1 The Case of the Naked Clams

As instructors, we often take for granted that our students have an accurate working knowledge of the natural world. Sure, they probably don't know the details of a particular fossil group or significant event in Earth history – that's why they are taking our course! – but they at least have a rudimentary understanding of natural processes, including how scientific inquiry works and the basic biology of plants and animals. Given the inherent time constraints of a semester-long course, we instructors have to assume some background knowledge in order to get to the interesting stuff, right? Unfortunately, this assumption is contradicted by research that shows all students enter a classroom with a variety of prior conceptions about the course topic, many of which are inaccurate. We ignore these prior conceptions at our peril, as the following example illustrates.

I teach an introductory undergraduate course for nonscience majors called "Life Through Time." This lecture-lab course provides an overview of how scientists study the ancient Earth and discusses key events in the history of life on Earth. We talk at length about evolution and natural selection and then explore specific evolutionary events, from the Cambrian Explosion to the origin of tetrapods to the Mesozoic Marine Revolution. Since I study the evolution of marine mollusks, I use molluscan examples frequently in the course. By the time we arrive at the Mesozoic Marine Revolution, about two-thirds of the way through the semester, I had always assumed my students are comfortable with the idea of paleontologists studying fossil shells to understand molluscan evolution. An off-hand comment made by a student to a graduate teaching assistant (TA), however, showed me how wrong I was.

One semester, in our weekly meeting following the lab activity on the Mesozoic Marine Revolution, I asked the TAs how students had done. Did the array of mollusk shells that students studied in the lab effectively show how mollusks evolved various defenses to make their shells more resistant to predation? One TA said that her students had trouble seeing how the shells related to the evolution of clams and snails, since, as one student put it, "they could pick out any shell off the beach." Huh? When asked to clarify, the student explained that clams and snails found their shells by crawling naked up onto the beach and looking at the various shells found there. They picked out one they liked, then crawled back into the ocean. But where did the shells come from? The student patiently explained that shells are rocks (made of the mineral calcium carbonate, just like she had been taught earlier in the semester) that formed by crystallizing out of the seawater when it washes up on beaches. After all, when you go to the beach, that's where all the shells are. The student was confused about how just looking at fossil shells could tell you about the evolution of particular animal groups, since the different shell forms would be randomly distributed among the animals who came to live in them. Other students then chimed in, telling the TA that they had been having the same confusion, but had been afraid to ask about it. In all, about one-sixth of the students in that lab section admitted to this understanding of shells.

How did these students come to think that shells are rocks, not biologically produced skeletons, part of the anatomy of the animal? For starters, common-sense observation. Where does one find shells in nature? On the beach, of course! And every child learns about hermit crabs, who shop around for a suitable shell to call home. So the naive idea that other shelly animals, like clams and snails, similarly find their shells is not unreasonable. The students then brought this prior conception into my course with them. When I said things that contradicted it, such as explaining that shells are biogenic, produced by organisms to be their skeletons (which I did early in the semester), the students ignored or forgot that information because it did not align with their own conception of what shells are. And all my arguments on how paleontologists use evidence from fossil shells to document evolution – a central learning outcome for this course – were then quite ineffective in the face of this fundamental confusion about "naked clams."

This example illustrates how important it is for instructors to identify and explicitly address the prior conceptions that our students hold. In this Element, I focus on the former problem. I review the scholarly research on prior conceptions, discuss methods for identifying them, and present data on common misconceptions students bring to introductory paleontology courses. A wide range of pedagogical approaches that can help to address these misconceptions is presented in the other Elements in this series.

2 The Challenge of Prior Conceptions

Science educators and education researchers have long worked to understand what strategies can help or hinder student learning. Most modern science education approaches are rooted in the ideals of constructivism, first formalized by psychologist Jean Piaget (Piaget, 1967, 1973; Piaget and Inhelder, 1969) and now used as an essential framework for understanding the learning process (Bransford et al., 2000; Weimer, 2002; Donovan and Bransford, 2005; Wiggins and McTighe, 2005; Kuh, 2008; Nathan and Alibali, 2010; Yacobucci, 2012; Dahl, 2018, this series). Constructivism argues that people learn by integrating new information into the framework defined by their existing knowledge to construct their own personal updated conceptual framework. Therefore, learning can only take place when the learner modifies preexisting conceptions to accommodate the new knowledge. This notion led to the development of a conceptual change model by Posner et al. (1982), which was further elaborated by Hewson (Hewson, 1981, 1992; Hewson and Hewson, 1988). Other key papers on conceptual change include those by Driver and Erickson (1983), Driver et al. (1985, 1994), Treagust (1986), Chi et al. (1994), Dole and Sinatra (1998), Duit and Treagust (2003), and Stepans (2008). Treagust and Duit (2008) provide an accessible review of the history of the conceptual change model in science education and empirical evidence for its effectiveness.

The conceptual change model argues that students must first recognize their own prior conceptions and compare them to the concept being taught. If they align, learning takes place relatively easily. But if the new idea contradicts the prior conception, learning is more difficult. As Hewson (1992) put it:

> Learners use their existing knowledge (i.e. their conceptual ecology), to determine whether . . . a new conception is <u>intelligible</u> (knowing what it means), <u>plausible</u> (believing it to be true), and <u>fruitful</u> (finding it useful). If the new conception is all three, learning proceeds without difficulty . . . If, however, the new conception conflicts with existing conceptions, then it cannot become plausible or fruitful until the learner becomes <u>dissatisfied</u> with the old conceptions. In that event, learning requires that existing conceptions be restructured or even exchanged for the new. (Hewson, 1992, pp. 8–9, emphasis in original)

Following the conceptual change model, then, effective classroom practices will provide students with opportunities to self-reflect on their prior conceptions and evaluate whether those conceptions align with the new information to be learned.

All students enter the science classroom with a host of prior conceptions. These may, in fact, be correct and align well with current scientific understandings, or they may represent incorrect ideas of one sort or another. The research literature on student conceptions uses various terms: 1) prior conceptions; 2) preconceptions; 3) alternative conceptions; 4) naive conceptions; 5) intuitive conceptions; or 6) misconceptions (Cheek, 2010; Francek, 2013; Baldwin and Cooper, 2014). As Cheek (2010) noted, it is important not to assume that any prior conception held by a student is likely to be invalid. Hence, I here use “prior conception” as the general term, reserving “misconception” for demonstrably incorrect ideas. Students come to hold these prior conceptions from a variety of sources, including teachers and instructional materials, but also family members, friends, and various media (Cheek, 2010; Baldwin and Cooper, 2014). Culture and language can also act as important influences on students' conceptual understanding, which has implications for science instruction in diverse classroom settings (Lee, 2001; Solano-Flores and Nelson-Barber, 2001; Luykx et al., 2008; Lee et al., 2009).

Prior conceptions are often deeply rooted and difficult to change, even with instruction (Driver and Easley, 1978; Vosniadou and Brewer, 1992; Chi et al., 1994; Bransford et al., 2000; Donovan and Bransford, 2005). For example, Anderson and Libarkin (2016) found that 22 of 73 questions on the Geoscience Concept Inventory (see later in this Element) showed very small post-instruction gains in a large, national sample. Confronting prior conceptions in the geosciences has some special challenges. Because of its synthetic nature, errors in thinking about geoscience processes may derive from incorrect prior conceptions in other disciplines, like physics, chemistry, or biology (Anderson and Libarkin, 2016). Also, students, even at the undergraduate level, have difficulty thinking in terms of processes and systems. Rather, they tend to focus on learning terminology – they can *name* processes like subduction but cannot explain how those processes actually work (Raia, 2005; Libarkin and Kurdziel, 2006). Paleontology and historical geology courses often use an integrative, Earth system science approach to presenting course material. This systems focus may make deep learning in these types of courses particularly difficult for novice students.

Libarkin (2006) noted that in developing the Geoscience Concept Inventory (GCI), a set of questions used to assess students' prior conceptions in the geosciences, some reviewers thought the questions were much too simplistic for undergraduates. However, many undergraduates have indeed been shown to have exceptionally naive views about how the planet works. Students think volcanic eruptions can only occur in warm climates, clouds are empty vessels that fill up with water or pollution, and Earth's magnetic field is what holds continents and people onto the planet's surface (Libarkin, 2006). Lest one think these misconceptions reflect poor scientific instruction in the United States, Felzmann (2017) found that elite German high school students believed that glacial ice forms when temperatures become very cold and snow "freezes." Intuitive or commonsense concepts (e.g., ice forms from freezing something, magnets pull things together) can lead to incorrect conclusions about natural processes. These ideas are generally invisible to instructors but can have a profound impact on the ability of our students to learn. It was only after years of teaching about the Mesozoic Marine Revolution that I learned about the "naked clam" conception, and only then because a graduate TA thought to probe a student's thinking in the lab and then share that thinking during our weekly instructors' meeting. What else are we missing about how our students think about the history of life on Earth?

3 Exploring Prior Conceptions

Most paleontologists to whom I have told the "naked clam" story have been shocked that anyone could think something so obviously incorrect. Most nonscientists have nodded and said, "yes, I can see where that idea is coming from." Therein lies the problem – we as experts are so far removed from the prior conceptions most of our students hold that it is hard for us to even imagine them (Libarkin, 2006). We just don't think like a novice does. To identify students' prior conceptions, then, we must deploy techniques that make use of students' own reports on their thinking.

3.1 Verbal Explanations

Perhaps the most obvious strategy for determining what prior conceptions students may have is to simply ask them. One might, for instance, make a habit of prompting students to explain the reasoning behind the questions they ask during class. However, students are reluctant to sound "stupid" in front of their instructor and peers, so they are less likely to ask questions rooted in their confusion about basic principles or processes during class time. They are more likely to open up, with some prodding, when talking with an instructor individually during office hours. It can be helpful, then, to invite students to office hours and conduct brief one-on-one interviews in which you probe their understanding of a concept. These interviews can provide the instructor with useful information on, for example, an exam question with which many students struggled, as well as helping the individual students to work through their reasoning.

Still, instructors are usually far removed from the novice-level learner's mind-set, and so may not be able to effectively question students to elicit their prior conceptions. It is more effective to deploy peer undergraduate or graduate student TAs for this task, who can then report their findings back to the instructor. In the "naked clam" example, the smaller-group lab section with a graduate student instructor was a classroom climate in which students were more likely to share their ideas (though even here, it took one student brave enough to broach the topic before other students revealed their similar thinking). The graduate student was able to understand where the student was coming from and ask questions that further elucidated the prior conception. Undergraduate student peer facilitators or learning assistants can also be invaluable informants about student conceptions. During in-class activities, undergraduate assistants can be tasked with circulating among student groups and asking students to explain their thought processes. Since these undergraduate assistants are closer in their knowledge progression to the "novice" students in the course than to the "expert" instructor, they are more likely to think of possible prior conceptions their peers may hold (ideas they may have only recently held themselves) and to be able to draw out student thinking in a nonjudgmental way. Taking this approach a step further, students in a course can be asked to discuss the conceptual basis of an idea or problem with each other, then report on a group's ideas without identifying individual students who held those ideas. The peer instruction movement pioneered by physicist Eric Mazur (Mazur, 1997; Zull, 2004) leverages this ability of fellow students to best understand the thinking processes of their peers; we should make use of this resource!

3.2 Written Explanations

Undergraduate students are generally very good at surface learning, that is, memorizing information in order to parrot it back on assignments and exams without really understanding the reasoning behind the answer (National Survey of Student Engagement, 2005; Nelson-Laird et al., 2008). To elicit student thinking and potential prior conceptions, then, it is useful to ask students to explain in writing *why* they gave the answer they did to a short-answer question and to include on exams and lab activities questions that require a longer written response that asks students to explain their reasoning. In addition to providing data on students' thought processes, requiring students to "write out loud" – work through their ideas as they write a response – can help them identify their prior conceptions and where these conceptions may be leading them to an incorrect understanding (Fulwiler, 1987; McDermott, 2010). Interesting prior conceptions can also be collected as "minute papers" at the end of a class session, by giving students a minute to write down anonymously what ideas they have about the topic or concepts they are confused about. Concept sketches are another effective way of quickly assessing how students are thinking about a problem or process (Johnson and Reynolds, 2005). For a more general sense of what ideas students bring into the classroom, one might create a set of open-ended questions derived from key concepts identified in scientific literacy documents (Climate Literacy Network, 2009; Earth Science Literacy Initiative, 2010). Students can then write about these concepts from their own perspective, perhaps followed up by interviews to further elicit student thinking (Libarkin and Kurdziel, 2001, 2002; Baldwin and Cooper, 2014).

3.3 Formative Assessment Probes and Surveys

Techniques like minute papers are types of formative assessment, activities that instructors use during a learning interval to get feedback on student thinking. This feedback is then used to adjust instruction in ways that improve student learning. If an instructor has some sense of the likely prior conceptions students may hold, formative assessment instruments can be created to determine whether students actually do hold those conceptions.

Formative assessment "probes" are narrowly targeted instruments used to elicit student thinking on one or a few central concepts related to the topic being taught. The use of formative assessment probes in K-12 science education has a lengthy history. Page Keeley and colleagues have developed a large library of simple probes that target particular concepts, mostly under the series name "Uncovering Student Ideas in Science" (Keeley, 2005, 2008, 2015a, 2015b; Keeley and Tugel, 2009; Keeley et al., 2005, 2007, 2008) and on the "Uncovering Student Ideas" website (Keeley, 2011). Figure 1 provides one paleontological example of a formative assessment probe, discussed in Keeley (2015a). Concept probes like this one are designed to be deployed, completed,

Mountaintop Fossil

The Esposito family went hiking on a tall mountain. Mrs. Esposito picked up a shell fossil on the top of the mountain. The fossil was once a shelled organism that lived in the ocean. The family had different ideas about how the fossil ended up there. This is what they thought:

Mrs. Esposito: A bird picked up the organism and dropped the shell as it flew over the mountain.

Mr. Esposito: Water, ice, or wind eventually carried the fossil to the top of the mountain.

Rosa: A mountain formed in an area that was once covered by ocean.

Sofia: The fossil flowed out of a volcano that rose up from the ocean floor.

Whose idea do you most agree with and why? Describe your ideas about how a fossil could end up on the top of a tall mountain.

Figure 1 Sample formative assessment probe (Keeley, 2015a) and scored quickly, so that the instructor can immediately see how many and which students have particular misconceptions about the topic. In the example in Figure 1, students are presented with four alternative explanations for the occurrence of a fossil shell on top of a mountain. Students must state which of the four explanations they agree with and why. While this probe is simple on its face, it forces students to confront fundamental questions about the nature of our planet. Has Earth's surface always been the same or has it changed over time? How do water, wind, and ice move things around the Earth's surface? How do mountains form? How do fossils form? A quick scan of the probe results can tell an instructor which big-picture concepts need to be addressed in class. A word of caution, though: it has been my experience that fellow faculty experts often get the Keeley probes wrong because they overthink the problem. For example, the explanation given by Mrs. Esposito – that a bird dropped the shell as it flew over the mountain – might be seen as perfectly possible, if unlikely, and therefore cannot be rejected with the evidence provided. (This view ignores the information that the bird picked up the "organism," presumably alive at the time and not a fossil.) In these probes, however, the most *likely* explanation is the "correct" one, in this case, Rosa's explanation that the rocks making the mountain were once under the ocean.

Another formative assessment technique built on the instructor's knowledge of likely student misconceptions is the use of student surveys of prior knowledge. In these surveys, students are presented with a set of statements, which may be accurate descriptions of a concept or common misconceptions, and asked to agree or disagree with them. This surveying technique is also meant to be quick to deploy and score, so that busy instructors can efficiently determine whether most of their students understand a concept or hold one or more particular misconceptions on the topic. Surveys can be used before and after instruction on a topic to determine whether the instruction led students away from misconceptions and toward correct understandings or had no (or even a negative) impact on student understanding.

Note that formative assessment techniques can only improve student learning if they are used intentionally and the results form the basis for instruction. Yin et al. (2008) found that formative assessment instruments were effective for eliciting middle school students' prior conceptions, but teachers often found it difficult to provide meaningful feedback to students or to explain to students *why* their misconception was incorrect. Other teachers in Yin et al.'s (2008) study did not modify their instruction at all based on the results of the assessment. These sorts of problems are likely to be exacerbated in university classrooms, where instructors are not well trained in pedagogical techniques or rewarded for committing time to revising course content.

3.4 Conceptests

Conceptests are short, multiple-choice instruments with questions that each target a specific concept and are designed to determine whether students have a correct understanding of the concept or hold one or more incorrect views (Lindell et al., 2007; Undersander et al., 2017). Conceptests are often drawn from an established concept inventory, a pool of at least 20 questions targeting prior conceptions, but they can also be derived from an instructor's own observations and data. The development and use of concept inventories was pioneered by the physics education community (Hestenes et al., 1992; Lindell et al., 2007); there are now established concept inventories for chemistry (Mulford and Robinson, 2002; Pavelich et al., 2004), biology (Garvin-Doxas and Klymkowsky, 2008; Smith et al., 2008; Smith and Tanner, 2010; Perez et al., 2013), astronomy (Bilici et al., 2011), and oceanography (Arthurs et al., 2015), among others (Libarkin, 2008). The GCI is a validated and reliable set of nearly 200 multiple-choice questions that can be used to assess students' prior conceptions on a variety of geoscience topics (Libarkin and Anderson, 2005, 2007a, 2007b; Libarkin et al., 2005, 2011; Libarkin, 2008; Ward et al., 2010). The GCI is available online, including access to all questions and with opportunities to submit new GCI questions (Geoscience Concept Inventory Wiki, no date).

Writing effective multiple-choice conceptest questions that provide meaningful feedback on student learning takes practice. Because undergraduates are often adept at memorization, surface learning, and test-taking, they may select the correct answer on a multiple-choice question by a process of elimination rather than an understanding of the question. It is essential that the distractor choices be plausible misconceptions (avoiding extremes like "always" and "never"), and formatted in a similar way to the correct answer so students cannot automatically eliminate them as choices (Libarkin, 2008; Anderson and Libarkin, 2016). Three to five options for answers are ideal. Avoid "none of the above" as a correct answer, as it does not reveal anything about whether the students know the actual answer to the question, as well as "all of the above," as it only requires the student to identify two correct options. Use caution with wording of both the question stem and distractors, avoiding scientific jargon and complex sentence construction, so as not to make the question a test of language ability rather than scientific understanding. Incorrect ideas observed in previous students' work in the same course generally make the most plausible distractors on conceptests. Also, conceptest questions that go beyond memorization by requiring students to apply their knowledge to a new problem or context will more effectively reveal student misconceptions. It is important to collect data on student responses over multiple administrations of a question. Distractor options that are consistently ignored by students should be replaced with more plausible ones.

3.5 Published Literature on Prior Conceptions

In addition to assessing one's own students, a variety of published sources can be used to identify common misconceptions in the nature of science, geoscience, and life science. Concept inventories like the GCI described earlier are a good place to start. Several websites also provide lists of misconceptions, including Indiana University's Evolution and the Nature of Science Institutes (ENSI) website (Flammer, 1999), and the excellent websites Understanding Science (Understanding Science, 2017) and Understanding Evolution (Understanding Evolution, 2017) created by the University of California Museum of Paleontology. A large literature reflects a steady stream of research studies that have identified common student misconceptions in the geosciences, including the topics of plate tectonics (Sibley, 2005; Clark et al., 2011; Smith and Bermea, 2012), Earth's interior (Steer et al., 2005; Capps et al., 2013), landscapes and surface processes (Martínez et al., 2012; Sexton, 2012; Jolley et al., 2013), glaciers and ice ages (Felzmann, 2017), geologic time (Trend, 1998, 2000, 2001; Dodick and Orion, 2003; Hidalgo and Otero, 2004; Libarkin et al., 2007; Teed and Slattery, 2011), climate change (Rebich and Gautier, 2005; Lambert et al., 2012; Baldwin and Cooper, 2014; Bodzin et al., 2014; McCuin et al., 2014; McNeal et al., 2014; Reichert et al., 2014), oceanography (Arthurs et al., 2015), and Earth systems (Raia, 2005; Libarkin and Kurdziel, 2006; Sell et al., 2006). For more general overviews of geoscience conceptions research, see Phillips (1991), Schoon (1992), Dove (1998), McConnell et al. (2005, 2006), Petcovic and Ruhf (2008), Reinfried and Schuler (2009), Cheek (2010), Francek (2013), and Wild et al. (2013). Of particular note are the extensive studies on geoscience concepts done by Julie Libarkin and colleagues, including Libarkin and Kurdziel (2001), Dahl et al. (2005), Libarkin (2008), Libarkin et al. (2014), and Anderson and Libarkin (2016). Life science education researchers have also identified common student misconceptions that might be useful to instructors of paleontology and historical geology courses (Anderson et al., 2002; D'Avanzo, 2008; Garvin-Doxas and Klymkowsky, 2008; Smith et al., 2008).

Despite this research base, a notable gap exists in the student prior conceptions literature on topics specific to paleontology, such as the fossilization process, the origin and nature of early life on Earth, major evolutionary