FEATURED ARTICLE

Bringing Astrobiology Down to Earth

CATHERINE L. QUINLAN

Abstract

Astrobiology seeks to understand life in the universe through various disciplines and approaches. Astrobiology not only provides crosscutting content, but its study supports the three dimensions of learning promoted by the Next Generation Science Standards. While astrobiology research has been progressive and has accomplished great feats for science and society, astrobiology education in schools and colleges has lagged behind astrobiology research. Astrobiology can be used in the classroom as an engaging context for the Socratic method or in long- or short-term projects to encourage higher-order thinking.

Key Words: *Astrobiology; biology; evolution; extremophiles; extreme environments; microbes; nature of science; origin of life; project-based learning.*

○ Brief History of Astrobiology Research & Education

Astrobiology, the study of life in the universe, is interdisciplinary in approach and multidisciplinary in content. Various disciplines – astronomy, physics, environmental science, geology, chemistry, and biology – explore three essential questions: "How does life begin and evolve? Is there life beyond Earth and if so, how can we detect it? What is the future of life on Earth and in the universe?" (Des Marais et al., 2008). The astrobiology field began in 1996, when NASA held its first astrobiology meeting as an outcrop of its exoplanet program, which searches for Earth-like planets within habitable zones. Scientists began to see the importance of an interdisciplinary approach to understanding life on other planets, mostly prompted by controversial interpretations, such as the Mars meteorites that some thought suggested the existence of life on other planets and spacecraft images that were interpreted as signs of ice on Europa. The National Astrobiology Institute (NAI) was created by NASA in 1998 to provide oversight and a virtual meeting space for scientists from all over the world (Hubbard, 2008).

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Although the United States has had great success in astrobiology research and has led the way in providing an astrobiology roadmap that the world could follow, there is reason to believe that astrobiology education has not been as progressive. More recently, in an NAI Briefing to the Planetary Sciences Subcommittee meeting in September 2014, the committee recommended that more needs to be done in relation to astrobiology in K–12 education, teacher training, and undergraduate teaching. Although the United States is ahead in astrobiology research, schools in the United Kingdom were the first to offer a stand-alone degree in astrobiology; U.S. institutions predominantly offer a certificate or minor in astrobiology (Dartnell & Burchell, 2009).

The University of Washington's PhD program requires students to complete their own major requirements in their specialized field as well as in the astrobiology program, which allows them the unique opportunity for mentorship and collaboration by other departments (Staley, 2003). According to Staley, students from this program develop a unique set of collaborative and multidisciplinary skills that comes from sharing information and being mentored by different departments; collaboration with other departments has resulted in unique perspectives that would not have been brought to fruition if the scientist was limited to his or her own major department. He also notes that in some cases, these discoveries were made by the students and not by the overseeing professor.

There is also reason to believe that the "astro" in astrobiology is much more emphasized than the "biology." In an extensive study on undergraduate and postgraduate programs in the United Kingdom, Dartnell and Burchell (2009) found that only 16% of students taking astrobiology

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courses were biology or biochemistry majors, whereas 26% and 28% were astronomy and physics majors, respectively. They found it difficult to gauge whether this was due to lack of interest or lack of opportunity in biology departments. However, there is no reason to believe that this trend is any different in the United States. From the NAI Briefing to the Planetary Sciences Subcommittee's report, which included the most common journals published in 2012, it is evident that the "astro" in astrobiology is more emphasized than the "biology." Unfortunately, few or no quantitative studies have been done to chart the progress of astrobiology research and education within schools and universities.

○ Crosscutting Content in Astrobiology

The study of microbes across disciplines is one crosscutting concept that has led to many important discoveries with important consequences for science and society. Biologists have come to believe that life could not persist without microbes and study microbes in extreme environments, such as Yellowstone National Park and Antartica, that serve as analogues for life elsewhere.

Yellowstone National Park (Figure 1) has provided a rich playground for the discovery of many archaebacteria that thrive in extreme conditions. These extremophiles are adapted to live in extreme conditions such as extreme heat, salt, metals, or acidity. Thermophiles, which thrive in extreme heat, have "very efficient DNA repair systems and proteins that coat or coil the DNA to protect it" from damage (Young & Fulton, 2010, p. 136). Therefore, their proteins do not become denatured in these extreme environments, and thus they are defined by their "protein thermostability" (Peters et al., 2007). It was in Yellowstone National Park that microbiologist Thomas Brock isolated the bacterial species *Thermus aquaticus*, which thrives at 70°C. This discovery led to the development of polymerase chain reaction, the method for augmenting genes that made it possible to study DNA on a larger scale and as part of crime scene investigations (Young & Fulton, 2010).

Knowledge of proteins and how they function in microbes is important for understanding adaptations in extreme environments. Proteins play many vital roles in organisms, such as creating channels, pumps, and organizational structures for important processes such as respiration. Proteins catalyze chemical reactions and function at different optimal pH levels and temperatures. Understanding how these extremophile proteins differ from those that function optimally at normal temperatures is important. Scientists who study proteins use the principle that a protein's function is determined not only by its linear sequence but also by how it folds. More recently, scientists such as Michael Hecht have approached their experiments from the perspective that proteins provide the molecular machinery that carries out life. Hecht and his team created a novel protein that did not previously exist in nature, using important characteristics of proteins such as polar and nonpolar regions and protein folding. They created various artificial proteins and inserted them into *E. coli* in which genes for important life-sustaining functions had been deleted. They wanted to see whether artificial proteins could carry out these functions in *E. coli* – and they did. The implication is that if we can create novel forms of life-sustaining machinery, then it is possible for alternative molecular machinery to exist elsewhere (Hecht, 2012).

The astrobiologist therefore asks what processes are essential to life and approaches this question from the perspectives of various disciplines. For example, given that proteins are used to channel electrons during cell processes and electrons are a source of energy in chemical reactions, examining oxidation–reduction reactions has provided insight into the importance of biogeochemical reactions to the existence of life. Organisms such as humans use organic compounds such as carbohydrates, fats, and proteins as electron donors in oxidation reactions in which the final electron acceptor is oxygen, which is reduced. However, in the hot springs of Yellowstone National Park, inorganic substances such as hydrogen and hydrogen sulfide are the electron donors while metals such as iron and arsenic are the electron acceptors (Young & Fulton, 2010).

Figure 1. Alien life on Earth: Yellowstone National Park's extreme environments (photos by the author, August 2012).

Recently, physicist Moh El-Nagger and colleagues from various disciplines examined electron transfer in organisms such as methanogens, sulfate reducers, iron reducers, denitrifiers, and aerobes. Electron transfer is important for organisms' use of the environment; metal reducers might exist in the iron-rich environments of Mars and use this abiotic component of life to direct the flow of electrons. El-Nagger's work on bacteria shows that bacteria create long, wire-like strings of membranes ("nanowires") that are used to transfer electrons. He found that they vary in length and are grown when bacteria need to create an outlet for electrons – for example, when sufficient electron acceptors are not available. El-Nagger performed experiments that enabled bacteria to grow nanowires toward electrodes, and he suggests that this redox pathway be viewed as a "fingerprint" of life (El-Nagger, 2014).

Microbes are therefore the "engines that drive Earth's biogeochemical cycles" (Falkowski et al., 2008, p. 1034), and knowledge of the metabolic pathways of microbes has provided information about evolutionary pathways, because microbes that evolved over different periods of time have the genetic markers for those periods. Microbes provide links between abiotic factors that persist in the atmosphere and that are used for various processes and cycles, such as photosynthesis, fermentation, methanogenesis, respiration, and nitrogen fixation. The electron acceptors for these processes are connected to geothermal processes that produce metals, hydrogen sulfide, and methane (Falkowski et al., 2008). Therefore, microbial mats, which are "structurally coherent macroscopic accumulations of microorganisms" (Des Marais, 1995, p. 251), have become a significant source of information for studying various biota and the effects of abiotic factors on the diversity of organisms that live in microbial mats. The importance of extreme environments, extremophiles, microbes, and water to understanding life is evident in the classroom resources available. Table 1 provides a list of resources, lessons, and activities on astrobiology and biology concepts.

○ Crosscutting Concepts & Three Dimensions of NGSS

In *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, crosscutting concepts are described as "concepts that bridge disciplinary boundaries, having explanatory value throughout much of science and engineering" (National Research Council, 2012, p. 83). The interdisciplinary approach of astrobiology makes many crosscutting concepts, such as nature of science, explicit across boundaries and within the various fields of biology. Concepts such as energy and electrons, extremophiles, extreme environments, evolution, reproducibility of life, water and other liquids, and building blocks of life are approached using various frameworks. Scientists look for *patterns* and *cause and effect* and ask questions such as "If we were to look for life elsewhere, would we recognize it? What form would it take?"

Scientists' questions about life have changed as our understanding has progressed. In 1977, when scientists discovered volcanic vents teeming with life forms, they began to understand that the impact of chemosynthesis was just as far-reaching as that of photosynthesis (Jannasch, 1998); chemosynthetic organisms such as tubeworms and shrimp relied on geothermal energy instead of energy from the sun. Today, scientists ask different questions when they study the deep sea. Victoria Orphan studies isotopic biosignatures in methane-derived carbonates formed from the sulfate-dependent anaerobic oxidation of methane by living things. She asks, "Is there evidence of viable microorganisms within the carbonate interior . . . ? Does the diversity of carbonate-hosted microbial communities differ between active and inactive seep sites? How fast does the community change?" (Orphan, 2014). She has explored these questions by studying the succession and nature of microbial communities in seep sites in Colorado, California, and Oregon. By examining the benefits and "spinoffs" of studying microbes in extreme environments, students perceive the progressive, tentative, interdisciplinary, and collaborative nature of science and its influence on society.

The striking differences in modes of discovery among disciplines beg the question, "How do scientists go about doing science?" This can easily be surveyed on either the macro- or micro-level using NASA resources. Scientists explore life by traveling to the seafloor of the Galápagos or the coldest part of Antartica or the Panoche Hills of Northern California or anyplace in the world. Science can be adventurous and even dangerous.

Astrobiology supports the three dimensions of learning outlined in the *Next Generation Science Standards* (NGSS) by focusing on practices (dimension 1) specific to each discipline as crosscutting concepts (dimension 2) are studied using disciplinary core ideas (dimension 3). Astrobiology provides a framework that can be used in all grades to help students make sense of phenomena. Moreover, its application can vary from simple to complex. It can be adapted to both low- and high-level thinkers – or, better yet, encourage higher-order thinking among all – and it can be extended to the humanities when ethics and other sociological issues are addressed. Astrobiology can provide connectedness between all biology concepts (see Figure 2) by linking the study of life-forms in extreme environments on Earth and potentially on other planets.

Furthermore, many astrobiology concepts have implications for our understanding of the origin of life and how life evolved, so even more arrows could be added to Figure 2 – for example, to connect the redox reactions with biogeochemical processes and then to evolution. In describing the biogeochemical processes that are known in textbooks as the nitrogen cycle, carbon cycle, phosphorus cycle, and so on, Falkowski et al. (2008) noted that these are all redox reactions driven by microbes that possess a particular gene that enables a metabolic pathway to be preserved, even if it is not functional within another organism; hence, the environment can select for that pathway, which is maintained. Similarly, the study of archaebacteria in extreme environments preserves the genes (Young & Fulton, 2010) and consequent proteins that enabled them to thrive and be selected by that environment. Scientists consider these organisms the key to understanding how life began on early Earth. The study of archaebacteria led to changes in the evolutionary tree of life, in which archaebacteria now have their own branch apart from other prokaryotes, and more connections with eukarya. Therefore, the evidence gathered in astrobiology provides indicators for the origin of life, thereby answering one of astrobiology's key questions: How did life begin and evolve?

○ Astrobiology in the Classroom

Astrobiology can effectively engage students in the classroom because it capitalizes on humanity's preoccupation with space and aliens, as depicted in many popular books and movies. The

Table 1. Astrobiology classroom resources.

Astrobiology Topic	Question/Subject	Biology Concepts Covered	Activities	Resource
Extreme Environments & Extremophiles	How is hydrogen produced?	Microbes. Use of extremophiles to solve problems. Nature of science. Origins of life.	Questions for students Webquests, interactives, video clips, maps, panoramas. Other resources.	Educator's Guide: Hydrogen and the Environment: The Quest for Alternative Fuels http://hydrogen.montana.edu
	What is a microbe?	Scientific methods.	Create Venn diagram. Nature walk. Common misconceptions. Rubrics.	Growing Microbes in a Bag: An Educator Guide with Activities in Astrobiology http://quest.nasa.gov/projects/astrobiology/fieldwork/lessons/Microbes_3_5.pdf
	Habitable zones – fingerprints of life	Scientific inquiry, Temperature, metabolism, microbe, multicellular.	Labs. Build your own planet temperature calculator link. Video and Lesson Activities Links.	Habitable Zones http://www.nasa.gov/pdf/562183main_LS3_HabitableZones_C5.pdf
	Cause and effect	Hypothesize and observe effects of changing features on earth. Energy flow. Nature of science.	Interactive tutorial.	Astroventure http://quest.arc.nasa.gov/projects/astrobiology/astroventure/
	"Mars-The Xtreme-O-Philes"	Living and nonliving. Ecology. Earth and Mars investigations.	5E Lesson unit plans, activities, and resources. Use NASA data.	NASA Mars Education https://marsed.asu.edu/content/xtreme-o-philes
	What is an extreme environment?	Chemosynthesis, adaptations.	Video clips for engagement and discussions.	Hydrothermal Vent Creatures http://ocean.si.edu/ocean-videos/hydrothermal-vent-creatures The Discovery of Hydrothermal Vents http://www.divediscover.whoi.edu/ventcd/vent_discovery/index_discmulti_still.html "Aliens of the Deep" short video clip from youtube.com (several options)

Table 1. continued

Astrobiology Topic	Question/Subject	Biology Concepts Covered	Activities	Resource
	What can extremophiles teach us?	Extremophiles, nature of science ("think like a scientist… think like an alien"), nature of life.	Assessments. Tutorials. Lesson plans. Activities (e.g., Web-based dichotomous keys).	Free Astrobiology short course http://eu.montana.edu/astrobiology%2Dcourse/pdf%2Dversion/ (Use PDF options Unit 1, 2, 3.)
	Why is water essential to life? Where do we find bacteria?	Bacteria. Hydrothermal vents. Nature of science.	Unit activities, resource links.	Nassif, T.H. & Zeller, N. (2006). Astrobiology: using research to invigorate science curricula. *American Biology Teacher, 68,* 7–12.
	What is life?	Living versus nonliving. Defining life.	Activities using cards. Other resources.	Prud'homme-Genereux, A. (2013). What is life? An activity to convey the complexities of this simple question. *American Biology Teacher, 75,* 53–57.
	"Is it alive?"	Living versus nonliving. Using scientific observations.	5E lesson unit. Use NASA data from Opportunity and Curiosity	NASA Mars Education https://marsed.asu.edu/content/it-alive
	What is life? What does life require? What makes a world habitable?	Living versus nonliving. Scientific process. Light energy. Chemical energy. Growth. Environment. Math extension.	Activities. Labs and more. Hands-on activities for grades 5–8.	Astrobiology in your Classroom: Life on Earth…and Elsewhere. Educator Resource Guide. http://astrobiology.nasa.gov/media/medialibrary/2013/10/Astrobiology-Educator-Guide-2007.pdf
Origin of Life	The evidence for evolution	Moon – the Drake equation. Remote sensing biosignature of life. Natural selection.	Assessments, activities such as scavenger hunt. Design. Drake equation calculator. Video and resource links.	PDF version of Astrobiology course http://eu.montana.edu/astrobiology%2Dcourse/pdf%2Dversion/ (Use PDF options Unit 4.)

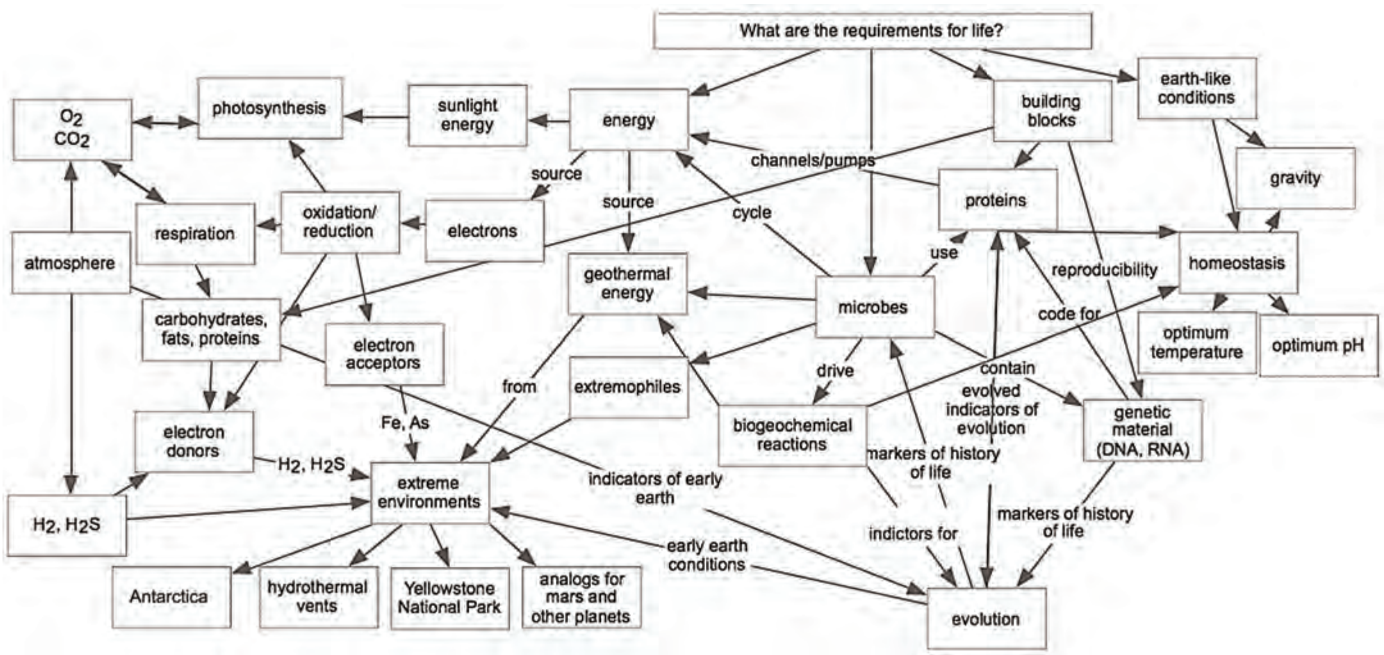

Figure 2. Connectedness of biology and astrobiology concepts.

"Engagement" phase of the 5E instructional model serves to create interest by generating curiosity and raising questions, to expose students' prior conceptions as well as to create a framework for examining concepts. Teaching the Socratic method along with astrobiology can engage students in learning biology concepts.

The Socratic method, named after Greek philosopher Socrates, is a method of questioning that encourages discussion, gauges students' understanding, and encourages meaning-making. While it can be used as an engagement tool in biology, it is not the best approach for an entire biology class in which students are learning new concepts. In biology, the Socratic method works well when it is infused into the lesson or included in segments, because science concepts must be explained and clarified, and students' misconceptions must be addressed; students are not only learning a new way of looking at life but are learning new content. Video clips and pictures depicting astrobiology can stimulate questions and discussions. Two examples of questioning sequences are provided below, with some possible reactions in parentheses (students' responses are omitted because of space limitations and with the understanding that this sequence will be different for every class and teacher).

Example 1

What is life? What are the requirements for life? (Some might say "sunlight" or "temperature," so I play a video clip of "Aliens of the Deep," which shows tubeworms and other strange organisms living in the deep oceans at ~400°C. This generates more discussion.) Is there light deep in the ocean? How do organisms survive without light? What is the purpose of light? What do you think is their source of energy? What about the other organisms living there – do they all use the same energy? What are the other requirements for life? (Some might indicate oxygen or water.) Do all organisms need oxygen to survive? Can you think of any organisms that do not need oxygen? Is oxygen a *requirement* for life?

Example 2

What do humans need to survive? (Food, water.) Why? (Role in chemical reactions. Examples.) If we were to become inhabitants of Mars, would our requirements for survival be the same? What else would we need? (Protection from radiation.) Why? What would happen if we were exposed to a high amount of radiation? What else would we need then? Have any of you ever heard of the International Space Station? What do you know about it? Have you ever seen astronauts on TV when they return? What do you notice? What would one not do/use in space? Why or why not? What do you think happens to an astronaut's bones? (Show pictures of an astronaut before and after living in space.) What do you notice about the astronaut before and after living in space? How do you think our bodily fluid becomes distributed in space? These kinds of pictures can be used as engagement for many biology concepts, including "what is life," human anatomy and physiology, or a specific astrobiology topic.

Long-term Research Projects

Students explored news articles on the NAI website for a topic of interest. Some students chose astrobiology as the focus of their project this year. Students generated five questions and used these to narrow down an essential question, from which they generated a claim or hypothesis. The NAI website and other NASA sites became the main sources of descriptive or quantitative data, which students organized into tables, analyzed, and wrote conclusions from in lab-report form, with the assistance of the teacher.

Much scaffolding is necessary to help students connect their claims or hypotheses to the evidence they gather. Many of the research questions that students chose were, by their nature, untestable, and therefore students required much help in selecting and using data. Some organized tables into two columns labeled "independent variables" and "dependent variables" or "claims" and "evidence."

Short-term Research Projects

Life in Extreme Environments. Students might choose one extreme environment of interest and explore questions pertaining to the geography, conditions, types of organisms and their adaptations, contributions to society, and current research, and how studying this environment and organisms helps us understand life on other planets.

○ Considerations & Future Work

As an approach and a content area, astrobiology aligns with NGSS in that it supports all three dimensions of learning. Astrobiology can be used for engaging lessons, for short- or long-term projects, and across grades. The study of astrobiology deepens with the sophistication of the student and simultaneously provides continuity and coherence across grades, without mere repetition of concepts. Students focus on science practices that fall within disciplinary core ideas and must make sense of phenomena in connection to a particular subject area or other disciplines. Astrobiology also has implications for the sequence of science within schools; an emphasis on the "biology" of "astrobiology" might be more meaningful if a student first has a foundation in chemistry or the physical sciences, or perhaps even the earth sciences.

References

Bybee, R.W., Taylor, J.A., Gardner, A., Van Scotter, P., Powell, J.C., Westbrook, A. & Landes, N. (2006). The BSCS 5E Instructional Model: origins, effectiveness, and applications. A report prepared for the Office of Science Education, National Institutes of Health, http://science.education.nih.gov.

Dartnell, L.R. & Burchell, M.J. (2009). Survey on astrobiology research and teaching activities within the United Kingdom. *Astrobiology*, *9*, 717–730.

Des Marais, D.J. (1995). The biogeochemistry of hypersaline microbial mats. *Advances in Microbial Ecology, 14,* 251–274.

Des Marais, D.J., Nuth, J.A., III, Allamandola, L.J., Boss, A.P., Farmer, J.D., Hoehler, T.M. et al. (2008). The NASA astrobiology roadmap. *Astrobiology, 8,* 715–730.

Doran, P. (2012). Human and robotic astrobiological research in the McMurdo Dry Valleys, Antarctica [online]. NAI Director's Seminar Series. Available at https://astrobiology.nasa.gov/seminars/featured-seminar-channels/nai-directors-seminar-series/2012/5/21/human-and-robotic-astrobiological-research-in-the-mcmurdo-dry-valleys-antarctica/.

El-Nagger, M. (2014). Hotwired life: microbial energy acquisition by electron transfer across the biotic–abiotic interface [online]. NAI Director's Seminar Series. Available at https://astrobiology.nasa.gov/seminars/featured-seminar-channels/nai-directors-seminar-series/2014/10/27/hotwired-life-microbial-energy-acquisition-by-electron-transfer-across-the-biotic-abiotic-interface/.

EQuIP (2013). EQuIP rubric for lessons & units: science. Available at http://www.nextgenscience.org/resources.

Falkowski, P.G., Fenchel, T. & Delong, E.F. (2008). The microbial engines that drive Earth's biogeochemical cycles. *Science*, *320,* 1034–1039.

Hecht, M. (2012). Enabling life with a molecular toolkit of genes and proteins designed de novo [online]. NAI Director's Seminar Series. Available at https://astrobiology.nasa.gov/seminars/featured-seminar-channels/nai-directors-seminar-series/2012/3/5/enabling-life-with-a-molecular-toolkit-of-genes-and-proteins-designed-de-novo/.

Hubbard, G.S. (2008). Astrobiology: its origins and development [online]. NASA. Available at http://www.nasa.gov/50th/50th_magazine/astrobiology.html.

Jannasch, H.W. (1998). Chemosynthetic production of biomass: an idea from a recent oceanographic discovery. *Oceanus, 22,* 59–63.

National Research Council (2012). *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas.* Washington, DC: National Academies Press.

NGSS Lead States (2013). Three dimensions [online]. Available at http://www.nextgenscience.org/three-dimensions.

NOAA (2011). Strange vent-fellows: explorers on NOAA expedition discover chemosynthetic shrimp, tubeworms together for first time at hydrothermal vent, also first live vent tubeworms seen in Atlantic waters [online]. Available at http://www.noaanews.noaa.gov/stories2011/20110907_mid-caymanrise.html.

Orphan, V. (2014). Methane-based life in a deep-sea concrete jungle [online]. NAI Director's Seminar Series. Available at https://astrobiology.nasa.gov/seminars/featured-seminar-channels/nai-directors-seminar-series/2014/4/21/methane-based-life-in-a-deep-sea-concrete-jungle/.

Perlman, D. (1977). Deep questions from the sea [online]. *San Francisco Chronicle*, March 25. Available at http://www.divediscover.whoi.edu/ventcd/pdf/SFChr32577.pdf.

Peters, J., Bothner, B. & Kelly, S. (2007). Unfolding the mystery of protein thermostability. *Yellowstone Science*, *15,* 5–14.

Staley, J.T. (2003). Astrobiology, the transcendent science: the promise of astrobiology as an integrative approach for science and engineering education and research. *Current Opinion in Biotechnology, 14,* 347–354.

Young, M. & Fulton, J.S. (2010). Yellowstone extremeophiles [*sic*]: the life of heat-loving microbes. In J. Johnson (Ed.), *Knowing Yellowstone: Science in America's First National Park.* Lanham, MD: Taylor.

CATHERINE QUINLAN is a high school biology teacher in New Jersey and an instructor for U.S. Satellite Laboratory's NASA Endeavor graduate course. She has a doctorate in Science Education from Teachers College, Columbia University; e-mail: drcatherinequinlan@gmail.com