Modifying Scientific Research into Introductory Science Course Lessons Using a 5E Lesson Format: An Active Learning Approach

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Abstract

Science faculty are being asked to create active learning experiences that engage students in core concepts and science practices. This article describes an approach to developing active learning lessons from authentic science research projects using the 5E lesson format. Included is a description of the 5E's and a template for creating a 5E lesson. A description of the authors' scientific research and the resulting 5E lesson for an introductory biology course are provided as an example of this approach. In the lesson described, students collected, analyzed, and interpreted data to construct explanations about the potential for evolution to occur in response to climate change. This approach supported students in learning core concepts and science practices, and allowed the instructors to implement an active learning environment based on national science reforms. The results of this exploratory study and the rich descriptions of the lesson design should be used to raise awareness of one active-learning approach. Scientists can consider using this approach in their own teaching, and science education researchers can consider this approach in future comparative studies across various active-learning approaches.

Introduction

Science, technology, engineering, and mathematics (STEM) play a vital role in society (President's Council of Advisors on Science and Technology, 2012). Instructors at all levels are crucial in having a scientifically literate society and meeting the increased demand for students pursuing STEM careers. Most STEM instructors implement the form of instruction they received as students (Ball, 1990; Sakshaug & Wohlhuter, 2010), which in undergraduate STEM courses often consists of extensive lecturing (Hurtado, Eagan, Pryor, Whang, & Tran, 2012; Stains et al., 2018).

Instead of extensive lecturing, undergraduate science courses should engage students in learning science through active-learning (Freeman et al., 2014). Two documents have specific suggestions for how this instruction should be enacted: the *Next Generation of Science Standards* (*NGSS*) (NGSS Lead States, 2013) and *Vision and Change* (American Association for the Advancement of Science [AAAS], 2011).

Both documents challenge science faculty to create learning experiences that engage students in both core concepts and science practices. Learning core concepts should occur through participation in the practices of science. According to the *NGSS* (NGSS Lead States, 2013), these practices include asking questions, conducting experiments, testing hypotheses, analyzing data, constructing explanations, and using models.

This paper describes our attempt to turn our scientific research, focused on evolution and climate change, into a learning experience aligned with *Vision and Change* (AAAS, 2011) and the *NGSS* (NGSS Lead States, 2013). Framing our instruction was the 5E lesson format (Bybee et al., 2006) that is widely used in K-12 science teaching and is emerging in undergraduate science instruction (Sickel, Witzig, Vanmali, & Abell, 2013). This paper will enable other scientists to consider one way to implement active-learning through the 5E model. This paper also will provide the foundation for future comparative studies of this model of instruction to other forms of active-learning through rich descriptions of the lesson.

The Pedagogy

It is well documented that active-learning increases student performance when compared to traditional lecturing in undergraduate STEM courses (Freeman et al., 2014). Active-learning was defined as:

> "engaging students in the process of learning through activities and/or discussion in class, as opposed to passively listening to an expert. It emphasizes higher-order thinking and often involves group work." (Freeman et al., 2014, p. 8413-8414).

Active-learning can vary widely in intensity and implementation. Erol et al. (2015) describe a range of active-learning from entry level techniques (e.g., clickers) to more advanced techniques (e.g., flipped classrooms and case-studies).

Freeman et al. (2014) argued that studies comparing various kinds of active-learning to traditional lecturing represented the "first-generation" of research in this field (p. 8413). They also argued it is time for "second-generation" research that moves beyond comparisons to traditional lecturing (p. 8413). Instead studies should evaluate what aspects of active-learning are most effective at promoting student learning. For example, Jensen, Kummer, and Godoy (2015) compared an active flipped classroom to an active non-flipped classroom. The authors used the 5E model to design both courses. Results indicated equivalent student learning outcomes in both courses.

The purpose of this paper is to describe how the authors used the 5E model to modify our scientific research into a classroom investigation. We did not compare this approach to traditional lecturing as results in the literature are overwhelming that active-learning better supports student performance than extensive lecturing (Freeman et al., 2014). A quasi-experimental design comparing the 5E approach described here to another active-learning approach was beyond the scope of this study. The results of this exploratory study and the rich descriptions of the lesson design should be used to raise awareness of one active-learning approach. Instructors can consider using this approach in their own teaching, and science education researchers can consider this approach in future second-generation active-learning studies.

The Science

Understanding the impact of climate change on organisms is important, and constitutes a portion of our scientific research. Beyond increases in global mean temperatures, climate change is expected to result in more frequent extreme weather events (Easterling et al., 2000; Vasseur et al., 2014; Williams, Henry, & Sinclair, 2015). These events include snap-freezes, in which local temperatures rapidly shift from warm to cold. Snap-freezes are well known for their impact on crops, but they also have major effects on ectothermic animals, such as insects, lizards, and turtles. Insect populations are critical in many ecosystems, and their fluctuations during stressful temperatures will affect these ecosystems (Scheffers et al., 2016).

Our research focuses on chill coma recovery time, a genetically controlled trait relevant to snap-freezes, in the fly *Drosophila melanogaster* (MacKay et al., 2012; Williams et al., 2014; 2016). An effect of cold temperatures on *Drosophila*, and many ectotherms, is an induced state of narcosis known as ‘chill coma’ (Gibert, Moreteau, Pétavy, Karan, & David, 2001). Chill coma recovery time is the time it takes an organism to return from an inactive state to an active state. This is often measured by recording when the insect regains the ability to stand on all six legs.

The organisms used in our research were a series of lines from the *Drosophila* Genetic Reference Panel (DGRP) (Mackay et al., 2012). Almost 200 genetically distinct lines were created by inbreeding females captured from a wild population in Raleigh, North Carolina. Inbreeding removes genetic variation within each line so each line represents a single genotype. Together, the lines represent a sample of the standing genetic and phenotypic variation in the wild population. By investigating this sample we can characterize the genetic and physiological mechanisms underlying climate-relevant traits (MacKay et al., 2012; Williams et al., 2014; 2016).

A secondary science curriculum was initially designed based on this research (Broo & Mahoney, 2017; Broo, Mahoney, Bokor, & Hahn, 2018). This research was further modified into a 5E lesson for an undergraduate biology course for preservice teachers. In the lesson, students recorded and analyzed chill coma recovery times of multiple lines of genetically distinct *Drosophila* flies. Students explored how some lines handle snap-freezes better than others, and predicted how this population could respond via natural selection to climate change.

Lesson Design

The lesson was designed using the template found in Figure 1. The 5E lesson plan template was created to support undergraduate STEM instructors' implementation of active-learning. The first box in the template provides space to describe the concept(s) targeted in the lesson. In this investigation the concept was the potential evolutionary impact of climate change on ectotherms.

SUMMARY OF INVESTIGATION (FOCUS ON PHENOMENA)				
NGSS Disciplinary Core Ideas: Science and Engineering Practices: Crosscutting Concepts:		VISION and CHANGE Core Concept: Core Competency:		
ENGAGE (Describe activity that engages students and elicits prior knowledge)	EXPLORE (Describe activity within which current concepts, processes, and skills are identified and conceptual change is facilitated through generating new ideas, exploring questions, and designing and conducting an investigation)	EXPLAIN (Describe how a concept, process, or skill is directly introduced by the instructor or other resources to guide learners toward a deeper understanding)	ELABORATE (Describe how students will apply their understanding of the concept through additional activities)	EVALUATE (Describe the evaluation of student progress toward achieving the learning outcomes)
REFLECTION ABOUT THE INVESTIGATION (After the lesson, reflect on the enactment of the lesson and record evidence regarding student performance)				

Figure 1. Template for the development of an inquiry-based investigation in a life science course using the 5E model.

The next two boxes provide space for instructors to list the learning objectives of the lesson. This lesson aligned with the *NGSS* performance expectations in evolution and ecology, and engaged students in the *NGSS* science practices of carrying out investigations, analyzing and interpreting data, and constructing explanations. From *Vision and Change* (AAAS, 2011), the lesson spanned two core concepts: evolution and systems. Within evolution, the lesson emphasized genetic variation and natural selection. Within systems, the lesson emphasized the dynamic interactions of components in a system.

The *NGSS* can be utilized by faculty across science disciplines. The *NGSS* include interdisciplinary science and engineering practices and cross-cutting concepts, and include disciplinary core ideas in physical science, life science, and Earth and space science. *Vision and Change* (AAAS, 2011) focuses on core competencies in biology. Faculty in other disciplines can substitute the box for *Vision and Change* with core competencies in their discipline. For example, the American Chemical Society provides conceptual topics and practical tools students should know.

The entire lesson was placed in a 5E Format (Table 1). Throughout the 5E lesson students interacted with each other and the instructor. These interactions allowed students to exchange their unique perspectives, promoted collaborative learning, and served as a formative assessment for instructors to evaluate students' understandings and guide instruction (e.g. McDonald, 2016). The third row of boxes in Figure 1 was designed for instructors to describe the activities planned to engage students in each of the 5E's.

The instructor evaluated the lesson by interacting with students throughout the lesson. Both during and after the lesson, the instructor reflected on the lesson and recorded student performance. The last box in the template in Figure 1 was designed for instructors to record these reflections. For instance, after class the instructor could note areas in which additional instruction might be useful, or instructors could identify concepts that students grasped easily.

Table 1. The 5E's (Bybee, 2014).

Engagement	The teacher or a curriculum task helps students become engaged in a new concept through the use of short activities that promote curiosity and elicit prior knowledge. The activity should make connections between past and present learning experiences, expose prior conceptions, and organize students' thinking toward the learning outcomes of current activities.
Exploration	Exploration experiences provide students with a common base of activities within which current concepts (i.e., misconceptions), processes, and skills are identified and conceptual change is facilitated. Learners may complete lab activities that help them use prior knowledge to generate new ideas, explore questions, and design and conduct an investigation.
Explanation	The explanation phase focuses students' attention on a particular aspect of their engagement and exploration experiences and provides opportunities to demonstrate their conceptual understanding, process skills, or behaviors. In this phase teachers directly introduce a concept, process, or skill. An explanation from the teacher or other resources may guide learners toward a deeper understanding, which is a critical part of this phase.
Elaboration	Teachers challenge and extend students' conceptual understanding and skills. Through new experiences, the students develop deeper and broader understanding, more information, and adequate skills. Students apply their understanding of the concept and abilities by conducting additional activities.
Evaluation	The evaluation phase encourages students to assess their understanding and abilities and allows teachers to evaluate student progress toward achieving the learning outcomes.

Enacting the Lesson

Below we describe the enactment of our 5E lesson. First, we describe the context of the course in which the lesson was enacted. Then, we describe the enactment of each of the 5E's.

The students and the class

The lesson was implemented in an undergraduate general biology class for preservice teachers. The class met once a week for three hours in a standard classroom without laboratory space. Lessons in the class had minimal lecturing. Instead, students regularly worked in pairs or small groups and presented their emerging conclusions to the class for further discussion.

Eight of the 11 students in the course were pursuing a Bachelor of Science in Education (BSEd), and three students were completing a Master of Education (MEd) in Science Education degree. Students' experiences with post-secondary science content courses were similar to many non-science majors and included minimal science courses beyond general education requirements. Ten of the students were female, and one was male.

The 5E Lesson

Engage. Prior to the investigation students completed a concept sketch of how changes in climate affect various organisms to elicit students' prior knowledge (see problem 1 in Figure 2). The concept sketch process can be used as a formative assessment to evaluate the content knowledge of undergraduates (Johnson & Reynolds, 2005). The sketch included a plant, an ectotherm, and a mammal from a single food web. This formative assessment elicited students' preconceptions of how organisms are connected in ecosystems, and how environmental change (e.g., climate change) can impact populations within ecosystems.

The instructor then introduced students to the DGRP lines and the concept of snap-freezes through the 'think-pair-share' approach. Discussions centered on a series of questions that built on the formative assessment in Figure 2. Questions included: “How does temperature affect organisms?”, “What impacts would a changing climate have on organisms?”, and “What are ways in which organisms can respond to climate change?” Students first individually wrote their ideas in their lab notebooks, then students discussed their answers in small groups, and finally students shared their answers in a whole class discussion. The instructor used follow-up questions to push students thinking, and had several slides prepared to introduce students to content with which they were unfamiliar, such as snap-freezes.

(Insert Figure 2 about here)

In this study, students’ initial ideas about climate change were limited to increases in mean temperatures. Students’ initial ideas about the impacts of climate change on organisms were limited to effects on individual organisms. Students did not consider how impacts on one organism would affect others until prompted with follow-up questions.

Explore. Next, students were introduced to the chill coma assay (Denlinger & Lee, 2010). In preparing for the investigation, six genetically distinct lines of *Drosophila* from the DGRP were obtained from Daniel A. Hahn’s research group. Three lines consisted of cold-resistant flies (25186:DGRP-360, 25198:DGRP-555, and 28178:DGRP-356) with faster chill coma recovery times (averaging approximately eight minutes), and three lines consisted of cold-susceptible flies (28253:DGRP-861, 28254:DGRP-879, and 28260:DGRP-897) with slower chill coma recovery times (averaging approximately 20 minutes). These lines are publicly available for order from the Bloomington *Drosophila* Stock Center at the University of Indiana (http://flystocks.bio.indiana.edu).

For each of the six fly lines, vials were prepared containing approximately 20 flies. Enough vials were prepared so each pair of students could measure chill coma recovery times of a vial of cold-susceptible flies and a vial of cold-resistant flies. Three hours prior to the investigation the vials of flies were placed in an ice bath (0 °C) to induce chill coma. For more details on the assay see Broo and Mahoney (2017).

At the start of the investigation *Drosophila* were transferred from vials to petri dishes to measure chill coma recovery times. Students recorded in seconds the time it took each fly to stand on all six legs in their course notebooks. Following data collection each student pair entered their data into a single Excel spreadsheet for the whole class to use during data analysis. This resulted in a pooled data set of approximately 40 flies in each of the six fly lines. The mean and standard deviation were calculated for each line.

Explain. Students used the class data to make inferences about variation in chill coma recovery time across fly lines. In a follow-up class discussion, students were asked about the potential for this population of flies to adapt to climate change through selection for faster chill-coma recovery.

One ideal conclusion reached by the students was that climate change (e.g., increased frequency of snap-freezes) could lead to directional selection in genetically diverse populations. Selection would favor advantageous traits (e.g., fast recovery time). Class discussion on student data led to the construction of the following inference: "Flies from line A had faster recovery times than flies from line C. Because flies are projected to experience cold snaps more often in the future under climate change, flies from line A will survive and reproduce more frequently than flies from line C. This will lead to selection for the alleles represented in line A over those alleles represented in line C in this population over time".

Elaborate. In the elaboration phase of the lesson, students extended their understanding to a more complex system with plants, ectotherms, and endotherms. Students were given data from studies on oak trees (*Quercus robur)*, winter moths (*Opheroptera brumata)* that feed on the new oak leaves, and birds, the great tits (*Parus major)*, that feed on winter moths (Visser, Van Noordwijk, Tinbergen, & Lessells, 1998). Students observed increasing differences between the date great tits laid their eggs and the date winter moth caterpillars peaked over time. This challenged students to apply the lessons learned from the investigation to a new and more complex context. Students considered how organisms can respond to climate change at different rates and that natural selection can act on some populations more rapidly than others. For example, one student described, "Changes in one organism can affect others. If insects died from an extreme cold snap, they would not be able to pollinate plants leading to less food for herbivores and omnivores."

Evaluate. A week following the investigation, students were asked to again sketch or describe ways in which climate change impacts various organisms in ecosystems (Figure 2, Problem 1), and to explain their answers. In addition, students were asked a more direct question assessing their understanding of the chill coma investigation (Figure 2, Problem 2). Students were asked to predict what would happen in the population of *Drosophila* that was investigated if extreme cold events occurred frequently over a 10-year period. This question assessed the degree to which students understood that climate change could result in directional selection over time for advantageous genetically controlled traits and selection against unfavorable genetically controlled traits.

Exemplary responses included:

> "Organisms with traits that confer an advantage in response to environmental pressures survive and reproduce more frequently than those with less favorable traits".

> "It appears that it would be advantageous to be a fly from a strain that recovers most rapidly. Lines A and B will survive more than lines C, D, E, and F because they have shorter chill coma recovery times".

(Insert Figure 3 about here)

While not all students' responses reflected sophisticated understandings of evolution and ecology, all students demonstrated progress during the lesson. Students' final concept sketches built on their initial sketches in several important ways (Figure 3). In their original drawings, students generally focused on how individual organisms are affected by warmer temperatures. Students did not initially recognize how these effects could disrupt the interactions among other organisms within the same ecosystem or consider environmental effects of climate change other than increased mean temperatures (e.g., cold snaps). In the final concept sketch, all students recognized multiple effects of climate change and described how the responses to climate change in one organism can affect other organisms. For example, one student stated, "Endotherms and ectotherms respond differently to temperature changes." All students noted that different responses to climate change among interacting organisms could potentially disrupt ecosystems. As one student stated, "If one organisms falls out of the system, the system can crash."

Discussion

We developed this lesson in response to the calls for science experiences that require students to collect and analyze data to understand important concepts in science (AAAS, 2011; NGSS Lead States, 2013). The lesson was based on our scientific research and highlights one impact of climate change that can affect ectotherms. It is important that scientists continue to consider how to present their research in ways that are accessible to students.

This model of instruction engages students as active participants and promotes students' learning (Freeman et al., 2014). Several different types of interactions contributed to the learning process. To begin with, the instructor elicited the students' prior knowledge through formative assessment. The instructor also interacted with the students as they generated explanations from their data, allowing the instructor to point out important trends that students may have overlooked or misinterpreted. Finally, students interacted with one another about their emerging ideas throughout the lesson.

The lesson planning template was essential for helping the instructor move beyond traditional instruction and implement the 5E's. Reform-based instruction is difficult to implement even for experienced instructors. The template provided here can be used to guide lesson planning at the undergraduate level to engage students in science content and science practices.

Reform-based instruction is especially important for undergraduate science courses that enroll preservice teachers. Beyond promoting the conceptual development of science content knowledge for all undergraduate students, this approach models effective instruction preservice teachers can later implement in their own teaching. It is important to engage preservice teachers in science practices and active-learning in science content courses because teachers will generally teach in the ways they were taught (Ball, 1990; Sakshaug & Wohlhuter, 2010). Ultimately, active-learning benefits future teachers and their students by demonstrating how to learn science through engagement in science practices.

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Figure 2. Assessment of student understanding of natural selection in response to climate change. Students first completed problem 1 in the engage and evaluate portion of the lesson. A week following the lesson, students took an exam that included both problems 1 and 2.

Figure 3. A student's initial (top) and final (bottom) concept sketches. This student initially considered how a berry plant and bear would individually be affected by increased temperatures, but recognized the bees might be affected by the death of plants (though not acknowledging any direct effects of climate change on bees). In the final sketch the student recognized varying intensities of climate effects and the interactions among organisms within an ecosystem.