A Field-Based Biomimicry Exercise Helps Students Discover Connections Among Biodiversity, Form and Function, and Species Conservation During Earth's Sixth Extinction

Constance M. Soja[1,a]

ABSTRACT

In a first-year seminar on mass extinctions, a field-based, paleontology-focused exercise promotes active learning about Earth's biodiversity, form and function, and the biomimicry potential of ancient and modern life. Students study Devonian fossils at a local quarry and gain foundational experience in describing anatomy and relating form to biological function. Another goal is to give students a firsthand opportunity to evaluate the fossil record and what it reveals about past mass extinction episodes on our planet. Students who complete this exercise acquire the basic tools for developing and testing hypotheses. They become more skilled at making observations and inferences about familiar species that live in modern environments and about the strange and marvelous creatures that inhabited Earth's lost worlds. Finally, students gain valuable insights into how bioinspired designs can solve human problems in a sustainable way, elevating their appreciation for the value of species conservation as the Sixth Extinction gains traction. © *2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-095.1]

Key words: biomimicry, biodiversity, form and function, Sixth Extinction

INTRODUCTION

This exercise is designed to promote active learning about Earth's biodiversity, form and function, and the biomimicry potential of ancient and modern life. Students explore these concepts in a first-year paleontology-focused seminar titled "The Sixth Extinction," in which they compare Earth's "big five" mass extinctions with our modern biodiversity crisis (Eldredge, 1991; Leakey and Lewin, 1995). During the first half of the term, students examine the timing, causes, and consequences of the Ordovician, Devonian, Permian, Cretaceous, and Pleistocene mass extinctions (Elewa, 2010). In the second part of the course, students use their knowledge of these past events to hypothesize about and investigate the severity of the Sixth Extinction, which many scientists believe is already under way as a result of a relatively new and formidable evolutionary force, *Homo sapiens* (Hooper et al., 2012; Soja, 2012).

Students examine scientific evidence for climate and ocean change (Blois et al., 2013; Moritz and Agudo, 2013; Norris et al., 2013), and they discuss modern conservation practices that strive to enhance the future existence of a biologically diverse planet (Sodhi and Ehrlich, 2010). To expand awareness of ecosystem services (Baskin, 1997) and the value of species conservation, the students complete a final project by undertaking library- and Web-based research on biomimicry, an emerging field that uses novel scientific approaches to solve human problems through biologically inspired designs and innovations (Benyus, 1997, 2007; Baumeister, 2013). That final research project helps students explore how a particular organism might be (or is already) the basis for bioinspired designs (Forbes, 2006; Holtcamp, 2009; Danigelis, 2011; Meyers, 2011; Eberlein, 2012).

By explaining in written and oral form how species inspire new ways to help humankind, improve sustainability, etc., students become more knowledgeable—and are able to help educate others—about the value of nature during a time of rapid environmental transition (Baskin, 1997; Benyus, 1997; Cardinale et al., 2012; Schmeisser and Doss, 2014). Their ability to do so in a meaningful way is enhanced by the completion of the field-based biomimicry exercise, in which students gain confidence relating anatomy to biological function as the basis for assessing a species' biomimicry potential.

OVERVIEW OF COURSE AND STUDENT DEMOGRAPHICS

First-Year Seminar Program at Colgate University

Colgate University is a small, private, liberal arts college that enrolls ~2,900 students, primarily 18–21 years in age. First-year seminars (FSEMs) at Colgate are designed to be small, writing-intensive courses that are restricted to 18 students. The goal is for all incoming students to gain experience in writing, critical reading, and information literacy during their first semester in college. Instructors of FSEM courses are responsible for explaining Colgate's academic honor code to ensure that students are familiar with how academic dishonesty is defined; with behaviors that constitute academic dishonesty, including plagiarism; and with procedures for reporting violations. Most FSEMs cover course content that allows students to fulfill an additional graduation requirement in Colgate's liberal arts core curriculum. Finally, instructors of these courses serve as academic advisers of their FSEM students until those students declare a major, no later than midway through the second semester of their sophomore year.

Received 17 September 2013; revised 10 February 2014 and 18 April 2014; accepted 14 May 2014; published online 19 November 2014.

[1]Department of Geology, Colgate University, Hamilton, NY 13346, USA
[a]Author to whom correspondence should be addressed. Electronic mail: csoja@colgate.edu. Tel.: 315-228-7200. Fax: 315-228-7187

Student Demographics

Incoming first-year students submit course requests to the registrar a month before their arrival on campus for orientation in late August. Enough FSEM courses are offered each fall on a variety of topics that most students are registered in one of their top two (of six) choices for an FSEM.

Most of the students who have taken my FSEM in years past had no (or limited) knowledge of geology and planned to major in science, primarily biology (premed), neuroscience, chemistry, or rarely, geology. Nonscience-focused students typically leaned toward a major in economics, political science, or environmental studies. Generally, most hailed from New England and mid-Atlantic states, but a third of the students were from the Midwest, South, or West. Gender ratios have always been well balanced, but each class has been typically composed of 10% or less of non-Caucasian or international students (which reflects the approximate percentage of such students who major in geology at Colgate).

End-of-term teaching evaluation forms indicate that students selected my FSEM because "it sounded interesting," "it was relevant to today's climate of environmental concerns," "sustainability is becoming increasingly important so it is good to have a better understanding of it," and "it also fulfilled a Core requirement." Three students explained further: "It was a course about death and fossils, which was different from your everyday class"; "I was excited to learn about how we could be in the midst of an extinction and not fully know it"; and "I wanted to go on the field trip to the zoo."

FSEM on the Sixth Extinction

The goal of my FSEM on the Sixth Extinction is to introduce students to the fossil record and the insights it reveals about past and current intervals of significant change in Earth's biosphere. Students learn that paleontology's record of past life reveals that our planet has experienced multiple cataclysmic events, or mass extinctions, in its 4.5 billion-year history. In each instance, the mass extinction had a profound effect on Earth's history by redirecting the course of evolution (Elewa, 2010). As detectives attempting to solve the world's greatest mass die-offs, students examine when each of these catastrophic events occurred, what caused ecosystems and evolutionary processes to be disrupted, why and where biological diversity was greatly diminished, and who survived to begin the evolutionary repair of life during subsequent recovery and radiation phases (Rohde and Muller, 2005).

In the final part of the course, students compare these past mass extinctions with our modern biodiversity crisis, the so-called Sixth Extinction (Leakey and Lewin, 1995; Eldredge, 2001; Kolbert, 2009a, 2009b, 2014; Soja, 2012; ScienceDaily, 2013). Students examine a variety of modern conservation practices and debate controversial topics, such as whether an amendment to the U.S. Constitution should be ratified that would guarantee the right to a healthy environment (Orr, 2003, 2004, 2006), whether "rewilding" should take place in North America to reinstate apex predators and restore landscape connectivity (Donlan et al., 2005; Zimov, 2012), and whether human population growth should be controlled by limiting family size (*Economist,* 2010; Kunzig, 2011).

To foster proactive conversations about solutions to the global decline in biodiversity, each student completes a library- and Web-based research project and prepares a short, symposium-style talk on the biomimicry of one species. Students must uncover a connection between the form and function of their organism and bioinspired applications, and they must discuss sustainability implications.

Before undertaking this project, students learn how practitioners of biomimicry draw inspiration from nature and apply scientific knowledge to meet human needs in a sustainable way (Benyus, 1997; Forbes, 2006; Baumeister, 2013). For example, we discuss some recent advances in biomedicine that stem from the discovery of anticancer and other compounds in rainforest and reef species (Balunas and Kinghorn, 2005; ScienceDaily, 2007), the use of corals as "bone" grafts during orthopedic surgery (Guillemin et al., 1987), and new designs for medical pumps (and wind turbines) inspired by jellyfish (Moyer, 2010; ScienceDaily, 2010). Students also read about how butterfly wings, termites, and the scalloped edges of whale flippers are the basis for new products designed for human use (improved solar cells; energy efficiency, passive cooling, and ventilation; and submarine mobility, respectively; Holtcamp, 2009).

To dispel the notion that modern organisms alone have inspired biomimicry applications, students discuss Cambrian fossils that led to the development of military software. That computer program uses evolutionary theory and evidence for the first appearance of predators during the Cambrian "explosion" to predict terrorist attacks and to develop countermeasures that would prevent those and other kinds of threats (Parker, 2004). These and related discussions emphasize how the successful application of bioinspired designs is based on an understanding of the form and function of extinct and extant species.

With respect to learning objectives, students who pass the course are able to (1) describe organisms, ecological structure, and coevolutionary relationships among key species affected by mass extinction episodes in Earth's past; (2) explain the causes and consequences of biodiversity degradation in the past and today; (3) discuss a range of ecosystem services associated with past and present species; (4) converse about "shifting ecological baselines" and holistic conservation strategies; (5) understand biomimicry as an emerging field that can expand human awareness of the value of nature; (6) pose "what if" scenarios about the biomimicry potential of organisms based on their form and function; and (7) present orally—and write clearly about—the results of science-focused research.

BIOMIMICRY FIELD EXERCISE

The purpose of the field exercise is for students to collect data about fossils so that they can compare the biodiversity and the form and function of present and past life in central New York. That information serves as the basis for suggesting bioinspired design solutions to human problems. The field activity is best suited for instructors who teach in areas where fossils are exposed in local quarries or "spoil pits." Central New York State is world famous for the astonishing variety of well-preserved marine fossils that are found near the village of Hamilton and Colgate University in rocks of Devonian age (~375 million years old). These

TABLE I: Online resources for biomimicry and bioinspired design principles.

Resource	Web Site
Ask Nature	
"free, open-source project. . .that organizes the world's biological literature by function"	http://asknature.org/
Bio Dream Machine	
"a site for K–12 teachers and professionals looking for ways to show nature as an inspiration and guide for problem-solving"	http://biodreammachine.org/
Biomimicry 3.8	
"global leader in biomimicry innovation, training, and education"	http://biomimicry.net/
Encyclopedia of Life	
"global access to information and pictures of all species known to science"	http://eol.org/
Global Biomimicry Network	
"regional networks partnered with Biomimicry 3.8 to catalyze the application of biomimicry worldwide"	http://biomimicry.net/connecting/regional-networks/
The Challenge to Biology: Design Spiral	
"a visual representation of a biomimicry-inspired design process"	http://www.livingprinciples.org/biomimicry/

exceptional fossil-rich deposits are exposed across a 200-mile region in the rural center of the state, including a woodland quarry on Colgate's campus where stones were extracted for college buildings in the 1800s.

Although this field-based activity focuses on Devonian marine invertebrates, it can be adapted to any age of fossiliferous deposit or any type of preserved remains. For those who lack access to a nearby fossil locality, Devonian specimens from central New York may be available to teachers who request such materials from the Paleontological Research Institution as part of an educational, specimen-based project developed jointly with Cornell University (Fossil Finders, 2014). Alternatively, a suite of fossils or modern shells culled from university collections or purchased online could be used. Students could also study fossil and modern specimens on exhibit in natural history museums, zoos, or aquariums.

The exercise can be completed as a 2- or 3-h lab or extended class. As discussed below, the field exercise is divided into four sections: (1) examination of modern forms in nature, (2) investigation of Devonian fossil forms, (3) anatomical comparison of Devonian and modern species, and (4) "what if" scenarios for bioinspired applications. Instructor (and student) online resources for biomimicry, bioinspired design principles, and brainstorming techniques are listed in Table I.

Preparation for the Exercise

To prepare for the field exercise, students examine paleontological specimens during a 50-min, in-class discussion to gain an appreciation for symmetry in nature, fossil preservational styles, and the range of processes involved in converting bone to stone. In a guided inquiry, students work in small groups to see how many categories of symmetry they can recognize in a suite of specimens. Afterward, a group discussion focuses the students' attention on basic differences in symmetry: radial (more or less even repetition of parts around a central point), bilateral (plane of symmetry divides individual into two equal parts), and asymmetry (absence of symmetry in the proportion or spacing of an individual's parts). Students then work together to identify how the specimens vary in how they are fossilized so that they can begin to ascertain categories of preservational styles (Table II) that will be evident at the field site.

Students also watch a 20-min Technology, Entertainment, Design (TED) video online (on their own time) presented by Janine Benyus (Benyus, 2009), the author of the biomimicry text assigned for the course (Benyus, 1997), before engaging in classroom discussion about biomimicry in action. The TED video makes direct connections to the in-class exercise, emphasizing "In Nature, shape is synonymous with function" (Benyus, 1997:203).

Finally, students watch *Second Nature: The Biomimicry Evolution* (Lieberman and Rosmarin, 2010), a 25-min DVD that is placed on 2-h reserve in the library. Students are asked to view the program on a library computer, either on their own or in a small group, and to take good notes that will serve as a reference throughout the term. As a part of that assignment, students demonstrate that they understand the "what if" concept discussed in the video by filling in the blanks in Table III.

These preparatory exercises help students gain fluency with basic concepts. In particular, the exercises build on what students surmised earlier during the in-class exercise: form, as described by Gilbert (2007), refers to the shapes (or patterns of microshapes) that achieve a certain organismal function (e.g., the seed pod of an iris, a flowering plant, is cuplike; 5 cm, or ~2 in. deep; and holds small, dense seeds inside three rigid walls). Function refers to a series of actions that work together to achieve an end (e.g., the pod is a "package" for protecting and transporting seeds to a site where a new plant will grow after the pod breaks open). Bioinnovation is the process by which human problems are solved sustainably by replicating (or improving) time-tested adaptations evident in nature. The biomimicry design process begins by asking "what if" questions (e.g., "What if we could use a seed pod's form and function to design a new packaging system?" or "What if we could use biodegradable materials to recreate the pod's shape so that

TABLE II: Modes of fossilization.[1]

I. Hard part (skeletal) preservation	
	A. Unaltered: "Pristine" preservation of actual shells, bones, teeth, and wood and of "tests" (microshells) of microscopic organisms, etc., in the sedimentary matrix
	B. Altered: Preservation of hard parts resulting from one or more of the following processes:
	1. Carbonization: Original form preserved as a thin carbon film through distillation and degradation of unstable compounds; common in fish, plants, and insects
	2. Permineralization (petrifaction): Open spaces, pores, and voids filled in with minerals, sediment, or soil; common in wood and bone
	3. Recrystallization: Unstable mineral phase that changes to a more stable form involving no change in chemical composition but possible change in crystal size; common in shells
	4. Replacement: Original hard parts replaced by another mineral involving a chemical change in composition; common in calcite shells replaced by quartz or pyrite (fool's gold)
	C. Molds and casts
	1. Mold: Two-dimensional impression or imprint in sediment of an organism—without preservation of the hard parts that left the imprint
	2. Cast: Three-dimensional replica of the original organism produced by infilling of a shell and later dissolution of the hard part
II. Trace fossils: Evidence left—while organisms are alive—of their activities and behaviors	
	A. Track: Impression left by a single appendage of an organism (e.g., dinosaur footprint)
	B. Trail (or trackway): Series of tracks left by one organism (e.g., dinosaur trackway)
	C. Burrow: Excavation (hole or tunnel) made in soft material (e.g., worm burrow)
	D. Boring: Excavation made in hard substances, such as shell or wood (e.g., borehole drilled in a clam by a predatory snail)
	E. Coprolite: Fossil excrement typically preserved by replacement (e.g., dinosaur dung)
	F. Human artifacts: Evidence of human culture and behavior (Paleolithic art, stone tools, etc.)

[1]Fossils are actual remains, imprints, or casts (of bones, teeth, shells, wood, or rarely, fur or flesh) or traces (behavioral evidence derived from fossil footprints, burrows, feces, etc.) of preexisting life generally older than 10,000 years. Pseudofossils are naturally occurring, geologic objects that may resemble fossils but originate without organic influence. These "fake fossils" are objects such as concretions, nodules, mineral dendrites, porous volcanic rock, physical sedimentary structures, and weathering phenomena.

it is rigid enough for transportation but can be closed, opened, and reused without the need for tape?")

Ensuring that students are familiar with these concepts before beginning the exercise helps them appreciate that bioinspired products are based on studying organisms and their environmental adaptations (Baumeister, 2013). Students grasp that an organism's form and function reflects, to a large extent, life's response to physical forces and space constraints (Feininger, 1956). These phenomena act upon and modify shape, an individual's anatomy and morphology (Schneider, 1995; Burnett and Matsen, 2002). These concepts precipitate discussions about why evolution by natural selection favors certain anatomical traits as adaptations that are best suited to particular ecological and environmental conditions (because they impart reproductive advantages).

These conversations also help students comprehend why distinct morphologies in closely (or distantly) related species reflect widely divergent lifestyle pursuits and functions. Conversely, students can appreciate why distantly related species lineages that pursue similar lifestyles in similar types of habitats tend to have certain morphological features in common. We discuss, for example, distantly related marine predators, such as squid (invertebrate mollusks) and sharks (cartilaginous vertebrates), which shared a common ancestor more than 500 million years ago. Students who comprehend basic evolutionary principles can explain why both groups have bilateral symmetry, a streamlined shape, swimming dexterity, and refined sensory organs (natural selection favored those features as "best practice," or most reproductively successful, adaptations for the pursuit of prey in a watery environment).

TABLE III: While watching the *Second Nature: The Biomimicry Evolution* DVD, students record ideas about bioinspired applications by filling in the blanks below.

Critter	Form and Function	"What if" bioinspired product idea
Example: Kingfisher	*Streamlined shape allows for splash- and noiseproof entry into water*	*What if we could emulate the kingfisher's form and function by redesigning high-speed trains to increase fuel efficiency and reduce noise?*
Zebra		
Giraffe		
Your favorite critter—indicate & explain		

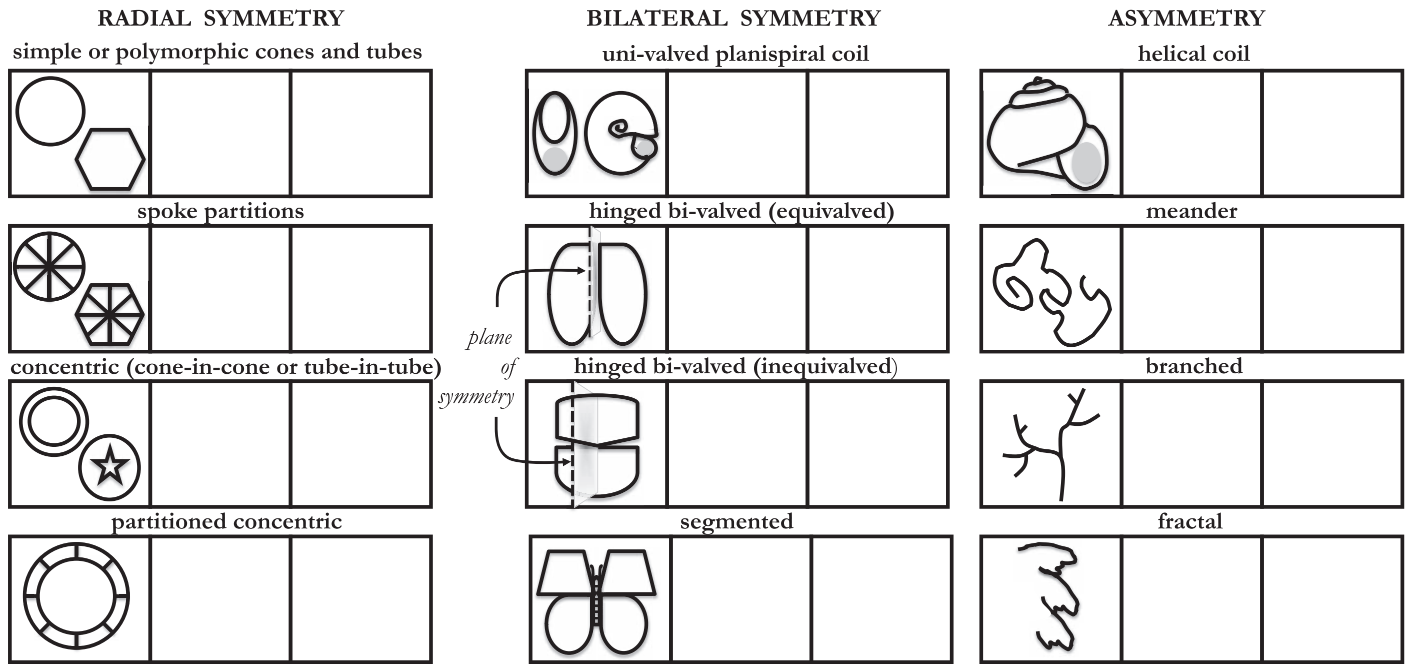

FIGURE 1: Students record their observations in the blanks above about modern and fossil species. This figure is duplicated in the assignment so that students have two copies on which to record information about modern species (Part 1) and Devonian fossils (Part 3).

Part 1: "Hunt in the 'Hood" (Modern Forms in Nature)

After arrival at the fossil site, a 15-min drive from campus, students do an expanded version (described herein) of Schroeter's "Numbers Hunt in the 'Hood" exercise (Schroeter, 2010:14). The goal of Part 1 is for students to learn more about the form and function of modern life as a basis for making comparisons with Devonian fossils. Students begin by examining the sketches in Fig. 1, showing symmetry and common forms in nature, as a reminder of what they deduced in the previous in-class, interactive discussion. They are allotted 15–20 min to explore nature near the quarry, searching for and collecting (but not harming) living organisms that have shapes associated with the three symmetry categories (or new categories to be discussed). To complete the first part of this exercise, students sketch and label two examples for each category in the blank boxes in Fig. 1.

Students' Results

During a short group discussion, students describe what they found, explaining which forms were easiest to locate and which were most difficult (and why this might be). Most students recognize that radial symmetry is well represented at the site, especially in plants, including their stems, flowers, berries, and the concentric radial symmetry exposed in the cross-section of weathered tree stumps. Students also note the bilateral symmetry of some plant leaves, seeds, and various kinds of arthropods—ants, butterflies, and beetles. Asymmetrical and fractal patterns are evident in branching plants and in insect bite marks and mold growth on plant leaves. Observations of moss with a hand lens reveal that individual stems support a radial arrangement of leaves, which belies the moss's otherwise asymmetrical clumped growth. In sum, working initially with living (and familiar) organisms helps students gain additional facility in recognizing symmetry and common shapes, reinforcing students' understanding of how form reflects function in modern species before turning their attention to evidence from the past.

Part 2: "Hunt in the 'Hood" (Fossil Forms in Nature)

In the second part of the exercise, students work with a partner to examine Devonian fossils with two goals in mind: (1) to test ideas about the diversity of Devonian life that once existed near Hamilton and (2) to assess whether forms in nature during the Devonian were similar to or different from those that are common today.

Students begin the second part of the exercise by writing a hypothesis about what they think the biodiversity of organisms was and what type of plant or animal was dominant in central New York in the Devonian. In other words, before examining the fossils preserved in the rocks at their feet, students must hypothesize about how life near Colgate was different in the past (more than 300 million years ago) from today.

Students may feel hesitant to state even a simple hypothesis if they lack background knowledge about past life. Yet this part of the exercise has value because it teaches students that hypotheses are a starting point for pursuing the answer to a scientific question. A goal of the exercise is to help students appreciate how scientific knowledge accrues when observations and data collected by many individuals are used to confirm, reject, or reformulate hypotheses. After students share their hypotheses with one another, they recognize the value of collecting sufficient information to determine which of the multiple working hypotheses (or elements thereof) is supported by the evidence. In truth, most students formulate hypotheses that their data refute, revealing that brachiopods—and not insects, trilobites,

FIGURE 2: Typical Devonian fossils found at the rock quarry. Photographs of Middle Devonian fossils from central New York State that are housed in the R.M. Linsley Collections, Department of Geology, Colgate University, Hamilton, NY.

clams, snails, plants, or "woolly mammoths and ancient bears"—dominated central New York in the Devonian.

Next, working with a partner and referring to Fig. 2, students turn over loose pieces of shale in the search for Devonian fossils (Fig. 3). They identify how many major groups of fossil organisms occur in the rocks and then estimate, based on the range of anatomical forms, how many different species occur within each major group. Students circle the type of "critter" in Fig. 2 that dominated during the Devonian and write an estimate of the number of species next to each major group. Student partners are then asked to explain why their data do or do not correspond to their original hypothesis.

Students' Results

After spending 45 min collecting fossils, students discuss their results. They are asked to explain how most of the fossils are preserved, referring back to the in-class exercise (Table II). They also must think about taphonomic processes (those that affect organisms from the time of death until burial and preservation) that could have influenced the geologic record of some of the original inhabitants. This discussion reinforces concepts considered in class about the incomplete nature of the fossil record and its impact on our assessment of mass extinction events.

Students note that most of the specimens they recovered are fossilized as impressions (external molds) or thin carbon films (carbonized; Table II and Fig. 2). In some instances, the last vestige of a brachiopod's shell has not worn away, revealing how molds formed at the site. Students are then asked to consider whether any of the fossils they examined have living descendants. This provides an opportunity for students to think about the impact of past extinction episodes on life near Colgate today. Discussions ensue

FIGURE 3: Students examining Devonian fossils exposed in loose shale beds near Hamilton, New York. Note modern species available for study in the background.

about surviving arthropods that are evolutionary "cousins" of the extinct trilobites, the abundance and diversity of surviving mollusks, the near demise of brachiopods in modern habitats (Emig et al., 2014), and the absence of woolly mammoth bones and teeth in Devonian rocks but their presence in local Pleistocene glacial gravels.

Using all available evidence, students then suggest the most likely type of environment in which the organisms lived near Hamilton 375 million years ago and write their answer in Table IV. The abundance of certain fossil types (clams, brachiopods, sea lilies, etc.) prompts discussions about the ancient aquatic environment that once supported a diversity of invertebrate life in central New York. Students are then asked to reflect on whether sufficient evidence exists to determine whether the aquatic habitat was freshwater or saltwater. For novice paleontologists, the answer is not immediately obvious. A guided discussion about the restriction of certain modern and extinct taxa (brachiopods, coral, crinoids, etc.) to marine habitats helps elevate student confidence in recognizing that the fossil specimens reflect the existence of a vast epeiric sea that once covered expansive portions of eastern North America. Invariably, students ask about the absence of fish, which spawns further discussion about the poor preservational conditions at the site for vertebrate remains.

Part 3: Comparing Anatomy in Devonian and Modern Species

Students learn in previous parts of the exercise, on the basis of observation, data collection, and discussion, that Devonian life near Hamilton was adapted to a drastically different kind of environment than what exists there today (ancient shallow-marine setting versus modern terrestrial woodland). To help gain more experience at recognizing how form reflects function, students are asked to complete this part of the exercise by finding out whether Devonian life shared forms in common life today.

Students begin this section by writing a hypothesis about whether they think Devonian life had forms that were like those commonly found today. In other words, students are asked to consider how Devonian life, specifically its anatomical forms, was similar to or different from what exists today. To focus students' attention on ancient examples of form and function, they next sketch and label how many of nature's common shapes are evident in specific types of Devonian fossils (Fig. 1).

Students' Results and Discussion

Most students readily appreciate that many invertebrates exhibit bilateral symmetry; thus, they predict they will find a preponderance of fossils with a variety of bilaterally symmetrical shapes. Yet students note surprise when comparing the widespread evidence for radial symmetry in modern species at the site and the general lack of radial shapes in the fossils. Further discussion helps students identify which types of marine invertebrates commonly exhibit radial symmetry. Corals, sea lilies (crinoids), and other radially symmetrical invertebrates are rare in the fossil quarry most likely because the fine-grained substrate, which comprised shifting silt and mud, prevented their colonization. The world's first forests evolved during the Devonian, but land plants (and their radially symmetrical stems and branches) are rarely preserved in marine sediment of that age (Stein et al., 2012).

The following questions can be used to elicit additional discussion and student insights *{ideas for instructors are bracketed in italics below}:*

- Do terrestrial and nonterrestrial life share any shapes (are conditions in those two environments similar enough to play a significant role in shaping similar

TABLE IV: Students fill in the queried blank with their hypothesis about the type of environment inhabited by the Devonian fossils.

	Hunt in the 'Hood: Part 1	Hunt in the 'Hood: Part 2
Environment	Terrestrial—open woodland	???
Age	0 million years (modern)	375 million years (Devonian)
Organisms	Living	Fossil
Form and Function	*Example: Flower: Radial symmetry & clustered petals provide expanded surface area for capturing sunlight, attracting pollinators, collecting dew, etc.*	TBD (see Table V)[1]

[1]In the final part of the exercise, they fill in the to be determined (TBD) section, describing a "what if" bioinspired application based on one of the Devonian fossils they examined (Table V).

TABLE V: Following the example provided, students complete the field assignment by generating an idea about a bioinspired application based on one of the fossil specimens. Student-generated ideas are tabulated below (A–F).

Fossil	Form and Function	"What If" Bioinspired Product Idea
Example		
Trilobite	*Streamlined body, plowlike head, and raised eyes facilitated burrowing in sediment as a camouflaged predator*	*What if electronic sensors attached to front end of a shovel's head could detect buried objects?*
Students' Ideas		
Your favorite fossil—indicate & explain		
A. Moss animal (bryozoan)	Large surface area maximizes water and nutrient filtration	What if we used this method of absorption and water utilization to capture moisture from clouds and improve water flow and waste removal in buildings?
B. Lamp shell (brachiopod)	Strong, layered shell, has multiple ridges and longitudinal grooves and is undeformed after millions of years of burial in rock	What if we could build a stronger, crack-resistant cement to protect buildings and sidewalks in earthquake zones? Or what if the sides of buildings had vertical grooves to capture and recycle rainwater? Or could door closures be improved by designing a perimeter door seal, rather than a single point where the door locks?
C. Sea lily (crinoid)	Long, cylindrical body with strandlike arms surrounding head used to filter food	What if we could produce strong, flexible filtration strands to aid in minimizing ocean pollution? Or what if robotic grasping appendages could be improved based on the flexibility of the crinoid's arms?
D. Worm burrows	Soft-bodied "critters" use strength to push through soft sediment, creating reinforced, uncollapsed, cylindrical, curved burrows	What if better subway systems could be built using tunnels based on nature's curves rather than straight lines?
E. Trilobite	Thin body and large surface area allow it to float and propel itself across ocean floor	What if submarines were redesigned after the trilobite to improve flotation and subaquatic hovering?
F. Snail	Spiral shell grows in ever-expanding radius, achieving seafloor stability	What if a better waterslide could be designed in the form of a snail?

anatomy)? *{Yes, most, if not all, of the shapes shown in Fig. 1 can be found in terrestrial and marine species. Students might have hypothesized that life on land, shaped by the medium of air, would be very different from aquatic life, lived submerged in a watery medium. In this exercise, students discover that the overriding physical forces that influence life apply "equally" in air and in water (i.e., gravity still operates underwater). Similar shapes in terrestrial and marine species reflect this.}*

- Which particular shapes are not shared among terrestrial and nonterrestrial life? *{As noted above (but see below), most, if not all, of the shapes shown in Fig. 1 can be found in terrestrial and marine species. Students may not have encountered bilaterally symmetrical, hinged bivalved species at the modern woodland site, but similar shapes occur in some seed pods of terrestrial plants, etc.}*
- Since life has evolved through time (speciation is life's response to environmental change), have any shapes disappeared since the Devonian (i.e., are not evident in modern life) or have any new shapes appeared since the Devonian (i.e., are evident now but not in the Devonian fossils)? *{Except for the radially symmetrical, partitioned concentric shape, all others have representatives today and in the past, beginning with the first appearance of shells about 550 million years ago. The partitioned concentric shape is characteristic of a once-abundant, highly successful, globally distributed group of sponges called archaeocyathids ("ancient cups"). The partitioned concentric shape appears to have gone extinct when archaeocyathids disappeared from Earth—and left no direct descendants—approximately 500 million years ago (Debrenne, 1991). Yet some students noted that the pumpkins growing in the farmer's adjacent garden were similar to the partitioned concentric form, given the pumpkin's "hollow" internal structure and the spokelike, radial arrangement of its seeds.}*

Part 4: "What If" Bioinspired Application

In the last part of the exercise, students are asked to brainstorm on how form reflects function in one of the extinct species they collected. Once students have identified a favorite fossil and identified its form and function, each student pair must suggest a "what if" bioinspired application (Table V). Before they start, we discuss examples of different anatomical forms that serve the same function for filtering food in radically different species (Fig. 4). To give additional examples, as shown in the fossil images (Fig. 2), some of the brachiopod species had an exceptionally wide hinge, which as an expanded snowshoelike "platform" gave it more stability on the seafloor, and the (rare) crinoid specimens that students found exhibited radial symmetry, which afforded the cylindrical, arm-bearing, stationary animal a

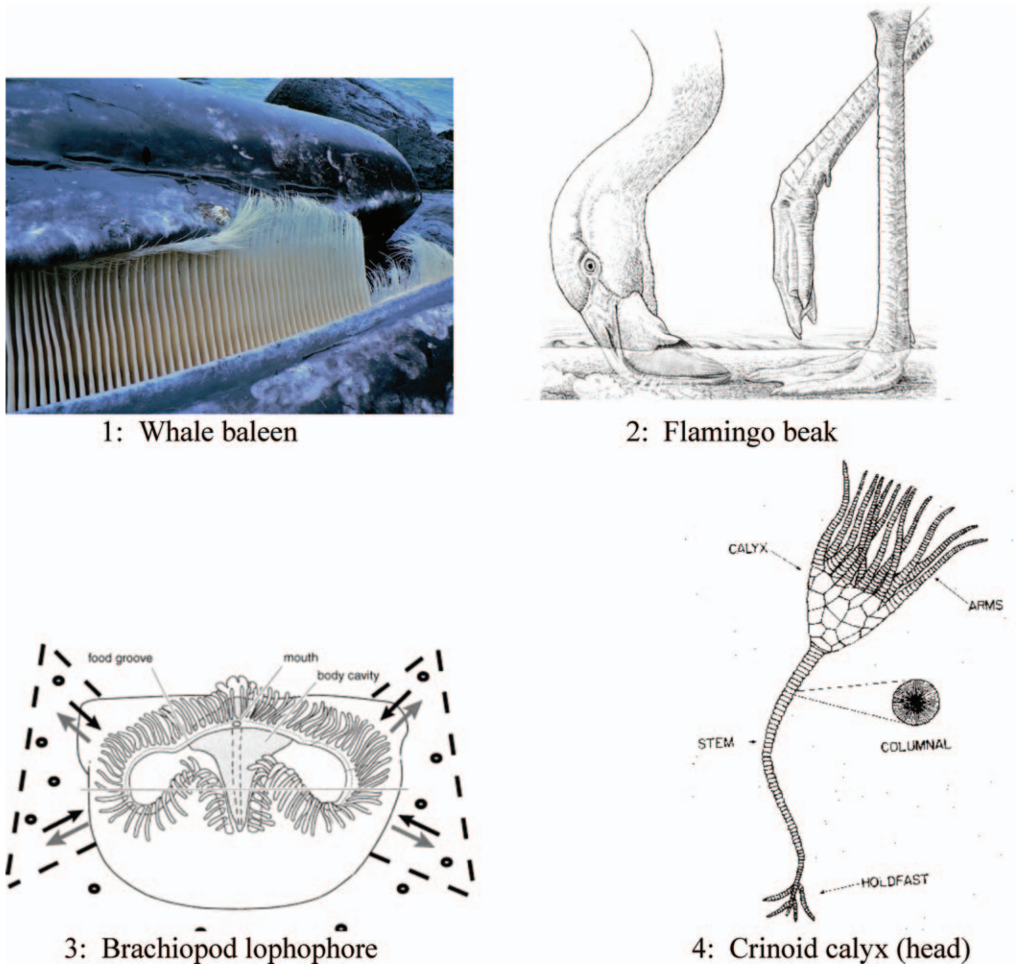

FIGURE 4: Examples of different anatomical forms that serve the same function for filtering food in radically different species. Image sources. (1): http://www.flickr.com/photos/alsal/6795437395/ (2): http://www.leveilleillustration.com/Pen-and-inkflamingosandotherbirds.html (3): http://www.sciencedirect.com/science/article/pii/S0031018205004451 (4): http://dcfossils.org/index.php/gallery6/ (accessed 25 May 2012).

360° panoramic existence for filtering food in its shallow-marine habitat (Fig. 4).

Students' Results

While completing a short description of their ideas in Table V, some students may feel that this is the hardest part of the exercise, suggesting that they lack the expertise to make meaningful suggestions. Yet by brainstorming with a partner, invariably all students are able to propose interesting ideas, including those with a focus on environmental sustainability (more efficient water acquisition, flow, and waste removal in buildings and better filtration of marine pollutants), improving building strength (to promote earthquake resistance), and whimsy (better waterslide; Table V).

Their thoughtful and, in some cases, intriguing suggestions indicate that the exercise has promoted a deeper understanding of how form and function are intimately connected and have been honed through evolution by natural selection (Benyus, 1997; Baumeister, 2013). Furthermore, gaining experience proposing a biomimicry application based on an extinct species' form and function elevates students' confidence before they commence the final research project on the bioinnovation potential of a modern organism.

Summary of Learning Outcomes

Because of the writing-intensive nature of Colgate's FSEMs, I do not offer a traditional midterm or final. Rather, two papers substitute for those exams. Yet two indicators supply some insights into how well this exercise (in conjunction with others) helped students identify the form and function and biomimicry potential of a fossil organism's anatomy before undertaking the final research paper due at the end of the term. That paper is the semester's culminating writing exercise in which students are asked to demonstrate proficiency using the library and Web to do college-level research.

In their paper, students discuss a modern species' form and function in detail (students draw from a hat the name of their organism, such as elephant, spider, butterfly, great ape, snail, wolf, coral, frog, snake, penguin, or tropical rainforest plant, before observing their target species early in the term at the local zoo, a 1-h drive away). They describe mechanisms used by that species to perform important functions and explain biomimicry research that demonstrates how that organism provides biological inspiration for solving a specific human problem or challenge. Students are also encouraged to suggest additional bioinspired ideas

TABLE VI: Student comments about learning outcomes, organized thematically.

Hands-On Learning in Field Trips
"I really enjoyed this course because I am a visual and active learner. This course allowed students to get out into the field and do research in. . .the rock quarry to search for fossils. I learn best by doing hands-on work like this, so I really enjoyed and grew throughout these experiences."
"I have greater knowledge of the past animal life and insight to the future. Amazing field trips and outdoor learning activities successfully engaged the class in interesting and informational exercises."
"All of the experiments and field trips really enhanced my learning experience."
"The field trips were nice for they gave some real world perspective on topics presented in class."
"The field trips tied in well with course material."
"The field trips we took made class exciting and interactive."
Biomimicry as a Tool to Help Solve Human Problems
"I have learned a lot about the previous mass extinctions and their causes. I have also learned about how we are causing a 6th extinction and how we can prevent it using biomimicry."
"This class taught me the skill of looking at something and possibly using it as a solution to another problem. . .and taught me how to address real world problems."
"I have come out of this course with a much better background in our Earth's history, an appreciation for Earth's natural processes, a deep respect for the part nature plays on this planet, and a better idea of how humans can figure out solutions to issues we create."
"I learned how to look for biomimicry in nature."
Environmental Insights and Species Conservation
"I gained a better understanding of how delicate life is. I now place more value on the natural world and truly consider how my actions influence the environment."
"After taking this course, I not only understand the stages of life on Earth, I also realize the importance of making environmentally beneficial decisions. Yes, I understand intellectually how humans came to be, but I now see how strong of an impact humankind has on the planet."
"I learned about the importance of saving the endangered species."
"I realized through this course that life evolves. It has been destroyed so many times, and every time it returns with a vengeance. The Earth is so perfect that it can support multiple evolutions of life. However, I have also learned that the damage done by humans now is irreversible. We cannot stop or change what has already been done. However, there is always hope, and it only takes one person who really cares to change the world."
"I learned a lot about how humans are impacting the environment but don't seem to care. I was inspired and began to believe one person really can change the world. Very interesting and inspiring."
Future Courses or Career Path
"It has opened my eyes to further study of geology."
"I have learned immense amounts of knowledge about the problems facing Earth today and in the past. I am looking to major in a similar field."

based on their research and on the observations they made of their species at the zoo.

Grades awarded on the biomimicry portion of the students' papers were, on average, in the 90th percentile. This strong overall assessment was also reflected in the high grades awarded for the short oral presentation that each student gave on their species' biomimicry using presentation software at term's end. This suggests that the field exercise was a valuable foundation for helping students gain confidence in assessing organisms' form and function and their biomimicry potential.

Second, end-of-term student evaluation of teaching forms suggest that the exercise was successful, although in many cases students do not write separate comments about the field exercise described herein and the zoo trip or outdoor taphonomy experiment (Soja, 1999). Yet, student comments relevant to this exercise infer that it was valuable in providing a hands-on learning experience while promoting a deeper understanding of environmental challenges and biomimicry as a new tool in species conservation, as well as identifying future career paths (Table VI).

CONCLUSIONS

Scientists and everyday citizens around the world share mounting concerns about the accelerating rate of environmental degradation and biodiversity loss (Barnosky et al., 2012; Cardinale et al., 2012). Since humans' existence depends on myriad species, many new ideas are emerging about how to save imperiled ecosystems and biological communities, including our own (Ehrlich et al., 2012). One such strategy is to elevate the success of conservation efforts by broadcasting geologic evidence to the public about the effects of significant environmental change in Earth's past (Soja, 2012; Schmeisser and Doss, 2014).

Many paleontological studies yield unique insights into extinction episodes, the rates and processes of ecological cascade and ecosystem collapse, and the delayed recovery of survivor species (ScienceDaily, 2013). Discussing these and related concepts is now regarded as a mandate—if not a moral, ethical, and cultural duty—by those who argue that scientists and educators must take greater responsibility for ensuring that the public understands the impact of the global environmental crisis on humanity's future well-being (Jackson, 2008; Riegl et al., 2009; Schmeisser and Doss, 2014).

In my course on the Sixth Extinction, investigating mass extinction events helps students more fully appreciate the enormous environmental challenges that lie ahead. Conducting a biomimicry exercise in the field gives students the opportunity to collect, analyze, and synthesize paleontological data. In so doing, the exercise provides a firsthand look at the fossil record and the significant changes that have occurred in Earth's history.

Even as it promotes active learning about nature's past, present, and future, the exercise is a foundational platform on which students gain confidence in posing hypotheses and testing their ideas based on observations and data collection. It also helps students acquire the necessary tools to proceed with the final research project on bioinspired design innovations, many of which have real potential for solving human problems in a sustainable way.

In essence, appreciating the causes and consequences of global biodiversity loss in the past can help students learn and then teach others about the value of species and ecosystem services at the onset of the Sixth Extinction. Moreover, helping students improve critical and innovative (outside-the-box) thinking skills enables them to become more proficient at participating effectively in scientific and public policy conversations about the health of our planet—now and in the future.

ACKNOWLEDGMENTS

I thank students in my FSEM 136 (The Sixth Extinction) course for their enthusiastic participation in this exercise, which was inspired by Dorna Schroeter's 2010 "Numbers Hunt in the 'Hood" exercise and by Tom McKeag and Schroeter's "Hunt in the 'Hood" exercise during a biomimicry workshop they hosted in July 2011. Field trip support was provided by the Geology Department at Colgate and by Beyond Colgate funds awarded by the Office of the Dean of the Faculty and Provost. I am grateful to Sally Walker, another reviewer, and editorial staff for suggesting many helpful improvements to this paper.

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