1 Introduction

Students are drawn to paleontology courses by the promise of dinosaurs, mass extinctions, and survival of the fittest. They don't always begin with the understanding that there is much more to the history of life on Earth than *Tyrannosaurus rex* and meteorite impacts. Our job as paleontology educators is to guide students toward a deeper understanding of evolutionary processes, the history of life, and the nature of science. And while it is relatively easy to lecture and to hope that the drama and narrative of the history of life will keep students engaged, research shows that our students benefit most from student-centered, active-learning pedagogy (National Research Council, 1996, 2000a, 2000b; Ruiz-Primo et al., 2011; van der Hoeven Kraft et al., 2011; Mogk and Goodwin, 2012; Freeman et al., 2014).

Student-centered learning shifts the attention in a classroom from the instructor to the students. In a student-centered classroom, students are in control of their learning experience and the instructor functions primarily as a guide. Because students are building new understanding through activity and inquiry, student-centered classrooms trade traditional lecture for hands-on explorations of content and concepts. This can mimic true scientific inquiry, ranging from carefully guided activities to open-ended explorations in which students develop their own questions, hypotheses, tests, and conclusions.

Research on learning and cognition suggests that students learn better in student-centered classrooms, and that effective instruction should include three key components: (a) activation of students' prior knowledge on the subject, (b) active learning pedagogy that allows students to address existing misconceptions and build new understanding of the subject, and (c) metacognitive reflections that require students to evaluate their own learning processes during the lesson (Figure 1) (National Research Council, 2000a). Designing courses that incorporate all three of these components while also accounting for class size, audience, and other course constraints is challenging, but educators can draw from the existing pool of validated student-centered activities, units, and lesson plans.

As paleontology educators, our practice will benefit greatly from the body of research produced by our colleagues in the geoscience education research community. The purpose of this Element is to provide an overview of the research on student-centered active learning pedagogy in introductory geoscience and paleontology courses, and to provide examples of these instructional approaches. Two central questions guide this Element. How do people learn? And what is unique about geoscience education as compared to other science fields?

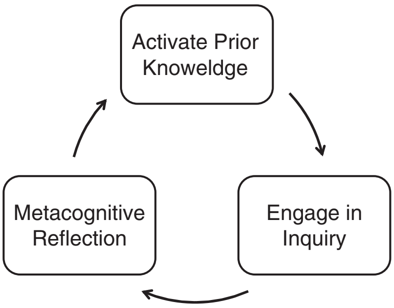

Figure 1 National Research Council framework for how people learn. (A) Activate prior knowledge. (B) Build new understanding via active learning. (C) Metacognition. (National Research Council, 2000a)

2 Student-Centered Learning

2.1 How Do People Learn?

Traditional, lecture-based courses often conflate teaching and learning. Lecturing on a topic delivers information to students, but there is little research support to show that students absorb, understand, and retain information that they receive through lecture (National Research Council, 2000a, 2000b). Thus, teaching does not necessarily result in learning in a lecture-based course. Lecture-based course design assumes that students enter the classroom as empty vessels, ready to be filled with new knowledge. In reality, students enter the classroom full of ideas, experiences, and preexisting frameworks for understanding the world around them. New knowledge must be delivered in ways that build onto students' preexisting frameworks, and lecture does not give students an opportunity to do that (National Research Council, 2000a).

While students in introductory courses are not likely to become true experts in the course topic, they should still develop the skills to think more like an expert. One important aspect of thinking like an expert is the ability to transfer understanding from one context to another (Hmelo-Silver et al., 2007). For example, a novice learner might successfully memorize the names and shapes of different types of trace fossils, but an expert would be able to classify new or unknown trace fossils based on their understanding of how traces are made. An expert has both a deep foundation of factual knowledge and the ability to fit new ideas into an existing framework (National Research Council, 2000a). An expert's frameworks for understanding are large and complex, and function like a filter to help sort and process new information (Hmelo-Silver and Nagarajan, 2002). With good course design, students can begin developing expert-like skills, even in introductory courses. Student-centered learning gives students this opportunity, which the science education research community refers to as *learning with understanding* or *deep learning*.

Students learn with understanding when they are able to engage authentically with course content (National Research Council, 2000a; Ruiz-Primo et al., 2011; Kyoungna et al., 2012; Freeman et al., 2014). Authentic engagement can take many forms, from activities in which students address real-world problems to true scientific inquiry. Inquiry, in this context, refers to activities that mimic the process of conducting scientific research. Inquiry in the classroom is often guided rather than open. In guided inquiry, students might follow a set of questions or procedures designed to prompt students to ask their own questions, pose hypotheses, design tests, and draw conclusions based on evidence. The results or conclusions of guided inquiry are often known or predictable to the instructor. Open inquiry is unstructured and less predictable. For example, students might be conducting true scientific research for which the results or conclusions are not known.

Student-centered classrooms are rooted in the theory that students will construct their own understanding of content through observation and inquiry during a lesson (Piaget, 1964; Fosnot, 2005). In a student-centered classroom, instructors function as guides as students engage in inquiry and problem-solving on their own or in small groups. Lectures are short and often occur midway through a lesson or even at the end. Lectures serve the purpose of clarifying or summarizing concepts that students have already explored earlier in the lesson.

The constructivist theory can prove difficult to put into practice, because it is hard to predict exactly what inferences or conclusions students will draw from their observations. This is in part because students will draw heavily from their prior experiences and knowledge when constructing new understanding (Piaget, 1964; National Research Council, 2000a; Fosnot, 2005). This prior knowledge is almost certainly incomplete and often includes misconceptions, so including opportunities for students to consider, write about, or discuss prior knowledge before engaging in new content allows the instructor to assess student's prior knowledge and address misconceptions (National Research Council, 2000a; Fosnot, 2005). Research also shows that if students' prior knowledge is not engaged, "they may fail to grasp the new concepts and information that are taught, or they may learn for the purposes of a test but revert to their preconceptions outside the classroom" (National Research Council, 2000a).

One way to elicit students' prior knowledge is a series of "initial ideas" questions designed to access students' prior knowledge or misconceptions at the beginning of an activity, and then check in with the class or individual groups to address any misconceptions before moving forward. Another approach to addressing misconceptions or confusion is to combine a constructivist approach with small interjections of explanatory reading or mini-lectures. Students can spend time engaging with the content and building their own understanding, and then they will have a more robust personal context in which to situate any subsequent reading or lecture.

Student-centered teaching benefits students, according to recent studies on the impact of student-centered teaching in geoscience classrooms (McConnell et al., 2005; Ruiz-Primo et al., 2011; Mogk and Goodwin, 2012; Freeman et al., 2014). For example, in a meta-analysis of research on the impact of student-centered instructional innovation in undergraduate science and engineering courses, Ruiz-Primo et al. (2011) found that students experience greater learning gains when student-centered instructional approaches were employed in large introductory science courses. In another meta-analysis of the impact of student-centered instruction, Freeman et al. (2014) found that these approaches improved student learning in all science, technology, engineering, and mathematics (STEM) disciplines, though the impact on geoscience courses was less pronounced than for other STEM disciplines. The sample size for geoscience courses was also much smaller than that for other STEM disciplines; only two geoscience studies met the requirements for inclusion in the analysis. This suggests an ongoing need for studies that quantitatively measure the impact of student-centered teaching in geoscience courses.

2.2 What Is Unique about Paleontology Education?

Some aspects of paleontology education are shared with other sciences, and some are unique to this field. Knowledge of this can help with instructional design, and a well-designed course will capitalize on paleontology's unique strengths while simultaneously addressing its unique challenges.

Student motivation for enrolling in paleontology and geoscience courses differs from student reasons for entering most other science fields. Many undergraduate students will have taken biology, chemistry, and physics courses in high school, and most STEM majors are required to take a year of chemistry and physics. Students will enroll in these courses because they are familiar subjects and are likely required. Paleontology and geoscience courses are not typically required for any majors besides geology. Furthermore, paleontology attracts students who are not STEM majors but are interested in learning about fossils. For these reasons, students in introductory geoscience or paleontology courses are likely there by choice but enter the course with less prior understanding of the content than students in other introductory science courses (McConnell et al., 2005; van der Hoeven Kraft et al., 2011).

Paleontology differs from most other sciences in that key phenomena cannot be directly observed. For example, even the most exquisitely preserved fossils are abstract representations of the living animal. Students are required to build mental models to translate what they see into what the fossil represents. While little research exists on students' conceptions of animals from fossils, we can extrapolate from research on students' spatial thinking skills and abstract reasoning to conclude that forming a mental model of a living animal is not an easy process (Chadwick, 1978; Kastens et al., 2009; Mogk and Goodwin, 2012). Evolution is another abstract concept that students encounter in paleontology courses. Evolution cannot easily be directly observed, so students have to build their own mental models in order to understand evolutionary change. For example, an instructor might illustrate the evolution of terrestrial tetrapods by showing students specimens or illustrations of several fossil fish, amphibians, and tetrapods. These specimens show the result of evolutionary change, but students must incorporate several concepts (natural selection, genetics, time, preservation, etc.) in order to build a mental model for the evolution of terrestrial tetrapods. Understanding the *process* is different and more difficult than memorizing the evolutionary progression of fossil taxa.

Paleontology and geosciences also often include opportunities to learn in the field. Class field trips can enrich students' learning experiences and lend themselves well to student-centered learning. In their synthesis of research on learning geosciences in the field, Mogk and Goodwin (2012) identified the primary benefits and opportunities of field experiences for geoscience students: embodiment, inscription, and initiation into a community of practice.

Embodiment is a concept borrowed from cognitive science that refers to our ability to use our physical relationship to an object or space to understand it in ways that are not possible for a machine or from a two-dimensional perspective. Frodeman (2003) describes this as "knowing your way around the topic, being oriented in conceptual space – or in an actual geographic and geologic space" (Frodeman, 2003, p. 127).

In the field, students can develop spatial thinking skills through the creation and use of inscriptions, which are constructed representations of natural phenomena like maps, sketches, and diagrams. Mogk and Goodwin (2012) refer to this as "inscription." Research has shown that this type of translation, from the real world to inscription, helps students filter and process information because they must distill the complexity of the real world down to only relevant concepts or details (Mogk and Goodwin, 2012).

Initiation into a community of practice means that in addition to learning how do geology, students learn how to *be geologists*. Mogk and Goodwin (2012) note that four categories of geoscience practice are learned in the field: language translated in the practice; tools used to acquire, organize, and advance community knowledge; shared ethics and values; and collective understanding of limits and uncertainties. Many students are initiated into the geoscience community in field camp, but they can gain these benefits during shorter field experiences too.

Field experiences can also present some challenges. Field trips are not possible for all courses or students; distance, time, expense, scale, safety, and accessibility all create barriers to field experiences. Furthermore, the real world is complex. If the activities and learning outcomes are not clear, students may have difficulty filtering and processing all the variables present at a field site (Ramasundaram et al., 2005; Mogk and Goodwin, 2012).

2.3 Student-Centered Instructional Design

Geoscience educators should approach course design with intention. Instructional design theory provides a framework to consider when building a new student-centered course or revising an existing one to incorporate more student-centered pedagogy. Using this framework ensures that a course addresses specific desired outcomes while also accounting for instructional conditions like class size, student demographics and cultural background, and time constraints (Reigeluth, 1999). The framework shown in Figure 2 helps guide an educator through design by first establishing specific desired learning outcomes for a course, module, class period or activity, then designing activities around those learning outcomes (Reigeluth, 1999). This approach, also known as "backward design," establishes the end goal and its appropriate

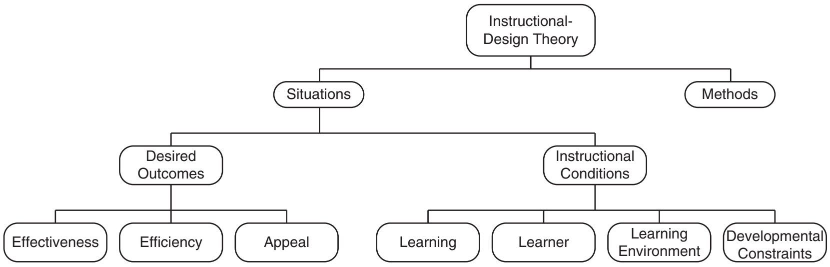

Figure 2 The components of instructional design theories (Reigeluth, 1999)

assessments (e.g., exam, lab report, essay) first and designs from that point back to the beginning of the activity, ensuring that every aspect of the activity helps to achieve the learning outcomes (Glossary of Education Reform, 2014).

Taking into account what we know about how people best learn paleontology and geoscience, we can now envision the ideal paleontology learning environment. The ideal course is one with clearly established learning goals and in which every activity and assignment is designed to guide students toward those learning goals. The ideal course is designed around the students and their learning experiences, and creates pathways for students to build new understanding of geoscience content and concepts. The ideal course positions students as scientists and allows them to ask their own questions and then to design their own methods for determining answers to those questions.

3 Student-Centered Pedagogy

Student-centered pedagogies are instructional methods that foreground student learning rather than teaching. Yacobucci (2012) provides a thorough list of active learning techniques, including some of the techniques described in this Element's activities, such as think-pair-share, concept maps, and guided inquiry. Additional techniques include peer teaching, brainstorming, responding to media reports, writing or drawing to learn, timelines, textual analysis case studies, games and role playing, debates and panel discussions, and service learning (Yacobucci, 2012). Ruiz-Primo et al. (2011) defined four broad categories of student-centered instruction: (1) conceptually oriented tasks, (2) collaborative learning activities, (3) use of technology, and (4) inquiry-based projects. These four categories, when used in concert with metacognitive reflection, encompass all aspects of the National Research Council's framework for how people learn.

3.1 Conceptually Oriented Tasks

Conceptually oriented tasks (COTs) are designed to engage students in conceptual schemes rather than isolated facts (Ruiz-Primo et al., 2011). COTs are intended to illustrate big ideas or to help students develop a framework for contextualizing new information. For example, students in a paleontology course must first understand the underlying process of evolution by natural selection before they can understand the driving forces behind the Mesozoic Marine Revolution or the Lilliput Effect. If students engaged in a COT focused on natural selection before they learned any information about specific evolutionary events, that COT would give them a framework to help relate, compare, or contrast specific evolutionary events.

COTs may also be used to at the beginning of an activity, module, or course to elicit students' level of understanding of or misconceptions about key concepts. For example, students may consider and discuss a series of questions or prompts before an activity begins in order to activate their prior knowledge of key concepts. Another example of a COT is a concept map, in which students visually represent the relationships that connect ideas, objects, or events (Novack, 1991; see Activity 1: Rock Cycle Concept Map for an example). COTs may engage students with real-world problems, which allows students to contextualize key concepts that can feel abstract or ungrounded until they are applied to a relevant issue. Ultimately, COTs focus on large-scale concepts, not isolated facts.

3.2 Collaborative Learning Activities

Collaborative learning activities are designed to engage students with peers in groups as small as pairs. Lessons designed around collaborative learning have been shown to promote a deeper understanding of concepts and content, because the sum knowledge of a group is greater than that of one individual (Lyle and Robinson, 2003; Tenney and Houck, 2003; Lorenzo et al., 2005; Arthurs and Templeton, 2009; Gilley and Clarkston, 2014; Bruno et al., 2017). Research on collaborative learning activities shows that group work improves learning for all students, not just those who are struggling with concepts (Gilley and Clarkston, 2014; Bruno et al., 2017). This is because collaborative learning gives students a space to discuss ideas and work through difficult concepts from multiple perspectives. Struggling students benefit from having a peer (rather than an instructor) explain concepts, and students who have a deeper understanding of the concepts benefit from the opportunity to explain it or to teach it to their peers (Yuretich et al., 2001; Gilley and Clarkston, 2014; Bruno et al., 2017). Collaborative learning provides students with opportunities to engage in explanations and discussions as they describe their reasoning, interpretations, and solutions to problems (Ruiz-Primo et al., 2011).

A simple example of a collaborative learning activity is a think-pair-share activity, in which students consider a question or problem on their own (think), then discuss and refine their ideas with a partner (pair) before reporting back to the class (share). By allowing students to process on their own and with a peer before sharing, think-pair-share increases students' confidence in their ideas and stimulates discussion. Activity 2: Mystery Fossil Observation is based on the think-pair-share model.

Another example of a collaborative learning activity is the jigsaw activity (Figure 3). In a jigsaw, students begin the activity in a small "home group," then

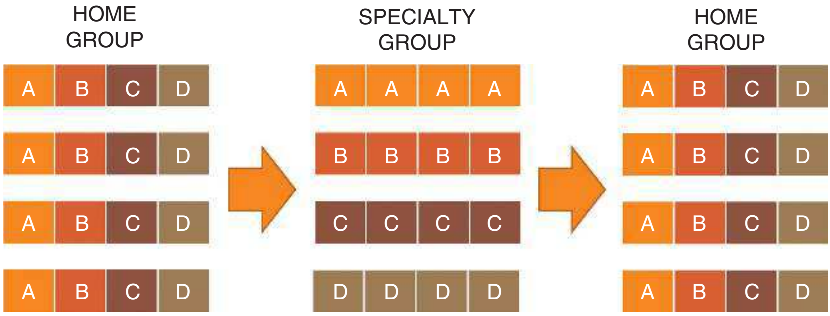

Figure 3 Jigsaw activity design, showing how students in home groups split apart into specialty groups, then return to home groups after mastering their specialty

split apart into "specialist groups" to focus on a specific aspect or topic. After mastering their "specialty," students return to their home group to tackle a complex problem collaboratively with representatives from each specialty. Jigsaw activities require a high degree of interdependence among students, because each specialist only possesses one "piece of the puzzle" and the whole group must work together to answer the question or to conduct the analyses (Aronson et al., 1978). Another benefit of the jigsaw activity is that it reduces the atmosphere of competition in a classroom; students are only successful when they work collaboratively with their group members (Aronson et al., 1978; Aronson and Patnoe, 2011). Activity 3: Sorting and Categorizing Fossils is an example of a jigsaw.

Student-centered classrooms may also utilize collaborative two-stage exams rather than traditional exams. In a two-stage exam, students take two identical versions of the same exam. In the first stage, they work independently. In the second stage, students work collaboratively in a small group (two to four students) on the same questions. Grades for two-stage exams are typically weighted, with ~75% assigned to the independent first stage and ~25% to the collaborative second stage. Studies of two-stage exams in large introductory geoscience courses show that students benefit greatly from the opportunity to work through the exam collaboratively with peers (Cortright et al., 2003; Lusk and Conklin, 2003; Gilley and Clarkston, 2014; Bruno et al., 2017).

Collaborative learning activities are central to a student-centered classroom. Working in collaboration and in small groups gives students the opportunity to engage directly with the content and with their peers, which promotes inquiry, discussion, and critical thinking skills. Even large lecture courses can be broken up into small groups throughout the class period to incorporate collaborative learning activities and to allow students to better process new content.

3.3 Technology

Technology can be incorporated into paleontology courses in a variety of ways, many of which are explored in other Elements in this paleontology series. In this context, technology can include any enhancement from viewing and analyzing digitized fossil specimens to building computer models to test hypotheses about evolutionary processes. Research shows an increase in student learning and engagement with content when technologies are incorporated into lessons.

3.3.1 Digitized Specimens

The ability to quickly and easily create high-resolution photographs and three-dimensional digital models of fossil specimens has revolutionized the study of paleontology, especially regarding the curation of collections. Most natural history museums are actively digitizing collections, and many are making their virtual collections available to researchers, educators, and even the general public. Digitized specimens can be used to enhance teaching collections, filling gaps and making the teaching of paleontology possible at institutions that do not have access to teaching collections.

3.3.2 Virtual Field Trips

As discussed earlier in this Element, field trips are a unique strength in geoscience education because learning in the field gives students the opportunity to both acquire knowledge and develop science skills and methods. Of course, field trips are not always logistically possible, especially for large enrollment courses, schools that are prohibitively far from "interesting" field sites, or students who are not physically able to conduct fieldwork. Virtual and augmented reality field trips are an effective alternative to actual field trips, and have been shown to increase student interest in studying geology because students can learn to "explore" a field site virtually without actually traveling there (McGreen and Sánchez, 2005; Bursztyn et al., 2017). For example, students who engage with virtual field trips scored higher on a geoscience interest survey, indicating that students were significantly more interested in learning geosciences than before taking the field trips