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Structuring Effective Class Discussions in Undergraduate STEM Classes: Examples from an introductory biology course

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Class discussions have been shown to provide numerous benefits to undergraduate science students, including fostering the development of critical thinking and communication skills, enhancing student understanding of course topics, and correcting misconceptions. While they are effective pedagogical tools for undergraduate science classrooms, special attention must be given to structuring class discussions in a manner that accomplishes the aforementioned goals, while at the same time providing students with interesting and challenging discussion topics that foster their learning both inside and outside the classroom. This report describes the manner in which classroom discussions were used in a semester-long, introductory biology classroom, and provides specific examples of discussions used to enhance student learning. While discussions are not a new pedagogical technique, literature on techniques for structuring effective discussions in undergraduate STEM classes remains elusive. The goal of this report is to present a framework which can be used by instructors to formulate more fruitful and lively discussions among students. To encourage participation and preparedness among students in the class, discussions were structured using a multi-step plan. Students first completed individual readings and assignments outside of class. Students then worked in small groups to complete a new, more complex task. Finally, students shared the results of their small group activities with the class to foster discussion involving the entire class.

Structuring Effective Class Discussions in Undergraduate STEM Classes:

Examples from an introductory biology course

Instructors teaching undergraduate STEM (Science, Technology, Engineering, and Mathematics) courses face the difficult task of providing students with foundational knowledge spanning a number of intricate and complicated topics, while at the same time instilling in students a sense of motivation and intrigue in their learning. This is especially true for lower-level undergraduate courses (e.g., BIO101). The multitude and depth of topics that must be covered in a short period of time often results in STEM instructors relying heavily on lecture-based pedagogy. However, research has shown that STEM students learn best when instructors vary their pedagogical approaches and cultivate a learning environment conducive to promoting lifelong learning among students (Hodges, 2015).

Instructors teaching introductory biology courses (e.g., BIO101) face the difficult task of providing students with a knowledge base spanning a number of complicated and abstract biological processes (e.g., photosynthesis, cellular respiration, evolution, etc.). Because of the many difficult processes that must be covered during the course of a single semester, instructors are often tempted to focus solely on pedagogical approaches that allow them to fit the required course concepts into a semester's worth of class meetings. This attitude results in classrooms that are centered on lecture-based pedagogy, rather than pedagogical approaches that encourage active participation among students. Indeed, introductory biology courses have been criticized for encouraging students to perform rote memorization of a large number of biological facts and definitions picked up during lectures, while de-emphasizing the development of important scientific skills, such as critical thinking and communication skills acquired during active learning processes (Momsen et al., 2010; Kim et al., 2012).

The literature on the scholarship of teaching and learning is ripe with studies attesting to the efficacy of active learning in undergraduate STEM classrooms (e.g., Knight & Wood, 2005; O'Connor, 2013; Pai et al., 2015; Misseyanni et al., 2016). In particular, class discussions have been shown to be effective tools that address many of the pedagogical challenges of undergraduate STEM classrooms. Instead of emphasizing rote memorization, properly structured class discussions have been shown to foster critical and creative thinking among students in STEM courses (Kim et al., 2012; Lee, 2013; Hodges, 2015). Additionally, class discussions help instructors uncover and correct student misconceptions that would not surface during traditional lecture approaches (Tran et. al, 2014). Class discussions can also be used as an alternative to oral presentations to build "soft skills" including teamwork and effective communication.

While the use of class discussions in STEM courses is not in itself novel, relatively little attention has been given in the literature towards providing instructors with specific ways to structure discussions to maximize student preparation and engagement. Despite the obvious pedagogical advantages of discussions for STEM students, discussions can be difficult to structure in a manner conducive to student learning and participation (Michaelsen et al., 1997). Educators who have attempted to use class discussions unsuccessfully will likely be familiar with the "awkward silence" that often accompanies discussion activities (Boniecki & Moore, 2003; O'Connor, 2013). This silence represents the manifestation of two common phenomena in undergraduate classes. First, many shyer students are intimidated by the prospect of speaking their ideas and opinions in front of the entire class. While one of the major objectives of every class discussion is to encourage participation by everyone, one or a few students often dominate class discussions, reducing the rest of the class to the role of onlookers (Fassinger, 1995). Second, students often view discussion activities as a “free class”, for which they do not have to prepare. This leaves students with nothing of substance to share aloud when asked. Unprepared students have not taken the time to synthesize the information being discussed in a manner sufficient to develop sharable ideas and opinions, and thus either remain silent or steer the discussion on tangents (Michaelsen et al., 1997).

The goal of this report is to disseminate a novel method of structuring in-class discussions that helps alleviate the aforementioned shortcomings and create discussion atmospheres that are more fruitful and conducive to student engagement. To help correct the aforementioned problems when implementing class discussions, instructors must provide a defined framework for students to use in preparation for discussions. To encourage student participation, class discussions must first and foremost present engaging and interesting topics that link course materials with the interests of students. Interesting discussions topics are those that challenge and encourage students to build upon their previous knowledge (Michaelsen et al., 1997). This approach encourages students to apply course concepts to new situations, which is a foundational goal of all undergraduate STEM classes. Secondly, discussions must include (1) pre-discussion assignments to help students prepare for the discussion, (2) challenging in class assignments to encourage group collaboration, and (3) post-discussion reflection questions that help students conceptualize what was covered in the discussion and link the discussion materials back to course topics previously covered. This framework for class discussions encourages the participation of all students in the class, since every student will have to participate in some way. In this report I describe a series of discussion activities that were conducted using this model in an introductory biology class at a two-year, associate degree-granting college. The discussions presented were part of a larger subset of discussions carried out during a single semester course. The discussions help students expand on fundamental course concepts for introductory biology, including photosynthesis, the biology of viruses, evolution, and the molecular basis of life.

Class Demographics

The discussion activities presented in this report were conducted in the first course of the major's Biology sequence at a two-year, open enrollment college located in the Midwestern United States of America. Class sizes for the course were capped at 24 students. Although the activities described here were used in relatively small classes, the activities could easily be used in large-enrollment classes by creating more groups and through the assistance of teaching assistants.

Goals of Classroom Discussions

Each class discussion was designed around the seven core goals presented in Table 1. The goals were divided into three categories. "Concept-based" goals were set to develop a deeper understanding of the specific topic of the discussion (e.g., photosynthesis). "Soft-skill" goals were set to encourage the development of important skillsets for success in various scientific careers (e.g., communication skills). "Enjoyment" goals were set so that discussion activities provided students with a fun learning environment. These goals were not shared with the students.

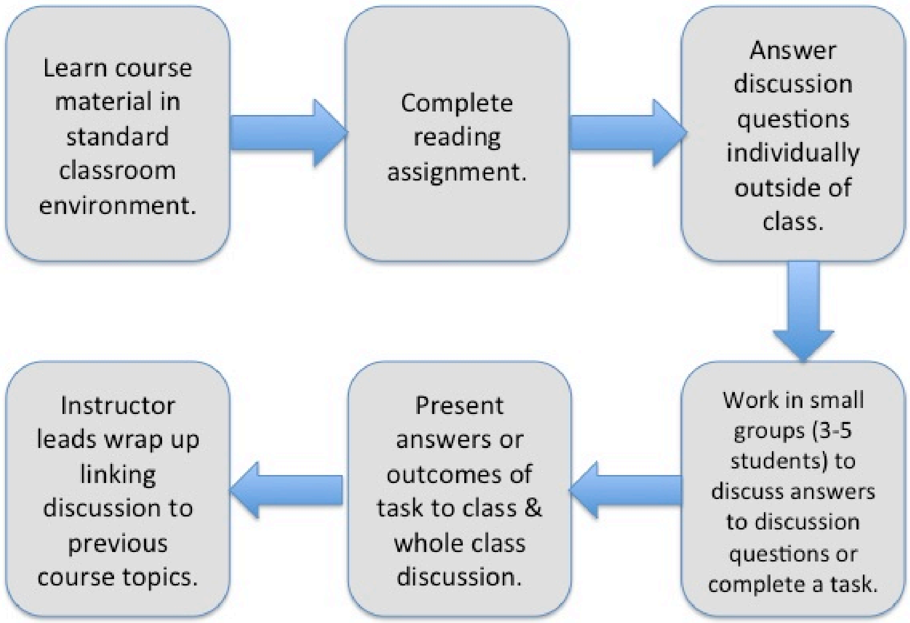
Table 1. Goals of Class Discussion Activities

Concept-Based Goals
1. Solidify and increase student understanding of important course concepts.
2. Apply course concepts to real life situations.
3. Uncover and correct student misconceptions of course concepts.
4. Encourage students to develop their own conceptions of course materials.
Soft-Skill Goals
5. Encourage the development of critical thinking, teamwork, and communication skills.
Enjoyment Goals
6. Increase student interest in the topics covered in class.
7. Encourage students to have fun in the learning process.

Pathway of Discussions

In order for class discussions to be worthwhile and engaging, students must possess sufficient background knowledge on the topic and enter the discussion prepared to participate. Additionally, many students tend to be actively engaged and participate in small group discussions but not in whole class discussions. Figure 1 shows the chronology of events used for each discussion conducted in order to encourage preparation and participation among all students in the class. This approach proved beneficial to the overall quality of the discussions because (1) it enticed participation by everyone in the class, including shy students, and (2) students came to the discussion with answers to discussion questions written out and ready to share.

Figure 1. Pathway of Successful STEM In-Class Discussions



Examples of Classroom Discussions for Introductory Biology Students

The following discussions were used, among others, during a semester long series of in class discussions. The discussion topics match those that were covered in class, but expand upon those topics to encourage critical and creative thinking among students. The goals of the discussion, student learning outcomes, background material given to students, preparation materials, and in-class activities are provided for each discussion example.

Figure 2. Discussion Example 1: The Atomic & Molecular Basis of Life

Discussion Goals: Have students apply their knowledge of the atomic and molecular basis of life to a new, novel problem.

Background Provided to Students: Students were provided the following prompt: "*Our first discussion will revolve around our conceptions of life on Earth, and will compare what we know about life on Earth at the atomic and molecular levels with what we think alien life will look like. Searching for extraterrestrial life has been a longstanding project for both government agencies and private citizens. Currently, the scientific search for alien life mainly consists of sending probes to other planets (such as Mars) and collecting environmental samples (soil, rocks, etc.) for analysis. These analyses focus on detecting compounds that are vital for all life on Earth, including water and amino acids. Thus, we are searching for the components of Earth life on other planets to determine if life could possibly exist on other planets. However, this raises the questions:*

- *Will alien life look like life on Earth?*
- *Will alien life be made of the same materials (atoms and molecules) as life on Earth?*"

Student Learning Outcomes:

1. List & describe major macromolecules that make up life on Earth.
2. Describe why carbon is used as the basis of all organic life on Earth.
3. Explain why water is vital to biological systems.
4. Explain the structure and function of nucleic acids.
5. Predict what life would look like on other planets by applying what you know about biological life on Earth.

Discussion Preparation: Preparatory activities were conducted outside of class for homework. Students read a short online article about current scientific theories of what alien life would look like, in which scientists give their opinions of alien life. Students prepared written answers to the following questions:

1. An Earth-like planet would likely be similar to the Earth in its composition of the atmosphere, have liquid water, and contain similar elements in nature. Do you think alien life can exist on planets that are not Earth-like? Explain why you believe so.
2. When searching for alien life, scientists almost always look for signs of liquid water on planets. Why do you think this is the case?
3. Do you think that life can exist on planets that do not have liquid water? Explain your answer.

In-Class Active Learning Activity: Working in groups of 3 – 5 individuals, students were asked to draw their conceptions of what alien life would look like. Once completed, students were asked to explain (1) if their alien was unicellar or multicellular and (2) the macromolecules that the alien is made of, including whether the alien used nucleic acids for its genetic information. Each group presented their drawing to the class using an overhead projector.

Figure 3. Discussion Example 2: Are Viruses Living Organisms?

Discussion Goals: The goal of this discussion is to introduce students to the ongoing debate among biologists regarding the classification of viruses as living or non-living. Students develop and articulate their own opinions based on the characteristics they believe make something "living."

Student Learning Outcomes:

1. Describe the characteristics that distinguish "living" organisms from "non-living" objects.
2. Describe why viruses are not currently classified as "living."
3. Articulate a scientific opinion and back it up with scientific evidence.

Background Provided to Students: Students learned the structural and functional differences between prokaryotic and eukaryotic cells in lecture. The instructor informed students that viruses are not currently classified as living organisms because they lack many of the characteristics that make something "living."

Discussion Preparation: Students complete a short online reading about how viruses alternate between infectious and dormant states depending on the availability of a suitable host. In preparation for the discussion, students answered the following preparatory questions on their own for homework:

1. What characteristics make something a "living" organism?
2. In your opinion, do you think viruses are living organisms? Defend your answer by explaining why you believe this.

In-Class Active Learning Activity: In groups of 3-5 individuals, students assembled a list of characteristics shared by all living organisms. A master list of all the defining characteristics was put onto the board at the front of the room. Students were then asked to work in their groups to determine the characteristics that viruses display (1) when they are dormant and (2) when they are infecting a host. These determinations were put onto the board for the entire class. The class was then polled to determine how many students classified (1) dormant viruses living and (2) infectious viruses living. Discussion of the student opinions was then conducted among the whole class. The instructor wrapped up the discussion by informing students that major scientific decisions, such as classifying viruses as living organisms, are made by groups of scientists who discuss the topic in a similar manner as conducted in this activity.

Figure 4. Discussion Example 3: Did Eukaryotes Arise From Endosymbiotic Prokaryotes?

Discussion Goals: This discussion explores the evolutionary relationships between prokaryotic and eukaryotic cells, and discusses the popular hypothesis that eukaryotic cells originated from symbiotic relationships between prokaryotic cells, in which one prokaryotic cell resided inside of another prokaryotic cell (i.e., endosymbiosis).

Student Learning Outcomes:

1. Describe the difference between prokaryotic and eukaryotic cells in regards to their structures and functions.
2. Evaluate a current scientific hypothesis and gather information to support or refute the hypothesis.

Background Provided to Students: Students learned the structure and function of prokaryotic cells, including how their genetic material is packaged into circular chromosomes. Students also learned the structure and function of eukaryotic cells and their organelles. Similarities between prokaryotic cells and eukaryotic organelles, such as the mitochondria, which contain circular DNA, were pointed out.

Discussion Preparation: Students completed a short online reading outlining the major evidence in support of the endosymbiosis hypothesis. The reading discussed the popular belief among biologists that the eukaryotic mitochondria and chloroplasts are descendants of once free-living prokaryotic cells that were engulfed by another prokaryotic cell. Students answered the following questions individually before class:

1. What evidence is presented in the article to support the idea that eukaryotic mitochondria originated from a symbiotic relationship between two prokaryotic cells?
2. What evidence is presented in the article to support the idea that chloroplasts in plant cells originated from a symbiotic relationship between two prokaryotic cells?
3. Can you think of any alternative explanations/hypotheses to explain how mitochondria or chloroplasts originated?

In-Class Active Learning Activity: Students discussed their answers to the discussion questions completed before class in small groups of 3 – 5 individuals. Students were asked to develop and articulate an alternative hypothesis to how eukaryotic cells originated. Students presented their evidence in support of the endosymbiosis hypothesis, as well as their alternative hypotheses, to the class.

Figure 5. Discussion Example 4: Terraforming Mars for Human Habitation

Discussion Goals: The goal of this discussion is to get students to conceptualize how photosynthesis has altered the composition of Earth's atmosphere enough to support animal (and thus human) life. Students were asked to use their knowledge of photosynthesis and atmospheric composition to help solve the current scientific problem of terraforming mars for human habitation.

Background Provided to Students: Students learned about the process of photosynthesis in class, with specific attention paid to the chemical basis of photosynthesis (e.g., converting inorganic CO_2 into organic molecules, releasing O_2 as a byproduct).

In-Class Active Learning Activity: After discussing their answers to the homework questions, students working in groups of 3 – 5 students were asked to develop a terraforming strategy for transforming the Martian atmosphere to permit human agriculture. Students drew their setup on paper and presented it to the class using an overhead projector. Students were specifically asked to address the following points in their plan:

1. What changes to the Martian atmosphere must be made to support agriculture?
2. What organisms will you start with? Would you start with plants, algae, microbes, etc.? Why?
3. How will you get enough liquid water to support photosynthesis?
4. Will you use a greenhouse or will you do open air development?

Student Learning Outcomes:

1. Explain the similarities between the early Earth atmosphere and the present day Mars atmosphere.
2. Explain how the process of photosynthesis has changed the composition of Earth's atmosphere allowing for animal life to exist.
3. Explain the atmospheric conditions needed for the growth of human agricultural plants.
4. Apply pre-existing knowledge to solving a complex scientific problem.

Discussion Preparation: Students completed an online reading about the terraforming of Mars. The reading specifically addressed (1) the similarities between the atmospheres of early Earth and current day Mars, (2) the role that photosynthesis has played in changing the composition of Earth's atmosphere, and (3) proposed ideas for the mechanisms of terraforming Mars. Students answered the following questions individually for homework before the discussion:

1. How does the current Martian atmosphere compare to that of present day Earth?
2. How does the Martian atmosphere compare to that of primitive Earth (before plants existed)?
3. What changes to the Martian atmosphere would need to be made for photosynthesis to occur at a level that would sustain human agriculture?
4. What Earth organisms, if any, could currently photosynthesize on Mars based on their biological and environmental needs?

Conclusions

The discussions presented here all followed the same chronology of events that aided in the success of the in-class portion of the discussions. By allowing students to adequately prepare for the discussion ahead of time, the actual in-class portions of the discussions were more fruitful and largely devoid of the “awkward silence” that is often associated with class discussions. Students were given time and encouragement to develop their own conceptions of the topic and formulate their own questions, which could then be shared with their discussion group and the class as a whole. One of the key components leading to success with discussion activities was having students work in small groups (3-5 students) on a task at the start of the in-class discussion. This allowed students to apply their background knowledge to new, complex situations, and encouraged shyer students to participate.

Student opinions of the class discussions presented in this report were qualitatively assessed through the analysis of post-semester student reviews of the course and informal conversations between the instructor and students throughout the semester. Post-semester reviews of this course over two separate semesters showed that many students viewed the discussion activities in a positive light. A number of students indicated that the discussions (1) were their favorite part of the course, (2) helped them learn the lecture topics better, and (3) increased their interest in the course topics. These positive reviews by students suggest that they enjoy class discussions and that the discussions can have positive impacts on their learning. This sentiment was echoed during informal conversations between students and the instructor of the course. One of the most positive outcomes of the discussions was the observation that the discussions would often be self-sustaining, with students interacting with each other by asking and answering their own questions with little need for guidance or steering from the instructor.

The efficacy of the discussions at enhancing student performance or knowledge-retention was not formally assessed. However, previous studies attest to the effectiveness of discussion activities in STEM courses for the development of critical thinking and other important skillsets for science majors (Kim et al., 2012; Lee, 2014; Pai et al., 2015). While outside the goals of this report, quantitative assessment of the effectiveness of these discussions is possible in the future by comparing assessment outcomes (e.g., exam grades, final grades, etc.) and critical thinking development between sections exposed to these discussion activities and sections taught using a traditional lecture-style pedagogy.

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