2007) that are typically incorporated into introductory biology courses, provide students with an opportunity to reflect on the process of inquiry. Reports typically contain an *Introduction* providing relevant background information, *Methods* explaining experimental procedures, *Results* describing and displaying analyzed data, and a *Discussion* drawing conclusions based upon results. Prior to conducting an experiment, students must create hypotheses through the process of inductive reasoning. After they gather the

data, deductive reasoning using experimental results is pivotal to formulating appropriate conclusions. Thus, the laboratory report is a writing exercise that enables students to go beyond the memorization of facts to the level of higher-order thinking practiced by scientists.

Table 1 Example Writing Assignments in Biology to Encourage Critical Thinking and Reasoning

Writing Exercise	Description	Critical Thinking Components
Scientific Proposal	A formal proposition of experiments to be conducted	Use of inductive reasoning to formulate hypotheses
Laboratory Report	Highlights the objectives, background information, methodology, outcomes, and conclusions of a scientific experiment	Use of inductive reasoning in formulating hypotheses; deductive reasoning to draw conclusions based upon analysis of results
One-Minute Paper	Informal writing on any topic; may encourage students to synthesize or evaluate a particular topic	Synthesis, evaluation, and application of information learned in class
Position Statement	Informal or formal writing assignment where students take a particular stance on an issue; can involve the evaluation of claims related to the issue	Construction of an argument; evaluation of claims
Concept Map	Diagram that joins various concepts together to depict how they are interrelated	Synthesis of information
Case Study Analysis	Concepts applied through a particular case or scenario	Application of information
Problem-Based Learning Reflection and Solution	Exercises where students are given an ill-defined problem that could have a variety of solutions and must step through the process of solving the problem; students can create an informal reflection describing the processes they utilized to come up with the solution and a formal write-up of their solution.	Synthesis and evaluation of research related to the topic; deductive reasoning to generate a solution

In reading laboratory reports, we see weaknesses in the critical thinking habits of students who never fully understand the objectives of the experiment, cannot ascertain how to relate the observed data to their hypotheses and scientific literature, and/or are unable to draw appropriate conclusions. Students who do not understand the purpose of an experiment often do not highlight key, relevant information in the *Introduction* of the lab report or relate experimental results to the appropriate objectives. Further, students who do not recognize the implications of the results can have a harder time drawing appropriate conclusions. Through lab reports, and being coached on them, many of our students do become more competent writers and, accordingly, more practiced critical thinkers.

Notable improvement of students' critical thinking through writing in the sciences has also been reported in the literature (Lawson, 2001; Quitadamo & Kurtz, 2007; Tyser & Cerbin,

1991; Rutledge, 2005). When critical thinking-based writing components are incorporated into undergraduate biology laboratories, students experience more critical thinking gains, compared to laboratories that involve only traditional quizzes (Quitadamo & Kurtz, 2007). In addition to writing components, another avenue through which to incorporate critical thinking is student assessment of claims in science-related articles. Students who engage in several of these exercises during the semester have been found to formulate better arguments compared to those not engaged in as many exercises (Tyser & Cerbin, 1991). Others have described analysis of claims in articles in the popular press as a means to develop critical thinking in biology (Rutledge, 2005).

We, too, have seen notable change in critical thinking through writing arguments (Addy & Stevenson, 2014). When second-semester General Biology II students were taught critical thinking and wrote position papers (pre-/post-instruction on critical thinking) based upon foundational topics within the course, they showed significant gains in their abilities to analyze scientific evidence in an article or passage related to a debatable scientific topic (e.g., the Blood Type diet). Their essays were assessed using an institutional rubric based upon the American Association for Colleges and Universities Value Rubric for Critical Thinking (AAC&U, 2013). These results demonstrated that students can improve their critical thinking within a single semester.

The Evolution of Biology Education & Pedagogy Enhancing Critical Thinking

With the presence of more widespread national movements in biology education—such as that elicited through the Partnership for Undergraduate Life Sciences Education (PULSE), which is a collaboration among several funding agencies (the National Science Foundation, Howard Hughes Medical Institute, and the National Institute for General Medical Sciences) to implement the ideals of the report *Vision and Change in Undergraduate Biology Education: A Call to Action*—there is a paradigm shift occurring within the field (AAAS, 2011; PULSE, 2013). The focus is now less on the memorization of facts and more on bigger-picture biological concepts and processes. Central to this movement are increased emphases on student-centered learning, where the backgrounds and abilities of students are the focal points in designing learning environments. There is a desire to set up classroom environments in order to more effectively meet student learning outcomes (Tagg, 2003). In addition, there is an increased espousal of various pedagogical ideologies for which higher order thinking skills are a major emphasis (Handlesman et al. 2004; Handelsman, Miller, & Pfund, 2006; Hoskinson, Caballero, & Knight, 2013).

Below we describe two particular learning environments that have been implemented in some of our courses, namely *flipping the classroom* and *problem-based learning*, and how they can be utilized to foster students' critical thinking in the biological sciences.

Critical Thinking in the Flipped Classroom

Generally, in the flipped classroom, students watch short-lecture video recordings as homework assignments prior to class to gain exposure to foundational concepts (Bergmann & Sams, 2012). To hold students accountable for learning from the recordings, instructors can assign homework to be completed before class or administer a short quiz on basic concepts at the beginning of class. Class time is then spent engaged in activities, such as experimentation and reviewing case studies. These in-class activities can create opportunities for students to learn material at a higher order of thinking, as students are prompted to go beyond basic recall to synthesize, evaluate,

problem-solve, and apply basic biological concepts. Below is a sample lesson utilizing the flipped classroom:

Learning Objective: Students will be able to perform simple monohybrid crosses and apply this knowledge to new contexts to demonstrate critical thinking.

Scenario/Sample Lesson: Students are assigned for homework a 10-minute lecture recording that describes how to carry out a simple monohybrid genetic cross, using Punnett squares, to predict the traits of offspring. They are also to read the accompanying section in their textbook and complete a short problem set on monohybrid crosses. At the beginning of class, students are given a 10-minute quiz on very basic concepts from their homework preparations. Misconceptions in student thinking can be initially identified through these pre-assessments. In collaborative groupings, students complete a case study involving a child with cystic fibrosis born to parents who do not have the disease. To this case, students apply what they have learned about the concept of inheritance from their homework assignments. The instructor facilitates discussion of the case and walks around the classroom to aid students in identifying and altering any misconceptions, by asking guiding questions that scaffold learning and challenge faulty thinking.

In this lesson, students gain foundational knowledge and apply its concepts. Students may solve problems through deductive reasoning when they utilize the information from the case to predict the parents' genetic makeup, as well as that of the grandparents, and construct a pedigree.

In general, flipping the classroom involves increased emphasis on student engagement with major concepts. In this type of learning environment, there are a variety of ways that critical thinking can be developed through writing. By creating an argumentative essay based upon the scientific claims made in an article related to the concepts learned, for example, students utilize higher order thinking skills.

In our teaching and/or research, we flipped the introductory biology classroom to allow for pre-exposure to course content (Addy and Stevenson, 2014). In class, students applied the content and participated in activities where they learned to identify faulty thinking. For these lessons, students evaluated scientific claims made in everyday newspaper articles and other sources. Through practice and coaching, students improved upon their abilities to evaluate scientific claims as illustrated through position papers written before and after these interventions.

Flipping the classroom can be difficult for some (students and instructors alike) to embrace, as it is not as conventional as the lecture learning environment. Students may perceive that they are not learning because they are not solely listening to a lecture and taking notes, when in actuality they may be learning, but in ways that promote critical thinking. Instructors may espouse similar hesitant beliefs about flipping, as well as feel uncertainty as to how to implement this type of environment in the classroom. While mostly positive support has been garnered for using the flipped classroom, more carefully designed investigations are needed regarding its

efficacy, as few studies have described its influences on student learning (Bishop & Verleger, 2013).

Critical Thinking in Problem-Based Learning

Another learning environment congruent with the major pedagogical movements in biology education is problem-based learning (PBL). This type of learning has its origins in medical and law schools (Barrows & Tamblyn, 1980). In its purest sense, PBL is not solely problem-solving, although this process occurs significantly within such learning environments. In PBL, the students are presented a problem that is not well-defined and has a variety of solutions. Therefore, the “correctness” of student responses is not confined to a single answer key. In PBL, the students identify the problem, determine what they need to know to solve it, find relevant information, and propose solutions, based upon their research and ideas. Through PBL, students learn foundational concepts by engaging in the process of problem-solving, using information, and reasoning to arrive at a well thought-out solution (see example below).

Learning Objective: Students will determine how a patient presenting symptoms of a particular metabolic disorder should be treated, applying their knowledge of enzyme structure and function.

Scenario/Sample Lesson: Students are presented with the case of an individual suffering from diabetes and must devise appropriate treatment methods. They work in collaborative teams of 4 – 6 students, with each member having a defined role in the PBL process. Students have several days to define the problem, perform research, and devise solutions. At the end of the problem-solving process, students write a summary of their research and solutions, as well as a reflection of what they have learned about the concept, their strengths and weaknesses in the problem-solving process, and what they plan to change next time.

In PBL, students devise solutions to learn basic concepts in the context of a real-world example. This use of real-world examples helps students with the transference of knowledge from the classroom to the workforce and other settings. In our classrooms, students synthesized research by conducting general background and literature searches on their topic. In class, students evaluated this information to devise a solution to the problem, and justified their decision. Students were charged with writing up a general summary identifying the problem, synthesizing their findings on the topic and solutions, and presenting the reasoning behind their respective solutions. Their ideas were presented to the class and their writing assignments graded based upon how they conducted the problem-solving process. Through this process, students practiced critical thinking by going beyond recall to exercise higher order thinking skills. Another item worth mentioning is that, anecdotally, students were at first often uncertain or uncomfortable with this process, but with more scaffolding, they demonstrated increased self-efficacy and competency in solving problems. This approach supports the notion that critical thinking can be practiced and improved upon within the classroom setting.

Conclusion

Critical thinking is integral to science. Moreover, outside of biology and other scientific disciplines, critical thinking is seemingly important (Arum et al., 2012; Arum & Roska, 2012).

Among our biology students, we see a strong association between their critical thinking and their academic achievement. In order to foster students' higher-order thinking skills, we use two learning environments along with writing exercises. A future step for the field is to assess the outcomes of this approach.

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