1.3 Online, Classroom and Wilderness Teaching Environments

Reaching Astrobiology Learners of All Ages Around the World

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CONTENTS

1.3.1 Introduction .......................................................................................................................... 27
1.3.2 Hybrid Textbook .................................................................................................................. 28
1.3.3 Open Educational Resources and Global Outreach ............................................................... 30
  1.3.3.1 SciFlix ............................................................................................................................. 30
  1.3.3.2 Emergence of Life Massive Open Online Course ................................................................. 30
1.3.4 Higher Education ............................................................................................................... 31
  1.3.4.1 GEOL 111 Emergence of Life .......................................................................................... 31
  1.3.4.2 Illinois Campus Honors Program .................................................................................... 31
1.3.5 Youth Outreach ................................................................................................................. 32
  1.3.5.1 Research Outreach Carbonate Hot-Spring Simulation .................................................... 34
  1.3.5.2 Scholar-Athlete Sports in Space Science Camps .............................................................. 35
  1.3.5.3 University of Illinois 4-H Academy ............................................................................... 37
  1.3.5.4 Outreach to Underrepresented Communities ................................................................. 37
1.3.6 Teaching Teachers ............................................................................................................ 38
  1.3.6.1 Student-Teacher-Scientist Partnership .......................................................................... 38
1.3.7 Teaching in the Wild ........................................................................................................ 38
1.3.8 Public Policy and International Engagement ................................................................. 39
  1.3.8.1 Chicago Field Museum of Natural History ................................................................. 39
  1.3.8.2 Arctic Change Course in Stockholm, Sweden, and Svalbard, Norway ......................... 40
1.3.9 Lifelong Learning ............................................................................................................ 41
  1.3.9.1 Illinois Osher Lifelong Learning Institute and Yellowstone Forever Institute ............ 41
1.3.10 Summary ......................................................................................................................... 42
Acknowledgments ..................................................................................................................... 42
References .................................................................................................................................. 43

1.3.1 INTRODUCTION

The clearest way into the Universe is through a forest wilderness.

—John Muir, 1890 (Wolfe 1966)

The search for life throughout the cosmos originates from the most basic of human desires: to understand the universe within and around us. That quest lies at the heart of the imagination and spirit of the NASA Astrobiology Institute (NAI). A highly interdisciplinary organization dedicated to interstellar science, the NAI seeks to answer three fundamental questions (Des Marais et al. 2008):

• How does life begin and evolve?
• Does life exist elsewhere in the universe?
• What is the future of life on Earth and beyond?
Founded in 1997, the NAI is designed to produce transformative research that: (1) infuses astrobiology science into ongoing and future NASA missions; (2) nurtures a coherent and interactive astrobiology research community; and (3) establishes dynamic, long-lasting Education and Public Outreach (EPO) programs that connect the public with the latest astrobiology scientific discoveries (Hays et al. 2015; National Research Council 2018; NASA Astrobiology Institute 2018).

A recent NAI program, *Towards a Universal Biology: Constraints from Early and Continuing Evolutionary Dynamics of Life on Earth*, was awarded in 2012 to a consortium led by the University of Illinois Urbana-Champaign that included Baylor University College of Medicine and the University of California, Davis (Illinois-Baylor-Davis NAI). The program was housed in, and orchestrated from, the Carl R. Woese Institute for Genomic Biology (IGB) on the University of Illinois Urbana-Champaign campus. The Carl R. Woese IGB opened the 186,000 sq. ft. open floor plan in Spring 2007, with the explicit intent of serving as a dynamic platform for cross-disciplinary genome-enabled research and education. The Illinois-Baylor-Davis NAI initiative has addressed multiple goals of the NASA Astrobiology Roadmap (Des Marais et al. 2008), including *Biochemical Adaptation to Extreme Environments and Biosignatures to be sought in Solar System Materials*. Major evolutionary transitions through geological time that occur in living matter, act to constrain the diversity of life, and govern the way in which energy and information are utilized by life have been studied. A unifying theme in these projects derives from NASA-sponsored research of the late Professor Carl R. Woese at the University of Illinois. As the first scientist to identify the Archaea, Woese established a three-domain Tree of Life, providing our first insights into the emergence of the Last Universal Common Ancestor (LUCA; Woese and Fox 1977; Woese et al. 1990). Of special importance to NASA missions, this Tree of Life is a fundamental framework for deciphering how life has evolved on Earth. The Tree of Life informs the search for extraterrestrial life forms, as well as their classification, as interplanetary explorations unfold.

The Illinois-Baylor-Davis NAI team has implemented an ambitious EPO effort for the rapid distribution of astrobiology research results. At the outset, the team identified and addressed learning challenges that impede understanding in scientific disciplines and targeted specific diverse demographic audiences by using multifaceted methods of content delivery to reach learners of all ages from around the world. These initiatives have been dedicated to the inclusion of new and challenging interdisciplinary scientific and cultural astrobiology content from active NAI research. Simply put, the goal has been to bring this work to learners around the world on their own terms. With that purpose in mind, dynamic delivery approaches were chosen for effectiveness in a wide variety of global learning environments. The resultant Illinois-Baylor-Davis NAI EPO program, which has already achieved considerable scope and scale, provides valuable insight for developing future astrobiology outreach initiatives that emphasize lifelong learning and global engagement.

This review highlights the accomplishments of the Illinois-Baylor-Davis NAI EPO, which has engaged more than 100,000 students of all ages from around the world via integrated online, classroom, and wilderness learning opportunities. These efforts have included the development and ongoing offering of: (1) a *Hybrid Textbook*, integrating the basics of astrobiology science with nature photography in Yellowstone National Park, with 6,000 hardcopies and more than 10,000 eBook versions distributed worldwide at no cost; (2) an *Open Educational Resources and Global Outreach*, providing a series of short two-minute videos called SciFilx and a free Massive Open Online Course (MOOC) on the Coursera platform that has enrolled 50,000 students internationally; (3) *Higher Education*: learning experiences for thousands of students on the University of Illinois campus, including an accredited 3-credit-hour course in the university’s Campus Honors Program, with a capstone field experience in Yellowstone National Park; an accredited 3-credit-hour classroom and laboratory Campus Honors Program course that has already served more than 500 students of the University of Illinois; and special outreach to underrepresented communities on the University of Illinois campus; (4) a *Youth Outreach* program that has served an additional thousands of students annually, with the help of classroom and laboratory lectures, laboratories, workshops, and camps, which included a Research Outreach Carbonate Hot-Spring Simulation (ROCHSS) laboratory teaching apparatus, Scholar-Athlete “Sports in Space” Summer Camps, and a 4-H Academy Summer Camp; (5) *Teaching Teachers*: workshops and field trips for a Student-Teacher-Scientist Partnership (STSP) program; (6) *Teaching in the Wild*: a series of outdoor astrobiology lectures and nature hikes taught in Yellowstone National Park in collaboration with the National Park Service (NPS), as well as Emergence of Life displays for exhibit at the Field Museum of Natural History in Chicago, Illinois; (7) *Public Policy and International Engagement*: a 2012 course with 38 undergraduate students that studied arctic climate change in Stockholm, Sweden, and Svalbard, Norway; and (8) *Lifelong Learning*: a blended course through the Osher Lifelong Learning Institute (OLLI) on the University of Illinois campus that to date has engaged more than 300 learners 50 years of age or older, in addition to lifelong learner wilderness courses with the Yellowstone Forever Institute (YFI).

### 1.3.2 HYBRID TEXTBOOK

A hybrid textbook, *The Art of Yellowstone Science: Mammoth Hot Springs as a Window on the Universe*, has been written for use in both formal and informal educational settings by science and non-science secondary and higher education students, lifelong learners, and visitors of all ages to Yellowstone National Park. Available in both hardcopy and eBook formats, *The Art of Yellowstone Science* (Fouke and Murphy 2016; *Figure 1.3.1*), is unique in its focus on the geological and biological history of the region; moreover, as a textbook, it is outstanding for the quality and abundance of its nature photography and instructional illustrations. A supplementary
are presented to showcase the elegant interconnectedness of life and the contextual history of an ever-changing Earth. This narrative requires an integration of many fields of study in the sciences and humanities, and *The Art of Yellowstone Science* demonstrates how both visual art and science originate from the same human desire to understand the world in which we live. Photographic art is melded with natural sciences to emphasize the importance of observation and the need for a willingness to embrace the unexpected. Because biological evolution is the ultimate expression of integrated life and Earth processes, Mammoth Hot Springs is studied as a window on the universe.

Co-authors Bruce Fouke and Tom Murphy first met at Mammoth Hot Springs in the winter of 2008, when NPS rangers requested a photographic record of the fieldwork being done there, for use in educational displays at the then-new Old Faithful Visitor Center. From this encounter began an extraordinary collaboration founded on a passion for the wilderness. *The Art of Yellowstone Science* contains 260 field and laboratory photographs that were shot over the course of 60 years. Fouke contributes his 30 years of integrated scientific research and teaching that focuses on hot springs, coral reefs, subsurface hydrocarbons, Roman aqueducts, human kidney stones, and astrobiology, bringing thousands of students into the field around the world. Murphy contributes three decades of nature photography and wilderness insights. In residence near Yellowstone since 1975, Murphy established Wilderness Photography Expeditions in 1986 and has built an internationally renowned photography seminar company, teaching natural history photography in Yellowstone and other locales around the globe.

*The Art of Yellowstone Science* is composed of seven chapters with the following content:

- **Chapter 1 Wilderness Laboratory:** It explains why Mammoth is such an extraordinary site for artistic inspiration and scientific inquiry.
- **Chapter 2 Perspectives:** It considers the basic approaches required to complete astrobiology science in complex natural environments.
- **Chapter 3 Dynamics:** It delves into the details of water-microbe-mineral interactions at Mammoth Hot Springs in Yellowstone National Park.
- **Chapter 4 Emergence of Life:** It explains the work of Carl Woese, his development of the three-domain Tree of Life, and its scientific implications.
- **Chapter 5 Deep Time:** It reviews major epochs that have shaped life and Earth interactions.
- **Chapter 6 Human History:** It reviews the westward expansion of the United States and events leading to the founding and scientific analyses of Yellowstone National Park.
- **Chapter 7 Worldwide Laboratory:** It explains how results from research on the natural laboratory of Mammoth Hot Springs provide a window for understanding natural processes around the world and throughout the universe.
The Art of Yellowstone Science relates how Mammoth Hot Springs has long served as a natural laboratory for astrobiology research that investigates how microbes form fossilized “biomarkers” in ancient calcium carbonate (CaCO₃) limestone (travertine) rock deposits. Similar to conditions found on Earth hundreds of millions of years ago, the water temperature, chemistry, and flow at Mammoth still support heat-loving (thermophilic) microbes that evolved in the earliest periods of life on Earth. Requiring a combination of field and laboratory experimentation, this research has expanded into practical applications: coral reef preservation, oil and gas exploration, the functioning of the Roman aqueducts, and human kidney stone disease. The overarching goal is to understand the unifying physical, chemical, and biological themes of biomineralization in a natural system like Mammoth on every level, from the single microbial cell to the entire ecosystem, and how these components and dimensions interact. After decades of investigation, Mammoth is beginning to reveal how it came into existence, how its vitality and scope can best be conserved, and how its secrets contribute to the well-being of humanity. The Art of Yellowstone Science emphasizes that the time is now for curious, inquisitive, caring, and good-hearted people to come together from all fields and sectors of science, art, and society to preserve nature and wilderness. Ordinary citizens everywhere, enticed by direct experience with natural settings or moved by photographs and paintings of the world around us, must join the quest to better understand Earth. For our survival on this water-rich planet, we must know much more about how physical, chemical, and biological components of natural systems have evolved to work together and to incorporate that knowledge into our everyday life.

1.3.3 OPEN EDUCATIONAL RESOURCES AND GLOBAL OUTREACH
1.3.3.1 SciFlix
A critical need exists to reduce the time lag between scientific discovery in university, government, and industry research centers and to disseminate that knowledge to formal and informal learning environments around the world. Illinois-Baylor-Davis NAI EPO program activities have been designed to reduce this delay. One effective approach has been the creation of a series of SciFlix, free 2-minute videos developed in collaboration with the Illinois Center for Innovation in Teaching and Learning (CITL) group. The SciFlix series targets secondary and higher education teachers and their students, as well as lifelong learners, to deliver clear, concise summaries of key advances in astrobiology science. For ease of access, these videos have been made available on YouTube. Because each SciFlix video and its supporting curriculum materials made available online have been designed to augment state and federal K-12 curriculum requirements in the natural sciences, decisions about the use of SciFlix reside with teachers, who can include these short-duration videos into lesson plans as they see fit. These resources are also further supported with free 1-day workshops to encourage teacher adoption. The SciFlix series also integrates with other federally funded educational programs such as the Global Learning and Observations to Benefit the Environment (GLOBE) program, Project WILD (conserving wildlife through education), the Worldwide Water Education (WET) program, and other initiatives commissioned by the National Academy of Science (NAS), the National Research Council (NRC), the National Science Teachers Association (NSTA), and a variety of non-governmental agencies.

1.3.3.2 Emergence of Life Massive Open Online Course
An Emergence of Life Massive Open Online Course (EoL MOOC) was developed, filmed, and produced over a 2-year period in collaboration with the staff of the Illinois CITL and has been offered on the Coursera platform since 2015 (Fouke 2015). Summarizing and updating the research of Carl R. Woese that established the three-domain Tree of Life, this no-tuition course delves into the implications of the Tree of Life for NASA astrobiology missions while exploring evolutionary history. Interviews with Woese, in which he explains how he approached and accomplished his scientific discoveries (Figure 1.3.2), are complemented with interviews of several of his renowned contemporaries and protégés in the fields of astrobiology, molecular microbiology, and evolutionary biology.

The target audience of the EoL MOOC are learners of all ages and incentives from around the world. More than 50,000 participants representing 160 countries have enrolled to date, of which approximately 25% finished the entire course.

FIGURE 1.3.2 (Top) Interview with Professor Carl R. Woese in the Emergence of Life Massive Open Online Course. (Bottom) Website home page for the GEOL 111 Emergence of Life course. Filming and production by Colleen Cook and the CITL staff.
Participants include middle and high school students, college and graduate students, postgraduate students, professionals, lifelong learners, and teachers, who receive continuing professional development units (CPDUs) for completing the course. There are two examples of the project’s global impact: in 2015, Fouke was completing research SCUBA on a coral reef off the coast of Na Trang, Vietnam. When he returned to shore at the end of a dive, he encountered a group of local high school students, two of whom had completed the EoL MOOC. Greeting Fouke by name, they asked him detailed questions about the Tree of Life as he emerged from the water. In another instance: via the EoL MOOC website, a single mother of five children, living in Dehradun, India, has engaged in regular weekly discussions about the Tree of Life with a retired petroleum geologist living in Tampa, Florida.

Though the EoL MOOC was initially offered with fixed start and end dates, after 1 year, it was transitioned into a constantly available “On Demand” format. Comprehensive teaching assessments were completed by the University of Illinois CITL staff. The 8-week EoL MOOC is composed of 80 video lectures, each approximately 4 to 7 minutes in duration, which cover the following topics:

- **Week 1: Geological Time, the Nature of Science and the Early Earth**
- **Week 2: The Tree of Life and Early Earth Environments**
- **Week 3: Fossilization and Precambrian Life-Earth Interaction**
- **Week 4: Paleozoic Life after the Advent of Skeletons**
- **Week 5: Paleozoic Plants, Reptiles and the Transition to Land**
- **Week 6: Mesozoic Reign of Dinosaurs and the Development of Flight**
- **Week 7: Cenozoic Mammals and Global Environmental Change**
- **Week 8: Astrobiology and the Search for Life in the Cosmos**

### 1.3.4 Higher Education

#### 1.3.4.1 GEOL 111 Emergence of Life

An 8-week version of the EoL MOOC, Geology 111 Emergence of Life (GEOL 111 EoL), with significantly expanded content and requirements, was adopted in 2015 as a formal full-credit 3-hour course in the University of Illinois Department of Geology (GEOL) through the College of Liberal Arts and Sciences. The target audience is formally enrolled science and non-science undergraduate students from disciplines across the University of Illinois campus. The course is offered in each spring semester and has an enrollment of 250 students. In 2016, GEOL 111 EoL became the first online course to be accredited as a General Education fulfillment. GEOL 111 EoL significantly expands beyond the composition and structure of the EoL MOOC and is intended to appeal to students from a wide variety of disciplines. This includes those taking GEOL 111 EoL for general education credit as well as those taking it as majors in the natural sciences, who take the course to broaden their background in earth system science and evolution. The course also makes full use of multiple asynchronous and synchronous methods of communication with the instructor and graduate student teaching assistants. In addition, the contributions of women and minorities who have worked on the origin and evolution of life are included and emphasized (e.g., the critically important yet overlooked accomplishments in x-ray diffraction analyses of DNA by Rosalind Franklin in the laboratory of Crick and Watson). GEOL 111 EoL also includes extended video recordings of instructor presentations, guest lectures, and virtual field trips to the coral reefs of Curaçao in the Caribbean, the hot springs of Yellowstone National Park, the dinosaur fossils of the Field Museum in Chicago, and an animated trip to Mars. In addition to learning from the instructor and teaching assistants through regular discussion forums, students are expected to learn from each other through peer-reviewed essays and reflections.

#### 1.3.4.2 Illinois Campus Honors Program

A formally accredited astrobiology and geobiology course has been offered for each year of the Illinois-Baylor-Davis NAI EPO program. *Yellowstone Biocomplexity*, a 3-hour credit seminar for advanced undergraduate students of all majors in the Illinois Campus Honors Program, has filled to capacity every offering, achieving a total enrollment to date of almost 100. The centerpiece of the course is to study about feedback interactions among thermophilic (heat-loving) microbes, extreme water conditions, and rapid mineral precipitation in terrestrial and marine hot springs around the world. Studies of the modern-day ecosystems are evaluated as a means to better interpret the ancient fossil record of microbes on Earth while aiding the search for life on other planets. The semester-long Illinois campus-based portion of each semester includes an extensive essay-based midterm examination and an oral presentation-based final examination. The seminar culminates with fieldwork on these astrobiology dynamics and interactions at the hot springs at Mammoth. Students work in groups of four to develop an experiment to be conducted from the boardwalks at Mammoth, using infrared thermometers and cell phone cameras. Resulting data is used to test meaningful astrobiology-relevant hypotheses, which the students then orally present and defend 1 week after their return to campus. These students have completed their work even under challenging field conditions (low temperatures and heavy snow), requiring them at times to conduct their research on skis and snowshoes.

Mammoth Hot Springs is a unique federally protected natural laboratory for these types of courses, which are offered under strictly controlled NPS educational permits. Mammoth contains a high diversity of microbial communities and travertine deposits that are systematically distributed along the outflow drainage channels of each hot-spring system (Fouke 2011). Students focus on tracking ways in which the environment influences and controls microbial life and, in turn, ways in which microbial life rises to influence and alter the environment. Students
are also exposed to system-scale dynamics and learn how linked carbonate-microbe systems grow, retreat, and change across large spatial and temporal scales. Gaining first-hand experience with four basic parameters within the Mammoth geo-ecosystem, students have learned to quantify, contextually integrate, track, and predict key mineral-water-microbe interactions. These include (1) spring water temperature; (2) spring water pH; (3) hot-spring water flow rate and dynamics; and (4) all basic contextual observations of the substrates flooring the drain outflow systems (i.e., travertine and microbial mat color, shape, size, growth rates, and distance along the drainage system, away from the vent). Concepts behind these basic modeling approaches to parameters are applicable to other sciences and can be translated to a broad range of grade levels. Several students have continued their Mammoth project as directed research in future semesters, contributed as co-authors to publications, and eventually joined the Fouke laboratory to complete their graduate degrees.

1.3.5 YOUTH OUTREACH

The current focus in the United States on standardized testing in secondary schools has produced unintended consequences observable in undergraduate populations of 4-year universities across the country. Professors and researchers in the sciences are concerned about a decline of critical thinking skills and curiosity, both of which are essential to scientific inquiry. At the same time, public secondary schools face constricted budgets, preventing teachers from enriching their curricula beyond state and national requirements. To address these issues directly, the Illinois-Baylor-Davis NAI EPO has developed a series of in-person classroom, laboratory, and field lectures, as well as summer workshops and camps, which have been presented to thousands of secondary education-level students. These teaching efforts, focused on the core astrobiology principles included in the EoL online courses and textbook, have been presented in secondary schools in the United States (Illinois, Wyoming, Idaho, Montana, California, and Washington, D.C.), Europe (Sweden, The Netherlands, and Italy), and Asia (Vietnam).

In this outreach, emphasis falls on five cornerstone illustrations from The Art of Yellowstone Science textbook (Fouke and Murphy 2016). These have proven effective in teaching cutting-edge astrobiology scientific principles and approaches that nurture curiosity and interest in students. The science content of these illustrations is also aligned with the Next Generation Science Standards (NGSS) (2018) in a variety of subject areas, including biology, chemistry, physics, and geology. These connections and free downloadable teaching materials are available online. The five illustrations receiving special emphasis include (1) Tree of Life (Figure 1.3.3), integrating geological time, specific geological events, the Tree of Life, and the origin of life in deep seafloor spreading centers; (2) Tree of Life Comparisons (Figure 1.3.4), illustrating the difference between the Woese three-domain Tree of Life and other constructs, now outdated, that still appear in textbooks; (3) Powers of 10 (Figure 1.3.5), an organizational principle relating examples from the Yellowstone ecosystem to immense hierarchical dimensions of space and time evaluated in astrobiology scientific studies; (4) Scientific Inquiry (Figure 1.3.6), graphically representing the

**FIGURE 1.3.3** The Tree of Life in a framework of geological time and geobiological events. Content by Bruce Fouke and graphic design by Killivalavan Solai. (From Fouke, B.W. and Murphy, T., The Art of Yellowstone Science: Mammoth Hot Springs as a Window on the Universe, Crystal Creek Press, 2016.)
Online, Classroom and Wilderness Teaching Environments

FIGURE 1.3.4 (Left) Diagram illustrating the single-trunk Prokaryote-Eukaryote Tree of Life. (Right) The three-domain Tree of Life constructed from molecular phylogeny. Content by Bruce Fouke and graphic design by Killivalavan Solai. (From Fouke, B.W. and Murphy, T., *The Art of Yellowstone Science: Mammoth Hot Springs as a Window on the Universe*, Crystal Creek Press, 2016.)

FIGURE 1.3.5 Powers of Ten space and time composition of Mammoth Hot Springs—from microbes to bison to glaciers and the supervolcano. Content by Bruce Fouke and graphic design by Killivalavan Solai. (From Fouke, B.W. and Murphy, T., *The Art of Yellowstone Science: Mammoth Hot Springs as a Window on the Universe*, Crystal Creek Press, 2016.)

FIGURE 1.3.6 Scientific inquiry, a systematic approach that generates new questions and spirals ever more closely toward the truth and knowledge of nature. (Top) Side view of the Scientific Inquiry spiral. (Bottom) Top view of the Scientific Inquiry spiral. Content by Bruce Fouke and graphic design by Killivalavan Solai. (From Fouke, B.W. and Murphy, T., *The Art of Yellowstone Science: Mammoth Hot Springs as a Window on the Universe*, Crystal Creek Press, 2016.)
Scientific Method as an endless spiraling process of inquiry and discovery; and (5) Deep Geological Time (Figure 1.3.7), coalescing the deep geological time into a handful of select ages, time intervals, and historical events.

### 1.3.5.1 Research Outreach Carbonate Hot-Spring Simulation

An experimental laboratory apparatus, constructed at the University of Illinois IGB, permits real-time, in-person, and online teaching of hot-spring astrobiology principles to secondary and higher education students. Named the Research Outreach Carbonate Hot-Spring Simulation (ROCHSS), this experiment simulates Mammoth Hot Springs in Yellowstone National Park by continuously heating and transporting 1,200 L of mineral- and CO$_2$-charged water along a 1-m-long precipitation runway (Figure 1.3.8). This apparatus allows students to manipulate and track a basic suite of physical, chemical, and biological parameters (i.e., temperature, flow rate, microbial composition, and water chemistry), using remote-controlled probes and video cameras. Students are therefore able to test directly astrobiology-relevant hypotheses pertinent to understanding the formation of biosignatures in the rock record on Earth, with likely relevance to other planets. The ROCHSS is designed to (1) expose 6–12 students and educators to university-level interdisciplinary scientific research applicable to a variety of middle and high school subject areas; (2) allow 6–12 students and educators to directly interact with university faculty, staff, and students; and (3) develop a sustainable experimental platform that can be used for both teaching and research.

The ROCHSS water begins in a pressurized mixing tank (Figure 1.3.8). Here, carbon dioxide (CO$_2$), CaCO$_3$, sodium chloride (NaCl), and other minerals and salts are dissolved...
to make a solution very similar to the water that erupts from the ground at Mammoth Hot Springs (Fouke 2011). At this point, the experiment either runs under default settings or is inoculated with living microbial cultures from our University of Illinois IGB laboratories. Next, the water travels through a heater, where the temperature can reach 70°C and pH can reach 6. It then flows along a runway (Figure 1.3.8), where CaCO₃ in the form of travertine is deposited and microbial mats grow simultaneously. As the hot water further cools and continues to degas CO₂, microbial mats upregulate proteins that serve to catalyze the travertine growth rate (Fouke 2011). Water flowing out from the downstream end of the travertine deposition runway is collected, pumped back into the mixing tank, and recycled with a circulating pump, while CO₂ is continuously bubbled through the recharge tanks (Figure 1.3.8).

The ROCHSS project was designed to support a broad range of teachers and students in learning basic hot-spring astrobiology principles, either in person at the IGB or online by accessing the experiment virtually. This virtual capability has dramatically expanded the reach of this University of Illinois campus project to national and international learning communities and can be easily coordinated into the EoL online courses. The online presence of the ROCHSS requirements that all sensors and cameras be controlled remotely with secure connections to a website that automatically organizes experimental data into an accessible database. This process includes streaming data from sensors that measure pH, temperature, ion concentration, CO₂, and flow. Cameras also feed streaming video and still images directly to the website, allowing for real-time monitoring and tracking of the experiment. At the conclusion of each trial, these data are “packaged” as downloadable files with associated time-lapse videos. Prior experimental data sets are also stored and accessible via the online portal for future reference and experimental comparisons. The versatility of this innovative platform will permit the ROCHSS to be utilized for a wide range of scientific topics, principles, and over a prolonged period of time.

Beyond accessing the experiment, educators and students can also access teaching materials, examples of experimental approaches, and laboratory exercises created using the five cornerstone illustrations from The Art of Yellowstone Science. These materials are linked to the astrobiology concepts presented in the EoL online course and are aligned to both state and federal NGSS (2018). Lessons cover up-to-date concepts on the Tree of Life, scientific inquiry, units of measurement, Yellowstone’s ecosystems and history, and a classroom outreach project. By connecting these foundational illustrations and the concepts they represent to the NGSS Physical Science, Life Science, Earth and Space Science, and Engineering Design Standards, the site supports diverse teachers in making connections to a variety of existing secondary education courses, including biology, chemistry, physics, and environmental science.

In addition to providing teaching materials, students have a chance to take an active role in the experimental design process using ROCHSS and to submit proposals for future experiments. Because these proposals need to include the specific experimental parameters to be measured, a hypothesis to be tested, a statement about the expected outcomes, and the astrobiology relevance and significance of the overall experiment, they provide important introductory experience in thinking like a scientist. When a proposal receives approval, IGB staff set the requested experimental parameters and run the experiment, monitored in real time by the students. The ROCHSS tests can run from a few days to several weeks in duration, given the millimeters-per-day growth rates of the travertine observed at Mammoth (Fouke 2011). Throughout these experiments, emphasis is placed on the concept that microorganisms are essential to the healthy functioning and evolution of all living things and that microbes are critical to solving global challenges in environmental sustainability, human medicine, food security, energy generation, and space exploration.

The IGB ROCHSS team will also host three in-person and online professional development days each year for middle and high school teachers. The goals of these workshops are (1) to support teachers in creating additional lessons aligned with the NGSS; and (2) to connect middle school and high school teachers with scientists, professors, graduate students, and the IGB staff. During these workshops, educators will have the opportunity to ask pertinent astrobiology questions, develop realistic and meaningful hypotheses to use in their classrooms, collaborate with other educators, and earn CPDUs. This professional development, identified as important by middle school, high school, and university staff, is vital to the ROCHSS project, as it provides a rare venue for middle school and high school teachers to discuss vertical alignment of standards and content, connect with university faculty, and build a sense of community in the ROCHSS program. Eventually, a group of teachers and students will also be included in a field trip to experience Mammoth and Yellowstone (Houseal et al. 2010).

1.3.5.2 Scholar-Athlete Sports in Space Science Camps

The Illinois-Baylor-Davis NAI EPO will partner with the Illinois IGB and the Illinois Division of Intercollegiate Athletics (DIA) in Summer 2018 to offer three 4-day Scholar-Athlete “Sports in Space” Science Camps for secondary education-level students. A total of 180 campers will participate from the Illinois DIA Men’s and Women’s Tennis, Men’s and Women’s Gymnastics, and Men’s Golf camps. If this experiment is successful, future camps could include thousands of campers from other Illinois DIA Division I sports, possibly including basketball, football, baseball, volleyball, and soccer. During each workshop, students will be exposed to cutting-edge astrobiology science in the integrated fields of genomic biology, medicine, geobiology, astrobiology, nutrition, kinesiology, and information technology through hands-on learning experiences. These experiences will
Handbook of Astrobiology

challenge students to consider (1) the role of the human microbiome and its possible implications on health and athletic performance; and (2) key concepts of space, including sports in space. Throughout the duration of these camps, each scholar-athlete will be asked to apply these concepts to their own athletic performance. Their camp experiences will aim to (1) increase campers’ awareness of Science, Technology, Engineering, and Mathematics (STEM) fields and research and increase their desire to pursue a STEM major in college; (2) have campers engage with interdisciplinary science underway at the University of Illinois and to build teamwork and laboratory inquiry skills in a variety of genomic-driven astrobiology scientific disciplines; and (3) provide campers with tools to evaluate their own health and performance long after the camp has concluded (Figure 1.3.9).

Building directly upon astrobiology insights contextualized by the Tree of Life, these scholar-athletes will learn about recent medical studies that estimate that as much as 90% of the total number of cells comprising the human body are single-celled microorganisms (microbes). These microbial communities (Bacteria, Archaea, and Eucarya) create a human microbiome that interacts with the mammalian host (Eucarya). They will also learn how the microbiome concept has fundamentally impacted all aspects of human medicine and will reshape how sports medicine is practiced in the future. From food and nutrient assimilation to muscle strength and fitness, the human microbiome is a fundamentally important concept for athletes to understand and incorporate into their training to maximize their health, strength, and athletic performance. The University of Illinois Department of Kinesiology is conducting research specifically on the influence of the human microbiome on sports performance (e.g., Allen et al. 2017). As a result, Kinesiology faculty and graduate students will assist our IGB team in presenting at these camps. During the Scholar-Athlete “Sports in Space” Science Camps, students will plate and grow microbial communities collected from their bodies. They will also record and analyze basic body measurements, including temperature, weight, CO₂ exchange, hydration, food nutrition, and athletic achievement, to gauge and evaluate performance and efficiency of their bodies over the duration of each camp. In turn, these factors will be related to fundamental principles of Yellowstone astrobiology and experimentation, using the ROCHSS laboratory. For instance, CO₂, temperature, nutrients, and extent of dehydration are the factors that influence microbial communities in both Mammoth Hot Springs (extent of travertine deposition) and the human body (sports performance). These linkages will be carefully explained to further emphasize the global interconnectedness of life and Earth processes.

Each camp includes 2 contact teaching hours each day, for a total of 4 consecutive days, as follows:

Day 1 Nutrition: Scholar-athletes are introduced to nutrition awareness and are asked to evaluate their eating habits based on their intake of water, sugar, protein-to-carbohydrate ratio, and their consumption of processed versus natural foods.

Day 2 Fuel and Hydration: Scholar-athletes learn about the role of the human microbiome in nutrition and sports; run experiments on their own bodies, including testing their substrate utilization with a certified sports nutritionist; and learn how to optimize their nutritional and water intake.

Day 3 Microbiomes, ROCHSS and Genomic Sciences: Scholar-athletes will evaluate the human microbiome

FIGURE 1.3.9 Scholar-Athlete outreach on the University of Illinois Urbana-Champaign campus. Urbana High School scholar-athletes in a lecture (left) and using microscopes (right) at the Carl R. Woese Institute for Genomic Biology at the University of Illinois Urbana-Champaign.
within the context of the Tree of Life, run real-time experiments on the ROCHSS laboratory device that utilize the same parameters that they have measured on their bodies, and have in-depth discussions about the role of their microbiome on sports performance.

Day 4 Exercise and Sports in Space: Scholar-athletes will evaluate human activity, health, and performance at low or zero gravity and calculate basic parameters such changes in the gravitational force that influence the way in which their sport will need to be played under extraterrestrial environmental conditions; campers will then predict how their chosen sport would need to be modified to be played on a spacecraft or other planets.

1.3.5.3 University of Illinois 4-H Academy

Closely following the content and approach presented in the EoL MOOC, a 4-day residential course for 30 secondary school students was offered to expose secondary education students to astrobiology sciences and work with university researchers through the University of Illinois 4-H Academy. Entitled Yellowstone: A Window on How the Universe Works (Figure 1.3.10), this course offered and explored fundamental astrobiology concepts and approaches, including (1) the structure and implications of the Tree of Life; (2) how Scientific Inquiry is conducted; and (3) key events in the Deep Geological history of the universe. In the process, students took a “virtual” trip to Yellowstone through high-definition videos and interactive laboratories. Students also scrutinized the dynamics of a flowing fountain on the Illinois campus (Figure 1.3.10), integrating their powers of observation with strategic photographic skills. Students were also provided with an overview of biotechnologies being used in the life and natural sciences at the Illinois Roy J. Carver Biotechnology Center. In addition, students also visited Illinois IGB laboratories in which cutting-edge genomics, proteomics, bioinformatics, and other analyses are underway.

1.3.5.4 Outreach to Underrepresented Communities

The University of Illinois Graduate College is committed to fostering an inclusive community, and Fouke serves on its coordinating Equity and Access Commission. The Illinois-Baylor-Davis NAI EPO program has been actively engaged with making astrobiology learning experiences a part of four major outreach programs within the Graduate College. The Community of Scholars Program is a campus-wide initiative that invites admitted students from these populations to visit and tour the campus, meet peers, and get to know faculty. The Grad Mentoring @Illinois Program is a mentoring network dedicated to increased recruitment, retention, and successful academic and career outcomes for underrepresented graduate students. The Summer Pre-Doctoral Institute (SPI) provides incoming graduate students from these constituencies with an 8-week orientation to graduate study before they arrive at Illinois for the fall semester. The Summer Research Opportunities Program (SROP) provides minority undergraduate students with an opportunity to explore careers in research, providing each student with an experience to strengthen his or her knowledge base, skills, and understanding of graduate work. The Graduate College has also worked with the Illinois-Baylor-Davis NAI EPO team to build connections with minority-enrollment institutions in Chicago, including Northeastern Illinois University and Chicago State University. The Illinois NAI E/PO program has also coordinated with the Graduate College office of the Educational and Equity Programs (EEP). The NAI faculty also worked work with the American Indian Studies (AIS) Institute to work with Native American populations in the Midwest. Working relationships have also been forged with the Illinois Center for African Studies and the Center for Latin America and Caribbean Studies to provide astrobiology learning experiences to students from those ethnic and racial backgrounds.

The University of Illinois campus is also a national leader in support and outreach to persons with disabilities. Formal
coordination has been established between the Illinois-Baylor-Davis NAI EPO program and the Illinois Division of Disability Resources and Educational Services (DRES) to integrate these students. The mission of DRES is to ensure that qualified individuals with disabilities are afforded an equal opportunity to participate in and benefit from the programs, services, and activities of the university through the provision of effective auxiliary aids and services, the establishment of innovative educational services, and the pursuit of interdisciplinary disability research.

1.3.6 TEACHING TEACHERS

1.3.6.1 STUDENT-TEACHER-SCIENTIST PARTNERSHIP

An STSP program was established in collaboration with the Yellowstone NPS, in which a series of 1-day workshops were held to teach teachers for several years at the Illinois IGB and at Mammoth Hot Springs. Each of these workshops had an enrollment of 20 secondary education teachers, who received CPDUs for participating. Emphasis was placed on the astrobiology scientific themes presented in the EoL online courses and the textbook, with these resources utilized throughout the workshops. After returning to their home classrooms, teachers presented these concepts as modules of 1 or 2 weeks in working with their students. Periodically throughout the ensuing academic year, the Illinois-Baylor-Davis NAI team of researchers held live question-and-answer sessions with each classroom on Google Hangout. An online supplemental curriculum was developed specifically for this project and made available online from Illinois servers, which included (1) real-time engagement with active astrobiology research in Yellowstone; (2) discussion of hypothesis-driven research by using an iterative systems model that focuses on field research best practices; (3) focus on systems-level, astrobiology-relevant water-microbe-mineral interactions at Mammoth, including the geological “plumbing” under the system, carbonate cycling, and microbial ecosystems within the hot springs; (4) familiarity with astrobiology principles and protocols intended to protect Earth from extraterrestrial inoculation; and (5) sharing of findings with student colleagues and partners.

1.3.7 TEACHING IN THE WILD

Illinois-Baylor-Davis NAI EPO activities have embraced Yellowstone National Park as a dynamic natural classroom and laboratory within which to offer astrobiology learning experiences that are contextualized by the grandeur of wilderness. In such a unique context, students can be immersed in the complexity, scale, and relevance of natural processes. There is no substitute for astrobiology exploration and teaching in the wild, where scientific encounter with the primordial origins of our humanity encourages students to contemplate urgent challenges to the survival of species, including our own (Fouke 2014).

Thus far in the course of the Illinois-Baylor-Davis NAI EPO program, more than 50 lectures have been offered to visitors and ranger groups throughout Yellowstone National Park, in collaboration with the NPS and the Youth Conservation Corps (YCC). Locations for these talks have included Mammoth Hot Springs, Old Faithful, Fishing Bridge, the Norris Geyser Basin, and the Lamar Valley. In addition to the previously described astrobiology themes of the EoL online courses and textbook, these talks focus on teaching visitors to view Yellowstone hot springs as a natural laboratory in which to develop new scientific understandings of global processes (Figure 1.3.11).

Though Mammoth Hot Springs and coral reef ecosystems may seem like wildly different and unrelated environments, closer examination indicates that these awe-inspiring places exhibit a host of striking similarities and scientific parallels. The spring water emerging from Mammoth Hot Springs in northern Yellowstone is derived from rain and snowmelt runoff in the Gallatin Mountains, which flow down along faults into the rock subsurface. Heated by the Yellowstone supervolcano to approximately 100°C, the water chemically dissolves deeply buried 350-million-year-old Mississippian-age marine limestone and evaporates deposits called the Madison Formation. The water then flows back up to the surface to emerge from vents at a temperature of 73°C (Fouke 2011), in a cycle requiring hundreds to thousands of years. During this hydrologic journey, the Mammoth water evolves into a salty chemical fluid that is remarkably similar to seawater. Furthermore, much of the travertine that precipitates to form the classic millimeter- to centimeter-scale terraced steps of Mammoth is composed of a mineralogical form of CaCO₃ called aragonite. This is the same mineral that corals use to precipitate and grow their skeletons in warm shallow tropical seas. Furthermore, several of the microbes identified in the 73°C–25°C hot-spring drainage patterns at Mammoth are similar, and sometimes closely related, to microbes inhabiting coral tissues, coral mucus, and seawater (Fouke 2011).

Results of our field-based controlled experiments at Mammoth are therefore being used to predict how corals will respond to future global warming and associated increases in sea surface temperature. Heat-loving (thermophilic) microbes living at 62°C–71°C at Mammoth can respond to rapid shifts in water flow rate and temperature by changing the rate at which travertine rock is deposited on the floor of the spring outflow drainage channels. Biogeochemical analyses further suggest that the microbes do this by producing different types of membrane-bound proteins under changing water temperatures and flow conditions (Fouke 2011). These proteins, in turn, change the level and distribution of cell surface energy that controls the rate at which ions in the spring combine to form a solid travertine mineral precipitate. These dynamics established at Mammoth are now being used to establish new interpretations of how density banding in the aragonite skeleton of tropical corals (similar to tree rings) reflects coral response to the changing sea surface temperature (Fouke and Murphy 2016).
1.3.8 PUBLIC POLICY AND INTERNATIONAL ENGAGEMENT

An ongoing series of lectures and displays has been developed for general audiences; this series presents astrobiology science themes highlighted in the EoL online courses and *The Art of Yellowstone Science* textbook. More than 20,000 people have participated across the United States, including (1) at Yellowstone, in collaboration with the NPS and YFI; (2) at the Field Museum in Chicago, Illinois; (3) at the Mayo Clinic in Rochester, Minnesota; (4) at libraries in small towns and large cities; (5) at organization gatherings such as 4-H and the Rotary Club; (6) at various public and private colleges and universities; and (7) at the European Union and other embassies in Washington, D.C.

1.3.8.1 CHICAGO FIELD MUSEUM OF NATURAL HISTORY

Illinois-Baylor-Davis NAI EoL displays were constructed on the Illinois campus, transported to Chicago, and shown as part of a 3-day University of Illinois IGB *World of Genomics* event presented in Stanley Hall, the largest venue at the Field Museum of Natural History. Situated between a complete *Tyrannosaurus rex* named Sue and the warring bull elephants, these NAI exhibits received more than 15,000 visitors, according to museum’s estimates. In addition to NAI, partners for the event included Carl Zeiss Microscopes, the Yellowstone NPS, and the YFI (the Park’s official education and fundraising non-profit partner). Featuring four Carl Zeiss petrographic microscopes and manned by 15 members of our NAI research group, the display included (1) the Emergence of Life on Earth and potentially on other planets; (2) microbial biomarkers in hot springs and potentially on other planets; and (3) the revolutionary NASA-supported work on molecular phylogeny, pioneered by Carl R. Woese. To further maximize the outreach impact of these exhibits, more than 500 students were bused to the field museum from schools in the Chicago Public School System, including Fenger Academy, Schurz High School, Gwendolyn Brooks College Prep, and Prosser Career Academy. More than 80% were students from underrepresented populations (Figure 1.3.12).
NASA runs multiple ongoing satellite-based missions that monitor Earth and that directly integrate with NAI planetary research goals (NASA Missions 2018). Upon receiving the NAI funding in 2012, an opportunity immediately emerged to develop a new broadly interdisciplinary course targeting university undergraduates from around the world. The course, as part of the Illinois-Baylor-Davis NAI EPO, fully integrated astrobiology science with Earth-based NASA satellite missions. This was made possible via a formal exchange agreement between the University of Illinois Urbana-Champaign and the KTH Royal Institute of Technology in Stockholm, Sweden (formally called the Illinois-Sweden Program for Educational and Research Exchange INSPIRE). Entitled Arctic Change, this 8-week formally accredited university undergraduate course within the INSPIRE program had a total enrollment of 17 students from the University of Illinois and 18 students from KTH. Arctic Change included 7 weeks of instruction in Stockholm and 1 week of instruction in Longyearbyen on the remote glaciated Svalbard (Spitsbergen) island archipelago, north of the Arctic Circle. Arctic Change offered a unique international integration of classroom, laboratory, and field experiences that linked Nordic humanities with environmental, life, and space sciences. The course contextualized these concepts with the Tree of Life and basic astrobiology sciences, while tracking these connections through deep geological time. This progressive breadth of cross-disciplinary education in a single field-based course is unparalleled in other universities around the world.

Arctic Change emphasized biocomplex relationships that arise from dynamic interactions between the physical, chemical, biological, and social components of the Svalbard ecosystem. Cornerstone parameters such as sea surface temperature, air temperature, glacier thickness and retreat, polar bear...
and reindeer ecology, the emergence of infectious disease, changing human behavior, and cultural history were evaluated across multiple spatial (microns to thousands of kilometers) and temporal (nanoseconds to eons) scales. These were then directly compared to astrobiology-relevant life phenomena, such as NAI studies of the Antarctic Dry Valleys (e.g., Gilichinsky et al. 2007), that are fundamental to the search for life on other planets. Emergent phenomena and feedbacks through time were used as a framework to better understand the development and logistics of Nordic society, language, and culture in its own unique environmental setting.

The *Arctic Change* course emphasized the powerful influence of the ecology and evolution of microorganisms when discussing natural resources and land use by human inhabitants in the Arctic (e.g., food, fuel, water purification, and erosion control). This was evaluated with cutting-edge molecular sequencing and OMICS science tools, which are also central to the role of new biotechnical initiatives throughout the Nordic countries. Discussions and exercises were consistently linked back to the Tree of Life. To reinforce these principles, students were brought to tour the KTH-Karolinska SciLifeLab in Stockholm prior to departing for Svalbard. *Arctic Change* students were from internationally diverse cultural and academic backgrounds. Student participants were majoring in everything from oceanography, geology, hydrology, microbiology, ecology, physics, chemistry, and the biosciences, as well as contemporary and historical Danish, Norwegian, Swedish, and Svalbard cultures, languages, and societies (Figure 1.3.13).

### 1.3.9 LIFELONG LEARNING

#### 1.3.9.1 ILLINOIS OSHER LIFELONG LEARNING INSTITUTE AND YELLOWSTONE FOREVER INSTITUTE

In order to strengthen and more widely disseminate astrobiology science to lifelong learners, the Illinois-Baylor-Davis NAI EPO program presented a series of new hybrid courses on the *Emergence of Life* and *The Art of Yellowstone Science*. These were offered through the University of Illinois OLLI and the YFI to participants who were 50 years of age and older. Future emphasize needs to be continually placed on learners in order to provide inspiring educational opportunities for this rapidly growing cohort of accomplished and experienced people around the world. The Illinois-Baylor-Davis NAI EPO courses at the OLLI were offered in the spring semester for 8 weeks, with one class meeting each week. The linked objectives of astrobiology, Yellowstone science, and art naturally lend themselves perfectly to the OLLI classroom presentations and seminars. As a result, the maximum enrollment

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**FIGURE 1.3.13** *Arctic Change* field course in Svalbard, Norway, that included students from the University of Illinois Urbana-Champaign and the KTH Royal University in Stockholm, Sweden.
of 103 students per course was quickly reached, with long waiting lists each time the course was offered. Mirrored courses were also presented multiple times through the YFI at Mammoth Hot Springs (Figure 1.3.14).

1.3.10 SUMMARY

An NAI’s program entitled *Towards a Universal Biology: Constraints from Early and Continuing Evolutionary Dynamics of Life on Earth* was awarded in 2012 to a consortium led by the University of Illinois Urbana-Champaign and included the Baylor University College of Medicine and the University of California, Davis. A key initiative in this work has been to further advance the work of Professor Carl R. Woese, whose pioneering research was the first to identify the Archaea, establish a three-domain Tree of Life, and provide our first glimpse of the evolutionary events that led to the emergence of the Last Universal Common Ancestor. The three-domain Tree of Life also provided the fundamental framework required to search for, identify, compare, and interpret extraterrestrial life forms that might be discovered in the foreseeable future. A progressive EPO effort that directly translated NAI team’s ongoing astrobiology research discoveries to online, classroom, and wilderness learning opportunities was completed. Mammoth Hot Springs in Yellowstone National Park was fully utilized as a dynamic classroom and natural laboratory for astrobiology research-inspired teaching opportunities, which have included development and presentation of (1) *Hybrid Textbook*; (2) *Open Education Resources and Global Outreach*; (3) *Higher Education*; (4) *Youth Outreach*; (5) *Teaching Teachers*; (6) *Teaching in the Wild*; (7) *Public Policy and International Engagement*; and (8) *Lifelong Learning*.

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