Using Problem-Based Learning to Deliver a More Authentic Experience in Paleontology

Homer Montgomery[1,a] and Katherine Donaldson[1]

ABSTRACT

This study is a research project focused on the implementation of problem-based learning in an honors, paleontology-oriented, Earth Science course. The course, the Age of Dinosaurs, is taught at the University of Texas at Dallas to undergraduates from a range of majors who seek core-curriculum science credit. All class work is centered on fossils and rock samples selected from a research collection accumulated from dinosaur-bearing beds in the Chihuahuan Desert of West Texas. A list of goals for the course was prepared during the design phase for the class. This list was used as a Likert scale questionnaire following completion of the course and dissemination of grades. Results from the goals questionnaire and from the official course evaluations present highly favorable responses to the course and to the problem-based learning methodology. Students provided free-response assessments and advice that influenced the next offering of this course. © *2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-085.1]

Key words: problem-based learning, paleontology, paleoecology, honors

INTRODUCTION

Scientists are natural, problem-based learners, intuitively functioning within a problem-based learning (PBL) process. They continually contemplate poorly defined, open-ended questions that must be answered to specific standards. They frequently establish associations with colleagues to gather and consider diverse ideas. These researchers set expectations, perform authentic (real-world) experiments, maintain rigor, evaluate findings, write up results, create presentations, and present final products. We would argue that this process is not the typical expectation for students in the usual college science class.

During the fall semester of 2012, the class of 20 students in the Collegium V (CV) Honors program met for a 75-min class twice each week. The philosophy of the CV program at the University of Texas at Dallas is as follows (Collegium V, 2013):

- To respond to the academic needs of our most outstanding and academically ambitious students
- To offer creative, challenging honors instruction that enriches the learning experience for both students and faculty by emphasizing interdisciplinarity
- To promote and facilitate closer, more productive interaction among students and faculty
- To nurture the highest level and quality of intellectual conversation on campus
- To promote undergraduate scholarship and research across all disciplines of the university

COURSE DESCRIPTION: AGE OF DINOSAURS

Age of Dinosaurs (AoD) at the University of Texas at Dallas is an introductory course that focuses on student engagement with the anatomy, physiology, ecology, and evolution of dinosaurs and aquatic and aerial reptiles, invertebrates, plants, and ichnofossils, as well as Mesozoic climates and basic Earth history of the age of dinosaurs. Introductory physical geology topics are addressed, as students are responsible for identifying enclosing rocks and for producing reasonable, but not particularly sophisticated, sedimentological interpretations. Each class provides an encounter with Mesozoic fossils and rocks from the research collections of Montgomery and colleagues at excavations near Terlingua in the Big Bend region of Texas. Approximately 90 fossils and 10 rock specimens are the basis for class exploration, discovery, and study.

AoD was taught during the fall semester of 2012 and was taught again in the spring of 2014. The instructors' experiences with PBL within the UTeach program (Montgomery is codirector of UTeach Dallas, and Donaldson is a UTeach Dallas master teacher) provided both the effective methodology and extensive experience that are necessary to achieve better comprehension and to meet problem-solving goals than had been the case with traditional lecture/laboratory classes.

AoD is an experiment into best educational practice. The curriculum is fundamentally a set of problems designed to address components that are typical of courses in paleontology, Earth history, and physical geology. The AoD process involves becoming proficient at problem solving while practicing self-directed learning in a group setting, a process described by Barrows and Kelson (1993). Learning is clearly oriented toward depth of understanding rather than simple breadth of knowledge. Much of the theoretical underpinning for educational practices in AoD was developed in Montgomery's Basis of Evolution class and in Donaldson's PBL course. (The AoD experience mostly substitutes fossils from which concepts must be derived for the theoretical examples in Basis of Evolution. It also draws from teaching practitioner training, which is an important component in PBL.)

PBL methodology offers an innovative approach to teaching Earth Science for mostly nonmajors—in this case, to honors undergraduates. Specimen identification and interpretation within each group followed by presentation

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[1]Science and Mathematics Education, FN33, The University of Texas at Dallas, 800 W. Campbell Road, Richardson, Texas 75080, USA
[a]Author to whom correspondence should be addressed. Electronic mail: mont@utdallas.edu. Tel.: 469-951-8110. Fax: 972-883-6796

of results and formal write-ups were the standard weekly activities. Questionnaire results support our claim that this course approximates the field/laboratory experience of some Earth scientists, particularly field-oriented paleoecologists and paleontologists.

RESEARCH OBJECTIVE

Our research objective was to determine the effectiveness of this AoD course in producing a practical, integrated framework in which students have meaningful learning experiences and achieve expected learning outcomes.

PBL APPROACH

The PBL approach to education is a constructivist methodology that is recognized for its successes in promoting comprehension and developing problem-solving skills in a range of subjects across the education spectrum (Boss, 2011). We found such successes increasingly difficult to achieve in our undergraduate course offerings, even with honors students. The time for a methodology rethink was at hand. PBL methodology is not widespread in undergraduate science courses (for an overview, see Charlton-Perez, 2013). The AoD course is our first experiment at the University of Texas at Dallas in producing a core-curriculum, PBL science offering for mostly non–Earth Science majors.

PBL is differentiated from project-based learning by a consideration of initial instructions. In PBL, a problem is outlined that must be addressed. In AoD, such a problem is put forward. Students work in groups over a period of time to provide solutions to this problem. In project-based learning, a specific problem may or may not be addressed. Otherwise, much of the same methodology as described by Markham et al. (2003) is employed.

COURSE DESIGN

Expected Learning Outcomes

Course objectives for AoD as stated in the syllabus are as follows:

1. Students will be familiar with evolutionary history of numerous Mesozoic fossils.
2. Students will have a basic understanding of Mesozoic geology and paleoecology.
3. Students will evaluate fossils from several of our dinosaur sites in west Texas using criteria presented in the class and in primary sources.
4. Students will apply their learning and understanding to real-world research projects.
5. Students will produce an original research project of extraordinary quality.

This course is fundamentally concerned with promoting and developing problem-solving skills both in the individual student and in students functioning in groups. The intent of this course is not for students to gain the breadth of experience with diverse fossils and rocks that can be attained in excellent, undergraduate classes or an understanding of all of the numerous concepts required in physical geology courses. Students did, however, have meaningful, research-driven experiences with fundamental concepts that were developed within a practical, integrated framework. We would also argue that a semester of intensive research produced students who have great depth of knowledge and, as the occasion demands, who will efficiently seek answers from reliable sources to widen their depth of understanding.

The course promoted expertise in collaborative learning. Much of the value of collaborative learning is the required use of oral language to put thinking into words. This process refines the student's thinking, which becomes more clarified, and the cognitive load for the writing/presenting component is lightened. The progression we seek to exercise and to make more efficient is a recursive process among thinking, language, and writing.

No attempt was made to test the students with questions from standard Earth Science courses for two reasons. First, we were less interested in whether the students gained a breadth of specific knowledge than we were focused on problem solving. It was clear that when the members of one group excelled in stratigraphic minutiae, students in another group became experts in anatomy. Thus, expertise was highly diverse within an overall framework of Earth history, paleontology, paleoecology, and so forth. Using group work, paired with a presentation format, allowed all students access to the specific knowledge constructed by each team. Granting students a significant measure of control (choice) for what they are learning has been shown to promote self-confidence and responsibility (Glynn and Koballa, 2006). Postcollaboration presentation discussions and questions deepened and broadened their learning.

Second, we were interested in whether an experiment, wherein students must operate within an authentic research realm, would be seen as successful by both students and faculty. One semester's course could be compared to the next in a qualitative way, but an attempt at quantitative comparison might prove difficult to interpret because of the shifting composition of the specimen collections and the somewhat unpredictable choices by the students for the details that they choose to study and the questions they choose to answer.

Class Structure

The immediate task during the first class of each week is for students to determine what has been discovered. Students were presented with a box or bag containing fossils ostensibly recovered during the past week at the site. By the end of this first class, students had identified the fossils (sometimes with a good bit of instructor assistance) and were beginning to discern how the fossils fit into the jigsaw of Mesozoic life and Earth history. We felt confident that once students at least had the identifications correct, they could effectively pursue their research. Based on conversations during the semester, we estimated that students spent at least 2 h each week seeking online, peer-reviewed references. Assembling the weekly analysis and updating the overall reconstruction required an additional 2 to 4 h of work, much of it conducted in collaboration with other group members.

As this recursive process continues and as the students near the end of the course, a dynamic and detailed paleontological and paleoecological reconstruction emerges. All students engage in probing discussions, activities, and presentations as they encounter numerous controversial topics such as behavior, biomechanics, homeothermy, soft tissue preservation, origin of birds, and extinction and as they complete weekly assignments about their discoveries. Final presentations consist of detailed, research-based interpretations using mostly fossil data to reconstruct the AoD in West Texas. The production of highly creative presentations is encouraged.

As is common in PBL classes, lectures are limited and are driven by student needs (Fyrenius et al., 2005). In AoD, lectures now persist no longer than a few minutes. These minilessons occur mostly when more than a couple of students require clarification or direction. Demonstrations, hands-on activities, short video clips, and whatever explanatory methods emerge as needed accompany these brief lessons. These teachable moments are referred to as workshops, and they combine with student research and group discussion to replace lecture as the main means of gaining information in the class. Early in the semester, a discussion about effective research strategies is a priority. Students conduct a great deal of research both in and out of class.

The open framework and self-directed nature of the course might be expected to lead to opportunities for less motivated students to participate in only a peripheral way. This has proven not to be the case for our honors courses, but preliminary and limited experiments with PBL in nonhonors courses suggest that effective measures must be devised for some of the less-motivated students. Each student has a responsibility to attend class and to be prepared. Course requirements are mostly self-policing, as a flurry of new specimens appears each week and are only available in class. Our impression, based on personal observations and on interviews with students, is that peer pressure and peer evaluations (which can influence a student's grade) that are carried out within a group contract framework are also effective motivators.

PBL Elements

PBL methodology is variable depending on the literature consulted, but for the purpose in this class, the *Project-Based Learning Handbook* (Markham et al., 2003) served as a guide. Modifications are derived from several years of collective experience with PBL methodology. The following sections describe major components one usually finds in a PBL course such as this.

Anchor Video and Entry Event

The first class of the semester begins with an anchor video to engage students in believable scenarios that present complex problem-solving opportunities (Kumar, 2013). The key is to elicit engagement rather than apprehension at the prospect of studying so much unfamiliar material. In the video, students learn that the Big Bend of Texas is an extraordinary window into life at the end of the Cretaceous Period soon after dinosaurs populated the coastline of the retreating Interior Seaway. Most of the rapidly moving, 3-min presentation showcases our discoveries with faculty and students working at our sites. The penultimate slide is the typical PBL entry document, and it prompts, "Obviously this was a very different world. How so?" The final slide presents marching orders, "You and your peers will work with many fossils in your new jobs as professional rangers in Big Bend National Park. You will be expected to present inspired observations and interpretations of recently discovered fossils. The director of the U.S. National Parks and a team of scientists will be visiting in three months. They will expect a detailed accounting and interpretation of this unique resource."

The video sets the scenario within which investigations will occur—in this case, various fossil sites. It also presents the expectation that much research into the appropriate literature will occur. Some students immediately appreciate the benefit of prior knowledge, especially those who have had Earth Science, organismal biology, or botany courses. Others seem lost at this early point, a condition that rapidly lessens as students have the opportunity for discussion and fossil analysis in their groups.

Driving Question

A driving question is the prompt for students to begin their work. Crafting an essential question is not trivial (Wiggins and McTighe, 2006). It helps the instructor focus the inquiry, and it must both interest and guide the students. The question must be open ended, complex, and challenging. Driving questions typically promote multiple approaches to problems (sometimes in several disciplines), all of which are subject to numerous detours. This question requires authentic artifacts such as research evidence presented at a professional meeting. It must be aligned with a professor's instructional objectives. Finally, a good driving question is provocative. Following much discussion, the driving question for AoD in the fall of 2012 was, "How can I characterize the Cretaceous ecology of the Big Bend using these extinct organisms as my guide?" This driving question, or thesis, conveyed a sense of purpose. It was provocative, stealthily complex, and, perhaps most importantly, correlated directly with the goals of this course.

Perhaps such a question sounds too simple or, at least, perfectly straightforward. It was not. The immediate response from students could be expressed as, "No big deal." Fifteen minutes later, that collective opinion changed considerably as the students began to appreciate the expanse of a seemingly trivial question. Members of each group were digging into the literature. A queue formed. Students disappointedly learned that the instructor in a PBL course is only one source of knowledge. That instructor is also prone to asking additional questions rather than simply presenting answers. Using questioning as inquiry is certainly considered best practice (Blosser, 1990). As instructors, we believe that properly managed chaos can be constructive. The first group to respond attempted to work out a concept map using Cmap software (Cmap, 2013). This was an excellent, and unprompted, approach by the group to establish correlations among fossil elements and tenuously understood processes (taphonomy, sedimentology, etc.). Others groups soon decided that Cmap constructions were useful tools for analyzing paleoecological relationships such as this tentative one for the Aguja Formation (Fig. 1). Concept map reconstructions always vary in completeness and accuracy, and all provide numerous seeds for questions.

Following several minutes of animated discussion in their groups, the students produced a lightly coached, collective protocol deciding that they must first identify as many of the specimens as they could. Next, and to the best of their ability, they would determine the ages of key fossils, followed by environmental characteristic of most taxa, and

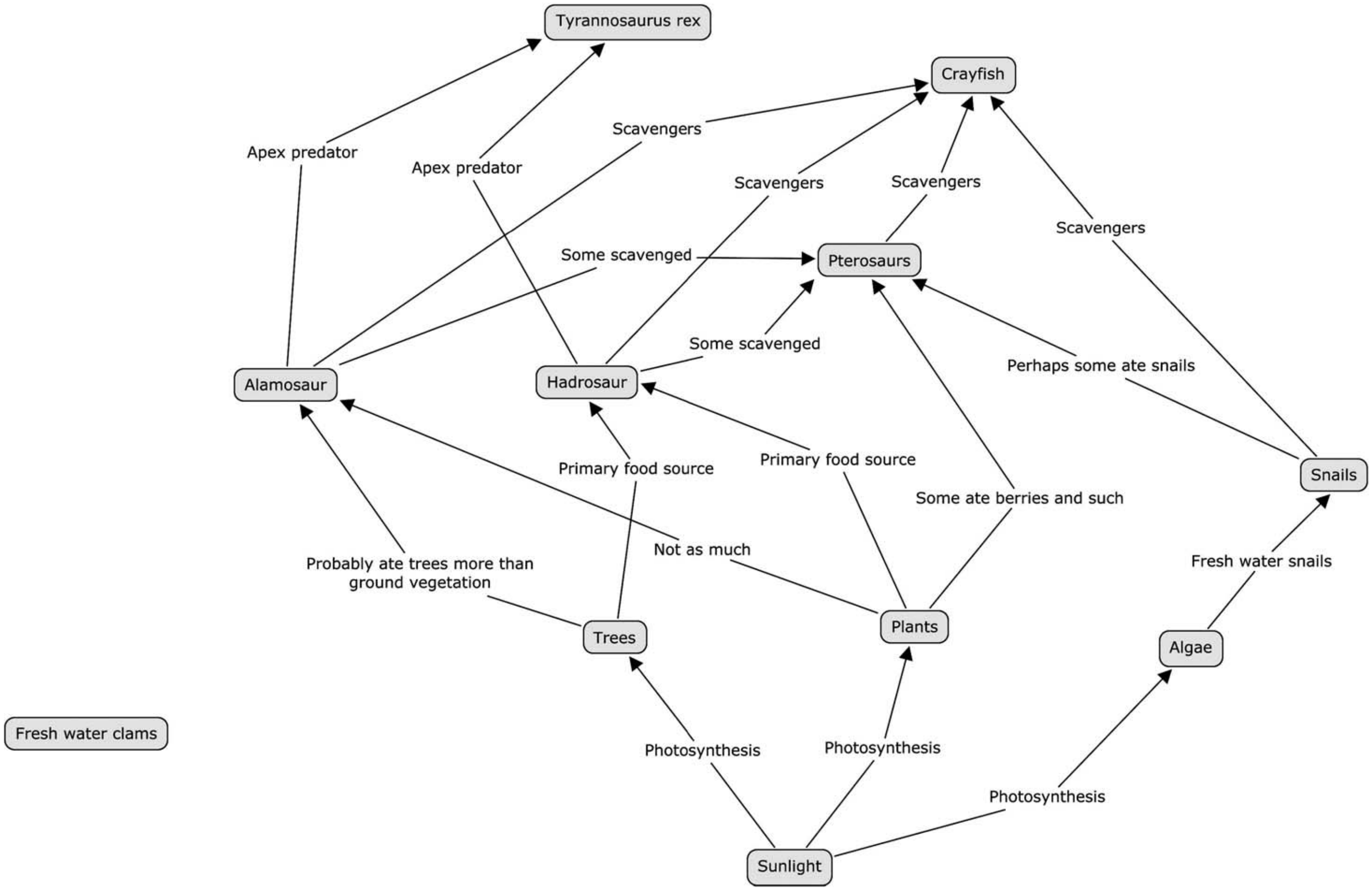

FIGURE 1: Student-generated Cmap food web reconstruction of the Javelina Formation.

then construct a paleoecological scenario that included food webs. Students also soon learned that initial identifications and assumptions can be wrong and that they must integrate all of their "discoveries" into a continuously evolving "answer."

Knows and Need-to-Knows

Students begin each week by listing what they know and what they think they will need to know. Students are required to be metacognitive. This process is as fundamental as it sounds. For the first cut, students frequently produce a list of knows that includes placing new specimens in an ever-improving stratigraphic column in the horizon from which it was collected and recording whether the fossil was discovered *in situ*. Noting fossil condition (bite marks, abrasion, etc.) usually follows. In the need-to-know category, identification is usually primary, followed by paleoenvironment association and other puzzles such as an organism's role in a food web. Online research persists throughout the semester, as students convert need-to-knows into knows. Students effectively explore as many facets as time permits.

Student Work

During the discovery of new fossils in the first class of the week, each group of four or five runs through the knows and need-to-knows, organizes tasks to accomplish, and divides the work among themselves. Even though there is a self-organized division of labor, each member participates in some facet of all of the work. By the end of the period, each group must draft a rough outline of a credible presentation for the upcoming Thursday. During the following class, we see groups working out final details and individuals preparing to present their presentations.

Fossils Presented to the Class

The fossils (Table I) are almost all research specimens from our various research sites. A detailed list is presented to demonstrate the diversity and difficulty of the specimens. Many are presented with rock matrix either adhering to or in a separate bag tied to the specimen. Outcrop B is from the uppermost Boquillas Formation, the oldest unit in this section. It contains a spectacular selection of giant *Platyceramus* encrusted (puzzlingly) on both valves with *Pseudoperna congesta* (Montgomery, 2012a). Other fossils include teeth and exceedingly rare preserved cartilage from *Ptychodus*. Mosasaurs and turtles are nearby but have not yet been incorporated into the collection.

Pits A to C are located in a small area in the overlying Aguja Formation at a site 12 km to the east of Outcrop B. These sites have been quarried by Montgomery and associates over the past decade. Pit A, the oldest, contains only reworked oysters and shark teeth. Pit B is a recent discovery that is rich in microvertebrates (Montgomery, 2012b) and spectacularly preserved leaves above logs with *Teredolites*. At the top of the section, Pit C continues to be

TABLE I: Fossils presented to the class.

Lowest in Section	Pit A	Pit B	Pit C	Highest in Section
Outcrop B				**Outcrop J**
Platyceramus platinus	*Crassostrea* sp. and minor *Venericardia* sp.	*Lepisosteus* sp. scales and teeth	Hadrosaur maxilla, teeth, ribs, vertebrae, sacrum, centrum with tooth marks, femur, tibia, fibula, long bone fragments	Pterosaur long bone fragments
Psuedoperna congesta	*Scapanorhynchus texanus*	*Hybodus* sp.	Chasmosaur cranial elements, femur	Tyrannosaurid tooth
Ptychodus mortoni teeth and preserved cartilage		*Lissodus* sp.	Ornithomimid longbone	Theropod coprolite containing bone
		Ptychotrygon sp.	Juvenile theropod neural spine	Unidentified broken and fused ribs
		Ischyrbiza sp.	Ossified tendon fragments	Adult *Alamosaurus* tooth, cervical vertebra, rib fragments, ischium, tibia, femur
		Serpentes sp.	Soft-shelled turtle fragments	Juvenile *Alamosaurus* vertebra
		Albanerpeton sp.	Unidentified rib and longbone fragments	*Lepisosteus* scales
		Scapherpeton sp.	Dinosaurian carnivore and herbivore coprolites	Soft-shelled turtle rib fragments
		Alphadon sp. and *Cimolodon* sp. teeth	Woody vines, leaves, stems, logs, amber, *Sabal bigbendense* seeds	*Unio* sp.
		Probable pterosaur, bat, frog, and other skeletal fragments	Shell *(Continuoolithus)*	*Viviparus* sp.
		Spheroolithus		Gyrogonites
		Teredolites and log remnants		Crayfish burrows
		Sabal palm seeds		Palm wood
		Well-preserved leaves		

expanded as it regularly produces abundant and sometime unique skeletal material, mostly from dinosaurs.

At the top of the local Cretaceous section, Outcrop J is in the overlying Javelina Formation and is located 12 km to the northeast. This area displays a rich Maastrichtian lacustrine landscape complete with a diverse fauna and was the subject of recently published work (Montgomery and Barnes, 2012).

Our field team collected all of the fossils. We are, thus, familiar with each specimen in context. This familiarity greatly facilitates answering student questions, or, more precisely, coaching their investigations. As is common for fossils in the Aguja and Javelina Formations of West Texas, most are fragmentary. Some of the fossils have definitely been transported and are not coeval (the palm wood, for example). A few skeletal elements show strong evidence of predation such as pits and long scars probably rendered by crocodiles or theropods. The microvertebrates in Pit B require stereomicroscopes and steady hands for study. Provisions were made throughout the course for students to photograph all of the fossils, including the microvertebrates. The images facilitate their description in notes and discussion in presentations.

Student Assessment

Measurement of student learning outcomes is framed by authentic procedures that seek evidence of active, comprehension learning on real-world, intellectual tasks without simple recitation of memorized information. Much research and careful analysis is required in this course. Despite careful work, some fossil identifications remain uncertain, and the ecological roles of extinct animals are difficult to define. Student output includes weekly electronic notebooks reviews, brief weekly and detailed final presentations, and evaluation of the final report—an extensive, original, and creative product. Students work in small groups, but all assignments are individual and are graded using a rubric (Table II) with which the students are familiar. A rubric for each student for each week is maintained. The point total for that student for each week begins with the first discussion each Tuesday and is not completed until after the final presentation. Thus, a student's grade for the week is an ongoing assessment not only composed of notebook and presentation but also influenced by instructor impressions of individual work noted while roving among the groups, in meetings during office hours, and via electronic media,

TABLE II: Rubric used by instructors and students to assess assignments.

	Exemplary (3 pts.)	Proficient (2 pts.)	Ineffectual (1 pt.)	Incomplete (0 pts.)	Points
Research & Critical Thinking					
Content	Accurate presentation of all characteristics of all specimens.	Accurate presentation of most characteristics of all specimens.	Inaccurate presentation of characteristics of a few specimens.	Inaccurate presentation of characteristics of several specimens.	
Research	Rich variety of peer-reviewed sources correctly evaluated and synthesized.	Required minimum of sources, correctly evaluated and synthesized.	Minimal research lacking support for arguments.	No appropriate peer-reviewed sources and/or incorrect interpretations.	
Synthesis	Inspired ideas and clearly based on research.	Research-based and integrates ideas in a cohesive product.	Researched, but incompletely integrates ideas in a cohesive product.	Series of unlinked concepts and/or work may not be logical and/or verifiable.	
Communication					
Oral	Logical presentation with rich detail that indicates synthesis of concepts.	Logical presentation that audience can easily follow.	Presentation with a few flaws in logic, but audience mostly follows.	Flaws in logic and lacks sufficient detail for the audience to understand content.	
Written	Indicates higher level thinking with accurate observations, appropriate references, and inspired synthesis.	Accurate observations and appropriate references. Reasonable synthesis.	Mostly accurate observations and appropriate references, but some flaws, especially in synthesis.	Mostly inaccurate observations and lacking appropriate references. Poor to missing synthesis.	
Graphics	All excellent (size and color) and support content.	Suitable, but not inspired, and all support content.	Mostly serviceable, but not all support content.	Not fitting and poorly support content.	
Creativity					
Creativity	Demonstrates spectrum of original thought. Ideas are inspired and ingenious.	Some original thought. Several new ideas and insights.	Several original (or, at least, logical) ideas and insights. Little evidence of original thinking.	Little to no evidence of original thinking.	
Collaboration					
Teamwork	Clear evidence of continuous and mutual effort in the creation of final product.	Evidence of working well together, but lacking some evidence of integrated teamwork.	Some problems working together. Lacking collaboration.	Not a collaborative effort.	
Score for the week (adjusted maximum of 10.0)					

including text queries. (Rubrics for each student for each week are now kept on an iPad). All notebooks receive extensive feedback. (An interrater reliability process is currently being implemented.) Opportunities to rethink and rewrite are standard procedure. Figuring into the instructor's evaluation are assessments carried out by each group member evaluating the performance of every other member of that group. The rubric used for this process is peer Collaboration and Teamwork (Buck Institute for Education, 2013).

IMPLEMENTATION AND EVALUATION

Delivery

Despite working on the same fossils, each group has different ideas concerning interpretation, even if most students eventually arrive at the same taxonomic identifications. Roving instructors (professors and teaching assistants, when available) independently vet these interpretations each week for each group. Thus, there is not a lot of sharing among groups on Tuesdays, but there is a great deal of discussion among groups on Thursdays. Instructors find that some groups are more adept at the use of technology-based resources than are others. In these cases, we might refer the group to Cmap or another such resource. An air of urgency to present discoveries and analysis, perhaps driven by a spirit of gentle competition, appears to be constructive in this situation.

Beginning in the first class, students quickly come to the correct assumption that there are no step-by-step instructions to formulating and answering their questions. Perhaps the major difference between what students (probably) did in the usual science class and what they do in this class is that in a PBL class, students construct their own solutions to questions that they generate. These are quite intelligent students, but rarely have they had to ask the questions. They are experts at providing (frequently memorized) "correct" answers to questions that they expect to see on multiple-choice or short-answer tests. For scientists, correct answers can be elusive. An early correct answer may be proved incorrect later. In paleontology, for example, students learn that a possible, or even probable, correct answer may exist within a range of possible taxa (within a range of possible correct answers). Or it may not. PBL is rather remote from our usual standardized and predictable educational upbringing. The experience can be unsettling for students who are practiced in a more traditional learning environment.

Presentations must be delivered in a modified PechaKucha (PechaKucha, 2013) format with 10 slides timed for 15 s each (10×15) rather than the specified 20×20. The format was designed by architects Astrid Klein and Mark Dytham to prevent the usual talk and/or PowerPoint presentation from going on and on. PechaKucha has gone viral and is used worldwide for creative presentations. In our version of this format, only images are presented. No charts, tables, or bulleted text is permitted. Each image should suggest a concept, and each speaker must thoroughly understand the material because there are none of the usual bulleted prompts. One benefit is that no student takes more than the allotted time. Following each presentation, additional time is provided. An unexpected and welcomed outcome of using PechaKucha is the surprisingly numerous and perceptive questions that each presentation invites. We consider this inquiry-driven presentation methodology to be a major improvement on the usual process.

Experiences Implementing the Course

We found that a great deal of preparation was required to assemble a diverse collection of fossils that would allow a rich reconstruction of the area during a time of changing climate, changing sea level, changing fauna and flora, and ending with the extinction of nonavian dinosaurs. Students in our master's program for science teachers also report that preparation for a new PBL course is substantial.

Instructors must learn to carefully listen and must not be quick with answers. We provide clues and/or resources rather than answers. Simply rephrasing a question will frequently lead to another student in the group having an epiphany. Following these revelations, students explain discoveries to other students. If another group runs into the same question, we ask the student who had the epiphany to visit that group and to help its members solve their problem (without giving the answer). We were surprised how rapidly the students picked up this technique.

The daily use of a rubric with which the students are familiar will continue. Conducting evaluations during each class is crucial. We did not experience any students falling behind as is common in some traditional classes. Students expect us to meet with them several times during each class. We expect the students to make careful observations and to conduct detailed research. We expect results. So do they.

Evaluation of Course Design and Delivery

Survey results prompted modifications in course design. Among the changes are more examples of successful previous projects and examples of how those projects improved during the course of the semester. Pursuant to this goal, we preserved examples of student work that will be posted on eLearning. The detailed and ever-evolving notebook format will remain. The PechaKucha presentations remain as is. Questions posed by other students are perceptive, learned, and provocative, quite unlike anything we have experienced in our traditional classes. Certainly, a major contributor to this enthusiasm is not in the format but in having the students primed to question in this probing manner by having practiced the technique during each class. PechaKucha simply provides an excellent platform.

Student Performance Evaluations and Survey Results

Evaluation was accomplished in four ways: questionnaire data from an instructor-designed instrument, university questionnaire results, free response statements, and weekly grade data throughout the semester. There is no other course to use for comparison. The previous version of this course was conducted in a lecture/laboratory format with nonhonors students wherein memory was stressed more than problem solving.

Student Performance

Student performance as assessed using the course rubric (Table II) began the second week and showed week-to-week variation over the semester. Out of 10 points, scores for week 2 through week 13 were 8.0, 9.6, 9.0, 8.8, 8.6, 8.6, 9.4, 9.0, 9.4, 9.4, 8.8, and 9.8. The trend in these scores is subtle, but it is certainly noticeable in class. Students adopt best practice and become comfortable with the class about halfway through. These numerical results reflect an interplay of regular improvement in student performance, in addition to varying difficulty of sample identification and interpretation and heightening of expectations for student research. Student course objectives 1 and 2, "Students will be familiar with evolutionary history of numerous Mesozoic fossils" and "Students will have a basic understanding of Mesozoic geology and paleoecology," respectively, were assessed weekly with the Content section of the rubric (Table II), as well as through evaluation of the final projects. In addition, the fulfillment of course objective 5, "Students will produce an original research project of extraordinary quality," was evident in the diverse and skillfully executed PechaKucha presentations discussed earlier. For details of a project of "extraordinary quality," see the Oral, Written, Graphics, and Creativity sections of the project rubric (Table II). Final projects were all highly coached through questioning, providing research, and showing examples. All finals projects met or exceeded the expectation of the instructors. Our long experience with honors students suggests that we can expect similar, highly satisfactory results in future semesters.

Questionnaire Data

Statements in the postcourse survey (Table III) were composed before the class began to help guide our instructional philosophy. Regular contact with the students certainly provided nearly continuous formative assessment that resulted in numerous minor modifications by the instructors during the semester, such as adjusting difficulty of fossils or modifying expectations for student research. Two weeks after grades were posted, all students were emailed the survey to assess their opinions about this class. This wait period before surveying was to hopefully provide time so that students would give us an overall view of the course. Survey responses went directly to the department secretary, who removed all identifiers. Eight students returned surveys, while 10 completed the university evaluation. The instrument was a standard 5-point Likert scale survey with a neutral choice having a value of 3. Statement

TABLE III: Likert questionnaire data.[1]

	Statement	Means
1	The class helped me learn to obtain information from a variety of sources.	4.5
2	“Discovering” new fossils each week approximated the work of paleontologists.	4.5
3	I honed my skills for working in groups.	4.0
4	My research skills have improved over the course of the semester.	4.5
5	The research document that I completed is of substantial merit.	4.4
6	This course helped me to evaluate new information and to reassess my knowledge.	4.8
7	I gained confidence in my understanding of how to properly conduct scientific inquiry.	4.4
8	If given an opportunity, I would like to take another PBL class.	4.6
9	Scientific inquiry requires consulting peer-reviewed research.	4.8
10	I gained an understanding of basic principles and concepts of geology and paleontology.	5.0
11	The next time I go to a museum, fossils will appear much more understandable.	5.0
12	I can apply the general principles that I learned in this class to other topics.	4.4
13	I grew in my ability to argue a point.	4.1
14	Students of every major should experience scientific inquiry in at least one course.	4.6
15	Knowing little to nothing about various fossils during the first weeks made me uncomfortable.	3.8

[1]Point values: 1 = strongly disagree; 2 = disagree; 3 = neutral; 4 = agree; 5 = strongly agree.

15 was analyzed separately, as responses registering the greatest agreement with a negative statement have the highest value.

Survey Composed by Instructors

Likert responses are probably best treated as ordinal data because there is no statistical certainty whether the intervals between values are equal. For this dataset, modes for each statement have a value of 5 with the exception of Statement 3, which had a value of 4. As is common practice, we can determine means, but we will make no claims based on intervals such as “twice the value” when comparing a “disagree” (value of 2) to an “agree” (value of 4). Means present a more valuable analysis tool as long as one observes the caution concerning comparing intervals.

Statement 15 (Table III) suggests some uneasiness existed at the first of the semester as a result of unfamiliarity with fossils. Average responses for the other statements are all in the “agree” to “strongly agree” range, indicating an overall positive response by students to these goals for the course. Two “disagree” outliers are present, with one to Statement 5 and one to Statement 13.

The survey data with mean values of 4.0 to 5.0 (“agree” to “strongly agree”) present an overall student perception of accomplishment in the categories selected for this questionnaire. Students studied specimens, engaged in research, formulated models, presented findings, and argued important points. They reported that they would like to take another PBL class (4.6). Statement 15 was interesting in that students reported with mild agreement (3.8) that encountering unknowns made them uncomfortable. They rapidly progressed beyond this state of mind. We will add a prompt next semester seeking to further qualify and quantify change in students’ comfort levels by the end of the semester.

Free Responses

The free response selections reflect both the most common themes and the most extreme.

Strengths of the course were mostly along the lines reported by this student:

> *“The availability of hands-on materials connected the information gained through occasional lectures with real work performed by paleontologists. I think many students create separate and disconnected spheres in their minds for ‘classroom learning’ (lecture-based, little to no collaboration with other students) and ‘out-of-class/real world/occupational learning’ (experience-based, mix of solo research and group work), and I think the PBL format helps to bridge this gap. It’s not that lecture-based courses are never useful or effective, in my opinion, but there is a tremendous bias towards them at educational institutions even though they do not represent what students will be doing for the rest of their lives. Many occupations that call for higher education require working with other individuals as part of a team to solve problems or accomplish tasks, yet there are few opportunities for students to experience that atmosphere in college.”*

Another expression of enthusiasm for the PBL method came from this student:

> *“When everyone thinks alike, no one is really thinking. In this PBL format, everyone contributes different ideas to the discussions, thus stimulating creativity and an eagerness from each student to prove the correctness of his or her beliefs.”*

Weaknesses reported for the course mostly reflect what we hoped would be start-up issues that would not be overlooked the next time the course was taught in the spring of 2014. This quote was not uncommon in that students did not respond favorably to lectures that by definition could not be focused on the topic each group was investigating during that part of class. Lectures lasted approximately 4–20 min. By

TABLE IV: Likert questionnaire data from University of Texas at Dallas course survey.[1]

Prompt	Means
The course objectives were clearly defined.	4.30
The course was well organized.	4.70
Overall, the course was excellent.	4.78
The instructor was well prepared in the subject area.	4.80
The instructor communicated information effectively.	4.50
The instructor seemed genuinely interested in teaching.	4.80
The instructor evaluated students fairly.	4.80
Overall, this instructor was excellent.	4.80
I was free to ask questions and express my opinions and ideas.	4.70
My performance was evaluated fairly.	4.60
I discussed ideas from this course with others outside the classroom.	4.50
This course has been (or will be) of value to me.	4.30
This course inspired me to learn more.	4.50

[1]Point values: 1 = strongly disagree; 2 = disagree; 3 = neutral; 4 = agree; 5 = strongly agree.

the end of the semester, lectures were pared to approximately 5 min.

> *"The lectures are beneficial, but I believe that these should supplement a textbook reading, which the student can read on his or her own."*

But then, others replied like this:

> *"The occasional lectures are an important part of the students' knowledge, and the materials facilitate scientific inquiry."*

Some students experienced pronounced frustration when given fossils that even professionals could not identify other than being "from a small, herbivorous dinosaur, probably." We sought to give students an authentic experience, and there are simply some fossils such as a small piece of a rib that leave all of us scratching our heads about any specific taxonomic assignment. Some students were happy to get close to the answer and then move on. Others simply could not let go without making heroic attempts to figure out every possible detail. The idea that a fossil might remain poorly identified was anathema to them. Grappling with problems that have limited solutions was a novel experience. We considered removing the few fossils in this category (five or six specimens) but decided to keep them in the course collection. The instructor plays a pivotal role in balancing frustration and learning. This is only accomplished via regular discussions with each student. We agree with this student's statement, but we prefer to wait to offer help until a student's best efforts have been exhausted:

> *"It was very aggravating when coming across the fossils and not being able to figure out the identity after long examination and research. Perhaps more information about the fossils could be given to the students, rather than leave them 'in the dark' on many fossils that even professional paleontologists have trouble identifying."*

These student responses make it clear that student objective 3, "Students will evaluate fossils from several of our dinosaur sites in west Texas using criteria presented in the class and in primary sources" was met. In addition, objective 4, "Students will apply their learning and understanding to real-world research projects," is evident in the student responses given here. Even the frustrations of the students mimic those of scientists in the field. Both of these objectives were also assessed weekly in the Research, Synthesis, and Teamwork sections of the rubric (Table II).

Questionnaire Data From University of Texas at Dallas Course Survey

Student responses to the university course evaluation instrument were positive, with 9 or 10 students responding to each prompt. Statements that go to the theme of this investigation are listed in Table IV. These scores would seem to exhibit student satisfaction, particularly for the first time such a different methodology is employed and for the first time any student had taken a PBL course.

Free response statements on the course survey (Table V) provide both reassurance and pause for thought about possible modifications. In the need improvement category, Statements 3 and 6 reflect uncertainty about assignments that were not made clear by Montgomery at the beginning of the semester. Modifications based on Statements 7–9 will be incorporated in the next offering of this course.

SUGGESTIONS AND CONCLUSION

Questionnaire data indicate a high level of student satisfaction with the course and with the process, in addition to successfully meeting the class objectives. Upon occasional quizzing during the course, students reported that the workload, while sometimes "substantial," was not onerous. Another anecdote of note is that the biology students were particularly pleased not to be required to memorize voluminous amounts of information that required neither active learning nor creative construction of research-based solutions. While presenting a PBL course can involve a daunting amount of upfront work for the instructors, this

TABLE V: Free response statements on the University of Texas at Dallas course survey.

Prompt	Statements by Students
What aspects of this course should remain the same?	1. Everything This class is very fun and dynamic.
	2. Class size is excellent, as is the class format. The hands-on, discussion-based class is a welcome break from the large, lecture-based classes that are more common. REAL FOSSILS AND MICROSCOPES
	3. Method of instruction
	4. The process at which we look at and evaluate fossils
	5. The hands-on approach and being able to work individually in groups to solve problems.
	6. The hands-on structure of the course was excellent and needs to be not only kept, but emulated in other classes.
What aspects of this course need improvement?	1. There were times when things were a bit poorly organized... but for the most part the professor was good about explaining everything in class. I imagine it would have been VERY difficult if I had had to skip any classes though.
	2. Friday night deadline for weekly assignments was a bit inconvenient at times. Perhaps a Sunday night deadline would work better for students, but I dont know if it would make grading more difficult for the instructor.
	3. Telling the students to make a cumulative report what is needed from the start would help, but was a small inconvenience.
	4. No changes needed.
	5. Objectives and requirements for the assignments should be clearly defined early in the semester.
	6. A little more basic information about paleontology at the beginning of the semester would be nice.
	7. Greater focus on learning about specific dinosaurs in class. Provide in depth background information on dinosaur origins or time frame.
	8. A little more instruction—maybe a bit more guidance in the beginning on how to identify fossils what are good bad sources to use, so that later in the course students can get the right information on the more complicated subjects.
Additional comments:	1. Wonderful CV class. Really pushes students. A must-take.
	2. Favorite class I have ever taken I have learned a great deal without being too overwhelmed by the subject. I would recommend this class to anyone.
	3. I thoroughly enjoyed this class
	4. Excellent course
	5. It was a very fun class.

load lessens for subsequent classes. By no means should one conclude that a PBL course would become static, however. We continue to include numerous new discoveries in the fossil rotation. As our understanding of these puzzling sites grows, the course will clearly change to reflect this understanding. The students are certainly aware of the somewhat fluid nature of the discovery process. We propose that students' recognition of knowledge building rather than simple learning is a powerful lesson (after the ideas of Scardamalia and Bereiter, 2007).

Implementing a PBL course requires both an understanding of the methodology and a fundamental relinquishing of the role of instructor as purveyor of all knowledge. Students gain the responsibility for constructing their own knowledge via a process not unlike that in which their researcher/instructor engages. In this example with honors students, undergraduates were sufficiently mature both to drive their own learning and to do this in concert with their peers. Such a process mimics the modern workplace wherein experts work in groups, gather data, solve problems, and present well-reasoned solutions. We would argue that PBL not only is an effective learning methodology but also is excellent preparation for the future careers of these inquisitive and industrious students.

REFERENCES

Barrows, H., and Kelson, A. 1993. Problem-based learning in secondary education and the Problem-based Learning Institute (monograph). Springfield, IL: Southern Illinois University School of Medicine.

Blosser, P. 1990. Using questions in science classrooms. Research Matters to the Science Teacher No. 9001. Association for Research in Science Teaching. Available at http://www.narst.org/publications/research/question.cfm (accessed 29 December 2013).

Boss, S. 2011. Project based learning: A short history. Available at http://www.edutopia.org/project-based-learning-history (accessed 29 December 2013).

Buck Institute for Education. Problem based learning. Available at http://www.bie.org (accessed 29 December 2013).

Charlton-Perez, A. 2013. Problem-based learning approaches in meteorology. *Journal of Geoscience Education,* 61:12–19.

Cmap. 2013. Cmap. Available at http://cmap.ihmc.us (accessed 29 December 2013).

Collegium V. 2013. The UT Dallas Collegium V honors program. Available at http://honors.utdallas.edu/cv/ (accessed 29 December 2013).

Fyrenius, A., Bergdahl, B., and Silén, C. 2005. Lectures in problem-based learning: Why, when and how? An example of interactive lecturing that stimulates meaningful learning. *Medical Teacher,* 27:61–65.

Glynn, S., and Koballa, T. 2006. Motivation to learn college science. *In* Mintzes, J., and Leonard, W., eds., Handbook of college science teaching. Arlington, VA: National Science Teachers Association Press, p. 25–32.

Kumar, D. 2013. Approaches to interactive video anchors in problem-based science learning. Available at http://www.fau.edu/IEEE_Lecture/PBL_IEEE_Lecture/PBL_Lecture.htm#clips (accessed 29 December 2013).

Markham, T., Larmer, J., and Ravitz, J. 2003. Project based learning handbook: A guide to standards-focused project based learning for middle and high school teachers. Novato, CA: Buck Institute for Education.

Montgomery, H. 2012a. Mysteries of giant *Platyceramus* of the Boquillas Formation sea floor. *Geological Society of America Abstracts with Programs,* 44:30.

Montgomery, H. 2012b. A new microvertebrate local fauna in the Aguja Formation, Texas. *Geological Society of America Abstracts with Programs,* 44:36.

Montgomery, H., and Barnes, K. 2012. Paleolimnology of uppermost Cretaceous lacustrine deposits in West Texas. *Palaios,* 27:386–394.

PechaKucha. 2013. PechaKucha 20 $\times$ 20. Available at http://www.pechakucha.org (accessed 29 December 2013).

Scardamalia, M., and Bereiter, C. 2007. Fostering communities of learners and knowledge building: An interrupted dialogue. *In* Campione, J.C., Metz, K.E., and Palincsar, A.S., eds., Children's learning in the laboratory and in the classroom: Essays in honor of Ann Brown. Mahwah, NJ: Erlbaum.

Wiggins, G., and McTighe, J. 2006. Understanding by design. Alexandria, VA: Pearson.