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Students' Pre-Instructional Beliefs and Reasoning Strategies About Astrobiology Concepts

by **Erika G. Offerdahl**
University of Arizona
Edward E. Prather
University of Arizona
Timothy F. Slater
University of Arizona
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Abstract

The purpose of this study is to identify and document student beliefs and reasoning difficulties concerning topics related to astrobiology. This was accomplished by surveying over two thousand middle school, high school, and college (science and non-science majors) students. Students were surveyed utilizing student-supplied response questions focused on the definition of life and its limitations. Careful, inductive analysis of student responses revealed that the majority of students correctly identify that liquid water is necessary for life and that life forms can exist without sunlight. However, many students incorrectly state that life cannot survive without oxygen. Furthermore, when students are asked to reason about life in extreme environments, they most often cite complex organisms (such as plants, animals, and humans) rather than the more ubiquitous microorganisms. Results of this study were used to inform the development of astrobiology curriculum materials.

Astrobiology can be defined as the study of the origin, evolution, distribution, and destiny of life in the universe. It exists as an interdisciplinary science at the intersection of astronomy, biology, chemistry, mathematics, physics, and geology. Recent discoveries reported in both scientific journals and the popular press have dramatically changed our view of the potential for life existing elsewhere in the universe. As one example, nearly ten times as many planets have been discovered outside our solar system as there are within it. Perhaps even more impressive is that life has been found to exist under conditions previously thought impossible. This includes organisms that thrive in extreme temperatures, in highly acidic and basic conditions, at thousands of feet below Earth's surface, on the dark ocean floor, and in the adverse radiation conditions of outer space (SpaceRef Interactive 2002). These discoveries are being made concurrently with discoveries that strongly suggest the existence of liquid water oceans beneath the icy surface of Jupiter's moon Europa, and that running water was likely present on the surface of Mars in the past. As a result, our understanding of the limits on life has forever been changed.

Because of astrobiology's truly interdisciplinary nature, many classroom teachers are actively considering the inclusion of astrobiology concepts in their courses. As a result, there exists a growing need to create effective astrobiology teaching resources. However, there is a severe lack of documentation of the specific conceptual and reasoning difficulties students have when encountering astrobiology topics. Furthermore, there is also a serious absence of more fundamental research into students' general pre- instructional beliefs concerning such topics. The preliminary research project presented in this paper describes our efforts to uncover and document students' beliefs about astrobiology-related topics prior to formal instruction. The results of this investigation were used to inform the development of a multitude of innovative, guided inquiry instructional materials in the field of astrobiology that are not described here.

1. BACKGROUND AND CONTEXT OF THE STUDY

Contemporary efforts to create effective teaching resources have a long history of relying on an understanding of how people learn. The behaviorist view of learning, and consequently teaching materials, strongly influenced how learning was viewed during the early part of the twentieth century. Behaviorism focuses on the examination of students' objective, observable behaviors rather than on the processes of the mind (Gardener 1987). Under this paradigm, teaching is conceived as creating a conditioned response in the student. For example, to teach a student about a complex process, teachers first break the process into its basic components. Next, the student is instructed on each of the individual components, followed by a demonstration of how each of the components is connected to the others. When the student has performed the "desired behavior," he or she is deemed to have successfully "learned" the complex process. We now understand that this behavioral view of learning is insufficient. It ignores two critical aspects of the active learning process: (1) the importance of engaged mental effort used by the individual in learning a complex process/concept, and (2) whether the individual is able to accommodate the learned process/concept in a meaningful and appropriate way into his or her existing conceptualizations (Posner, Strike, Hewson, & Gertzog 1982). Fortunately, with targeted effort, teaching resources can be created to engender deep thinking in students if their pre-instructional beliefs are taken into consideration (Prather & Slater, in press).

Our research questions are both motivated and guided by a constructivist view of the learning process. According to this perspective, students do not enter into the classroom as "blank slates" (Saunders 1992; Slater, Carpenter, & Safko 1993). Rather, new experiences and observations are actively interpreted and manipulated by students to create personal mental models of specific topics. The most important aspect of this viewpoint on learning is that students' pre-instructional beliefs strongly influence the creation of their mental models and how prior experiences and observations become incorporated into these models (Redish 1994; von Glasserfield 1992). Consequently, the acquisition of new knowledge is highly dependent on (1) the topic under investigation, (2) the students' prior exposure and experience with the topic, and (3) the instructional techniques used to introduce the topic (Prather 2000). In addition, students may even possess multiple and conflicting pre-instructional beliefs about the topic at hand. These beliefs may also simultaneously contradict and align with accepted scientific understandings of the topic. The more closely students' pre-instructional beliefs are aligned with new experiences and observations, the greater the likelihood that new concepts will be accepted by the students, and in a manner consistent with the original intent. It is our belief that student learning will be enhanced by the use of instructional strategies that are guided by an understanding of the pre-instructional ideas students bring to the astrobiology classroom.

2. METHODS

Because astrobiology is a relatively new and interdisciplinary science, educational research on students' prior knowledge related to astrobiology completed to date is sparse at best. Although over a thousand studies have been conducted that specifically examine the issue of students' understanding of broad-field scientific concepts, two-thirds fall within the domain of physics, while only about one third have examined issues in biology and chemistry (Wandersee, Mintzes, & Novak 1994). As a vital portion of astrobiology, biology studies provide valuable insights into astrobiology-related topics. However, little exists in the literature about students' understanding of cells, the interdependence of organisms within a system, or the flow of energy through ecosystems (AAAS 1993). Research that does exist focuses on topics such as students' concepts of animals and plants (Trowbridge & Mintzes 1985; Osborne & Freyberg 1985), the human body (Arnaudin & Mintzes 1985, 1986; Carey 1985), photosynthesis (Barker & Carr 1989; Eisen & Stavy 1988; Roth, Smith, & Anderson 1983), and other biological phenomena ranging from cells to food webs to natural selection (Wandersee et al. 1994). Because elementary students typically use "movement" and "breath" as criteria for life, many think that fire, the Sun, and clouds are alive, while plants and certain animals are not (Bell & Freyberg 1985; Leach, Driver, Scott, & Wood-Robinson 1992). Even high school and college students largely use surface criteria, such as growth and movement, to define life rather than cells or DNA (Brumby 1982; Leach et al. 1992). In total, the vast majority of biology studies largely fail to examine the more fundamental concepts aligned with astrobiology concerning the definition of life on Earth and its limitations in a way that serves to inform contemporary curriculum development.

According to the *NASA Astrobiology Roadmap* (Connell 2002), astrobiology strives to provide answers to three main questions: (1) How does life begin and develop? (2) Does life exist elsewhere in the universe? (3) What is life's future on Earth and beyond? Before one can thoroughly answer the latter two questions, one must begin by understanding and addressing the first. Similarly, our research into student pre-instructional understanding started with the first question as a central motif from which to build. We developed a series of student surveys designed to expose students' pre- instructional beliefs about life on Earth, including the definition of life as we know it, the requirements for life, and the limitations of life. The results from this study not only contribute significantly to the science education literature by filling in wide gaps concerning student beliefs about scientific concepts from an astrobiology perspective, but they also serve to inform the development of effective instructional materials in astrobiology.

Beginning in the spring of 2000, we developed a set of four surveys for distribution to over 2,000 middle school, high school (physical and Earth sciences), and college (both science and non-science major) students. In this population, middle school students generally represent children aged ten through thirteen years old, whereas high school students generally represent teenagers aged fourteen through eighteen years old. Because research into student understanding of astrobiology concepts is somewhat unprecedented, we began our exploratory investigation by developing a set of questions that were designed to uncover students' general pre-instructional beliefs and elicit possible reasoning difficulties. This approach is well documented in physics education research (McDermott 1991; Prather 2000; Slater 1993). The results of these preliminary questions provided insight into the development of further questions that often were, in turn, designed to target very specific astrobiology topics.

Each individual survey distributed consisted of two or more conceptually unrelated, student-supplied response items. The questions on each survey sheet were carefully selected to be conceptually separate so that the first question would not influence the response of the second, and vice versa. Examples of how the questions were paired on each survey can be seen in Table 1. When appropriate, each question prompted students to thoroughly explain the reasoning behind their responses. Prior to distribution, the students were told that the accuracy of their responses was of less concern than a detailed explanation of their actual beliefs.

Table 1. Distribution of survey questions

SURVEY #1:

1. Can life exist in places that never receive sunlight?

   Yes » What types of life forms could exist?
   No » Cite the physical reasons why life cannot exist without sunlight.

2. What elements are the most important for the existence of life? Explain your reasoning.

SURVEY #2:

1. Consider the following statement:

   For a life form to exist, liquid water must be present in the local environment in at least small amounts or for short time periods.

   Circle whether you **agree** or **disagree** with this statement.

   Agree » Explain why liquid water is necessary.
   Disagree » What type of life could exist and what would the environment be like?

2. *We know that there are 9 planets orbiting the Sun in our solar system. Would you expect there to be other planets orbiting other stars outside our solar system? Explain why or why not.*

SURVEY #3:

1. Can any forms of life exist in environments with temperatures much greater than 100°C (the boiling point of water) or much less than 0°C (the freezing point of water)?

   Yes » What types of life forms could exist at either of these temperatures? State the form of life and the corresponding temperature.
   No » Cite the physical reasons why life cannot exist at either of these temperatures.

2. *Circle the elements that must be present for life to exist. Explain your reasoning for each choice. (listed are hydrogen, potassium, zinc, oxygen, calcium, uranium, magnesium, sulfur, carbon, nitrogen, iron, and sodium)*

SURVEY #4:

1. Describe an environment on Earth that would *not allow any* form of life to exist. Cite specific examples and explain why these environments cannot support life.

2. *Do scientists have evidence that indicates whether life exists anywhere other than Earth? Explain your reasoning.*

Note: Results from *italicized* questions not discussed within the context of this paper.

The responses to each question were carefully analyzed and thematically grouped into conceptually separate categories based on the most common responses. As a preliminary study, the goal was to determine the full range of possible student ideas rather than the average response. This is distinctly different from more traditional science research studies. Because the questions were designed to elicit student-supplied responses, students were allowed to give more than one response to each question. Consequently, summation of all the response categories for each question results in percentages greater than one hundred.

3. RESULTS

Our research of students' pre-instructional beliefs is focused on five key astrobiology-related topics: sunlight, water, temperature, limiting environments, and necessary elements for life. Each of these topics provides insight into students' pre- instructional beliefs about the definition of life and its limitations, which are fundamental to astrobiology. After distributing the surveys and analyzing the student responses, we identified several repeated themes in student beliefs about astrobiology-related topics. In the following subsections, we present the results of the student-supplied responses.

3.1. Student Understanding of the Necessity of Sunlight

When asked to define life, students are expected to recite a list that will most likely include such requirements as the ability of a living organism to reproduce faithfully, to utilize an energy source, to grow and develop, and to respond and adapt to the surrounding environment. Since sunlight is a major source of energy on our planet, one of the first survey questions created probed students' beliefs about the importance of sunlight as a requirement for life.

A total of 642 surveys eliciting students' beliefs about the importance of sunlight were collected, 289 from middle school students, 177 from high school students, and 176 from college students. Of these, 61% (176) of middle school, 59% (104) of high school, and 78% (138) of college students responded that life can exist without sunlight. A summary of the "yes" responses to the question about sunlight is provided in Table 2.

Table 2. Student understanding of the necessity of sunlight

Sunlight Question (N=642):

Can life exist in places that never receive sunlight?

Yes » What types of life forms could exist?

No » Cite the physical reasons why life cannot exist without sunlight.

Student-Supplied Response Categories to *"Yes » What types of life forms could exist?"*	Middle School (N=176)	High School (N=104)	College (N=138)
Microorganisms	39%	47%	*59%
Creatures in the bottom of the ocean/deep underwater	32%	*52%	46%
Things that live in caves or underground	16%	12%	17%
Plants	7%	5%	7%
Insects	7%	3%	3%
Humans	7%	4%	1%
Other/No response	23%	16%	17%

Student-Supplied Response Categories to *"No » Cite the physical reasons why life cannot exist without sunlight."*	Middle School (N=113)	High School (N=73)	College (N=38)
No plants would live, therefore no oxygen on Earth	39%	37%	45%
Temperature of the planet would dramatically decrease	33%	23%	24%
Circle of life/food chain depends on it	18%	34%	29%
No energy from the sun means no food and no life	16%	19%	24%
Other/No response	4%	12%	10%

* Designated population demonstrates a difference that is statistically significant at a 95% confidence level from the other two populations.

In developing our student-supplied response question about sunlight, a "scientifically accurate" response from the student would be one in which the student responded "yes" and then cited microorganisms or other life forms known to exist in the absence of sunlight (i.e., fungi, bats, worms, etc.) In each of the three student groups, agreeing that life can survive without sunlight and citing microorganisms was one of the most common responses. The other commonly cited response, and equally acceptable, was the one including organisms living at the bottom of the ocean or in deep water where light cannot penetrate. One high school sophomore stated, "Yes, microorganisms live in the ocean where no sunlight exists ... other life forms must be of the type that do not depend on photosynthesis." When compared to responses such as plants, insects, and humans, the two most popular responses indicate that students are not only considering the immediate environment in which they live, but are also able to reason about places they cannot witness or experience firsthand.

In contrast to the students who responded "yes," 39% (113) of middle school, 41% (73) of high school, and 22% (38) of college students attested that life cannot exist without sunlight. A summary of the "no" response categories is also provided in Table 2.

Of the number of students that cited life cannot exist without sunlight, we see a large percentage of students exhibiting sophisticated models for why sunlight is necessary. Their responses evoke the relationship between sunlight and plant growth, planetary temperatures, and effects of sunlight (or its absence) on the food chain. For example, one college student responded, "the organisms at the beginning of the food chain rely on photosynthesis to help them perform their vital functions. Without these organisms ... the food chain would be devastated."

By examining the student-supplied responses of the students who responded that life cannot exist without sunlight, a clear difference in conceptual models between the ages is apparent. We see that the two most common middle school "no" response categories reflect a more simplistic and less intricate model of the Sun’s importance. One common middle school response (the temperature of the planet would dramatically decrease) was not cited from a global point of view. Rather, the middle school students seemed to be reasoning about the absence of sunlight with respect to their own locality and personal experiences. These middle school students attested that without sunlight, it would be cold outside "like when standing in the shade," and therefore *humans* couldn’t survive in the cold temperatures. Although many high school and college students also responded that sunlight is necessary to maintain the temperature of the planet, they seemed to conceptualize this model from a global perspective. For example, one college student responded that, "the Earth would get very cold like when the dinosaurs became extinct," which suggests a more global perspective than the statements made by middle school students. This is an example of (1) how middle school students have less scientifically sophisticated models about the significance of sunlight, and (2) how, when asked to consider life in general, middle school students in our sample often cite complex organisms such as plants, animals, and humans, but seldom life as simple or widespread as microorganisms.

The second most common middle school student-supplied response category encompasses a model relating sunlight to plants and their role in producing oxygen. This model includes that sunlight is necessary for plant growth, that plants are needed for oxygen production, and that oxygen is necessary for life. This model largely neglects to consider the microorganisms that sustain the ability to thrive in anoxic conditions, such as strict anaerobes. In contrast, some high school and college students acknowledged that an absence of sunlight would result in the death of plants, but noted that microbial life can exist in anoxic conditions. Whether the middle school students have not reached a point in their science curriculum that microbial life has been emphasized or whether students of this age do not have the conceptual maturity to extend their own experiences into a world unseen to them is unclear.

The third common theme in student-supplied responses for all age groups addresses the concept of the interrelatedness of all life on Earth, i.e., the circle of life. Students’ responses suggest that they conceptualize the necessity for sunlight based on the belief that an interdependence of organisms on Earth means that, in one way or another, all life depends on sunlight. However, there were differences in the sophistication of the responses between the age groups. As is indicated by the greater percentages, high school and college students reason about the connections between organisms more readily than middle school students. In general, we see a greater ability of the older students to express ideas scientifically, and having a more complete background in science. Furthermore, college students show a greater tendency to "activate" their definitions of life on a fundamental level and consider how a lack of sunlight would affect this basic definition rather than thinking solely about individual organisms and their responses to no sunlight.

3.2. Student Understanding of the Implications of Water

Over the past few years, the media has released much discussion as to whether water exists on any other planets, or their moons, in our solar system. The discovery of sufficient water could mean the existence of life or a potential place for human colonization. We were curious as to whether students understand the implications of such a discovery or even comprehend the significance of water. Liquid water is one requirement for life as we know it on Earth. As a result, one of the preliminary questions developed for our set of surveys was intended to reveal students' pre-instructional beliefs about the necessity of water.

A total of 310 students were surveyed with the question concerning the degree to which water is a necessity for life (115 middle school, 62 high school, and 133 college). Of these, 83% (95) of middle school, 73% (45) of high school, and 77% (103) of college students stated that liquid water is necessary in at least small amounts or for short periods of time. However, few students in any age group could provide evidence as to *why* water is necessary. Roughly 70% of all students responded that "life just needs it." The student- supplied response categories of recurrent themes are displayed in Table 3.

Table 3. Student understanding of the necessity for water

Preliminary Water Question (N=310):

For a life form to exist, liquid water must be present in the local environment in at least small amounts or for short time periods.

Circle whether you **agree** or **disagree** with this statement.

Agree » Explain why liquid water is necessary.
Disagree » What type of life could exist and what would the environment be like?

Student-Supplied Response Categories to *"Agree » Explain why liquid water is necessary."*	Middle School (N=95)	High School (N=45)	College (N=103)
All life just needs it	69%	69%	72%
Dehydration would occur without water	22%	13%	*6%
Bodily/cellular functions	7%	22%	10%
Organs are made of it	5%	18%	7%
Water is the basic element of life	1%	7%	4%
Movement	0%	4%	4%
Needed for chemical reactions	0%	4%	0%
Provides nutrients	1%	7%	4%
1st form of life started in water	2%	0%	2%
Other/No response	5%	2%	0%

Student-Supplied Response Categories to *"Disagree » What type of life could exist and what would the environment be like?"*	Middle School (N=20)	High School (N=17)	College (N=29)
Forms of liquid other than water may be used	25%	24%	14%
Life forms unknown to us may use a substance other than water	*25%	41%	41%
Microorganisms	20%	24%	24%
Organisms in the desert	0%	12%	7%
Viruses	0%	12%	3%
Other/No response	35%	18%	32%

* Designated population demonstrates a difference that is statistically significant at a 95% confidence level from the other two populations.

Less than one third of all students surveyed (17% of middle school, 27% of high school students, and 22% of college students) stated that water is not necessary for life to exist. Based on the responses of the minority of students who disagreed with the statement about water, six response categories were formed, as can be seen in Table 3.

Of these student-supplied response categories, it is interesting to note that some students cited that microorganisms could exist without water. This is one example, of many, in which students classify microorganisms differently from more complex life. This is typically demonstrated in one of two ways. The student either (1) testifies that microbial life is exempt from the same biological "rules" as complex life, or (2) classifies microorganisms as non-living.

After examining the data collected with the preliminary survey question asking students to agree or disagree with a statement about the importance of water, it became apparent that a majority of all students correctly identify that all life as we know it requires liquid water. For example, one sixth-grade student remarked "agree" and wrote, "Because everyone and everything needs water to survive." However, since few students could provide significant reasoning as to why water is necessary, we felt it was prudent to further probe student understanding of the necessity of water. Consequently, we modified the original question and asked a second water question on subsequent surveys. This new question eliminated the opening statement and therefore the necessity for students to agree or disagree with it. We started from the assumption that most students would agree that water is necessary for life and asked them to explain specifically why this is so.

A total of 347 students were surveyed with this additional water question (169 middle school, 134 high school, and 44 college). After careful analysis, student-supplied response categories were created based on the most common student responses, as can be seen in Table 4. Although the majority of these response categories represent true statements, they do not demonstrate a deep understanding of the significance of water for life as we know it. For example, these categories do not include statements concerning the high specific heat of water, its status as a nearly universal solvent, or the fact that water becomes less dense as it changes from a liquid to a solid.

Table 4. Follow-up question on the necessity of water

Second Water Question (N=347):

Describe why liquid water is essential for life. Give specific reasons of why organisms need water or how they use it.

Student-Supplied Response Categories	Middle School (N=169)	High School (N=134)	College (N=44)
Needed for bodily/cellular function	41%	39%	30%
Dehydration would occur without water	24%	34%	25%
Organisms are made of it	*16%	*28%	*41%
Oxygen is in water and we need oxygen	2%	5%	9%
Other/No response	27%	15%	14%

* Designated population demonstrates a difference that is statistically significant at a 95% confidence level from the other two populations.

The data resulting from both the water questions were robust. These results established that the majority of students in all age groups acknowledge water as a life- defining element. However, it also suggests that students may need prompting in order to elicit a response as to how or why water is important, and the implications that the discovery of water on other planets would have on our society.

This second question probing student understanding of the importance of water for life provided valuable insight into what students think. The results from this question strongly suggest that before we can truly expect students to understand the importance of finding water on other planets/moons, teachers may need to allocate time solidifying in students' minds why water is important to life as we know it. As can be seen, this question did not evoke responses concerning the chemical properties of water, such as polarity and high specific heat, that make water unique.

3.3. Student Understanding of the Implications of Temperature

Without a constant and moderate temperature, Earth would quickly become an inhospitable planet of extremes like our neighbors Mars and Venus. How students view this delicate balance is crucial to teaching concepts in astrobiology. To gain a foundation of how students perceive the effects of temperature on the existence of life, we asked a series of questions probing students' beliefs about temperature.

A total of 645 students were surveyed by a question probing if life can exist at extreme temperatures (283 middle school, 194 high school, and 168 college students.) Of these, over 60% of all students (59% in middle school, 65% in high school, and 86% in college) surveyed responded that life can live in temperatures greater than the boiling point and/or lower than the melting point of water. The student-supplied response categories found in Table 5 are types of organisms that students stated could survive in extreme temperatures. In analyzing our student-supplied response questions about temperature, the most "scientifically accurate" response from a student would be one in which the student responded "yes" and then cited microorganisms such as thermophiles and psychrophiles that are known to exist in environments of extreme temperature.

Table 5. Student understanding of the implications of extreme temperature

Preliminary Extreme Temperature Question (N=645):

Can any forms of life exist in environments with temperatures much greater than 100°C (the boiling point of water) or much less than 0°C (the freezing point of water)?

Yes » What types of life forms could exist at either of these temperatures? State the form of life and the corresponding temperature.

No » *Cite the physical reasons why life cannot exist at either of these temperatures.*

Student-Supplied Response Categories to *"Yes » What types of life forms could exist at either of these temperatures? State the form of life and the corresponding temperature."*	Middle School (N=168)	High School (N=126)	College (N=144)
Microorganisms	47%	58%	*75%
Organisms that live in the arctic (i.e. penguins, polar bears, etc.)	29%	24%	26%
Animals, fish, birds, etc.	*30%	*19%	*8%
Humans	15%	10%	13%
Organisms that live in the desert	7%	8%	3%
Plants	3%	5%	3%
Insects	4%	3%	2%
Fungi/spores	1%	2%	3%
Other/No response	7%	18%	7%

Student-Supplied Response Categories to *"No » Cite the physical reasons why life cannot exist at either of these temperatures."*	Middle School (N=112)	High School (N=68)	College (N=24)
It's just too hot	*58%	*42%	*22%
It's just too cold	55%	42%	*19%
These temps are higher/lower than the boiling/freezing point of H_20, life will burn up/freeze to death.	28%	39%	32%
Organisms will become dehydrated	11%	0%	6%
Organisms can't adapt easily to these temperatures	4%	8%	20%
Other/No response	13%	21%	10%

* Designated population demonstrates a difference that is statistically significant at a 95% confidence level from the other two populations.

Conversely, 41% (112) of middle school, 35% (68) of high school, and 15% (24) of college students stated that life cannot exist in the temperatures above 100°C or below 0°C. It is interesting to note that as the age of the students surveyed increases, the percentage of students who believe the temperatures are too extreme decreases.

Although a majority of all students correctly responded that life can exist in extreme temperatures, there was an inconsistency within the responses they supplied. Specifically, some students would both agree and disagree with the statement, citing that life can exist in extremely hot temperatures but not in extremely cold, or vice versa. For example, a college freshman wrote, "0°C: Humans, animals, trees, 100°C: Nothing can live at that temp (210oF)." Due to the categorization method used, we were unable to clearly quantify conflicting responses such as these. Consequently, we created two separate temperature questions from the original question for subsequent surveys, one probing student understanding of life in extremely high temperatures and the other probing student understanding of life in extremely low temperatures.

A total of 401 students were surveyed with a second temperature question examining life at temperatures above 100°C (145 middle school, 244 high school, and 12 college students). Twenty-six percent (37) of middle school, 46% (112) of high school, and 58% (7) of college students responded that life can exist in the high temperature range. Their responses included microorganisms, desert life, humans, plants, and insects, among other things.

Table 6. Follow-up question probing understanding of implications of high temperatures

Extremely High Temperatures Question (N=401):

Can any forms of life exist in environments with temperatures much greater than 100°C (212°F)? Circle either **Yes** or **No**.

Yes » State specific examples of life forms that could exist at these temperatures.

No » Cite the physical reasons why life cannot exist in this temperature range.

Student-Supplied Response Categories to *"Yes » State specific examples of life forms that could exist at these temperatures."*	Middle School (N=37)	High School (N=112)	College †(N=7)
Microorganisms	43%	54%	n=3
Organisms that live in the desert	14%	12%	n=1
Humans	8%	10%	n=1
Plants	8%	4%	n=0
Insects	8%	6%	n=0
Other/No example	38%	23%	n=2

Student-Supplied Response Categories to *"No » Cite the physical reasons why life cannot exist in this temperature range."*	Middle School (N=108)	High School (N=132)	College †(N=5)
It’s just too hot	34%	29%	n=2
The heat would inhibit bodily/cellular function	28%	20%	n=1
This is above the boiling point of water/we boil things to kill germs	26%	26%	n=2
Life would dehydrate or all the water would evaporate	13%	11%	n=0
Other/No example	13%	15%	n=0

† Upon distribution of the second iteration of our temperature question, access to large college populations was unavailable and is reflected in the relatively small number of college students surveyed.

A substantial portion of students cited microorganisms as being able to live in extremely high temperatures. It is worth noting that the high percentages in the "other/no example" response category result not from a high number of varying unclear responses, but from a large number of students circling "yes" without providing an explanation.

Of the 401 students surveyed, 74% (108) of middle school students, 54% (132) of high school students, and 42% (5) of college students responded that life cannot exist in the high temperature range. A summary of the "no" responses include that extremely high temperatures would kill germs, inhibit cellular function, and dehydrate life forms, among other things.

A total of 399 students were surveyed with a third question concerning the ability of life to exist well below 0oC. Of these, 146 were in middle school, 241 in high school, and 12 in college. Eighty percent (117) of middle school students, 90% (218) of high school students, and 92% (11) of college students responded that life can exist in this cold temperature range. These percentages indicate that roughly twice as many students think that life can exist in extremely low temperatures than those who cited that life can survive in extremely high temperatures. The most common student responses included organisms that live in the arctic regions, humans, and microorganisms. Although a large percentage of students did agree that life can exist in temperatures below 0oC, there were far fewer students who cited microorganisms than for the high temperature question.

Table 7. Follow-up question probing understanding of implications of low temperatures

Extremely Low Temperatures Question (N=399):

Can any forms of life exist in environments with temperatures much less than 0°C (32°F)? Circle either **Yes** or **No**.

Yes » State specific examples of life forms that could exist at these temperatures.

No » Cite the physical reasons why life cannot exist in this temperature range.

Student-Supplied Response Categories to *"Yes » State specific examples of life forms that could exist at these temperatures."*	Middle School (N=117)	High School (N=218)	College †N=(11)
Organisms that live in the arctics	45%	*57%	n=8
Humans	35%	27%	n=1
Microorganisms	7%	*24%	n=4
Mammals	10%	*19%	n=1
Plants	3%	11%	n=2
Other/No example	20%	12%	n=1

Student-Supplied Response Categories to *"No » Cite the physical reasons why life cannot exist in this temperature range*."	Middle School (N=29)	High School (N=23)	College †(N=1)
Just too cold	45%	57%	n=1
This is below the freezing point so there would be no liquid water for survival	14%	30%	n=0
Bodies/cells can't function	14%	13%	n=0
No plants could exist there would be no oxygen and no food	7%	0%	n=0
Other/No example	24%	13%	n=0

* Designated population demonstrates a difference that is statistically significant at a 95% confidence level from the other two populations.
† Upon distribution of the second iteration of our temperature question, access to large college populations was unavailable and is reflected in this relatively small number of college students surveyed.

Of those surveyed, 20% (29) of middle school students, 11% (23) of high school students, and 8% (1) of college students responded that life cannot exist in temperatures below freezing. Common responses included that 0°C is just too cold, that liquid water couldn't exist, and that bodies/cells can't function.

Analysis of all three temperature questions suggests several things. First, the preliminary temperature question revealed difficulties that students have with Celsius versus Fahrenheit. Consequently, the preliminary question failed to elicit student beliefs about temperatures as extreme as we had intended. For example, some students equated 100°C with a hot summer day. As a result, we provided the temperatures in degrees Celsius and degrees Fahrenheit in the second and third questions.

The secondary questions that resulted from revising our preliminary temperature question showed that more students cited that life can exist in a low temperature range than in a high temperature range. One possible explanation for this is that we did not prompt students to think of extreme enough temperatures when we asked them to consider temperatures well below 0oC. The freezing point of water may not seem extremely cold to students who live in climates experiencing a harsh winter season.

Another potential explanation for why more students cite that life can exist in low as opposed to high temperatures relates to students' personal experiences. A large percentage (47% middle school, 57% of high school, and 100% of college students) who responded that life can exist in the cold temperature range listed some type of arctic creature, e.g., a penguin, polar bear, or seal. These students have a tangible, common, and simple example of an organism that can live in low temperatures. However, it seems less likely that students have heard of thermophiles (or other microorganisms that survive extremely high temperatures), which they could supply as examples for the high temperature range.

From the students who responded that life can't exist in either temperature range, there were several interesting results. First of all, a large portion of students either stated the range was too hot or too cold but were unable to explain why. This percentage was higher for the low temperature range (45% of middle school, 57% of high school, and 100% of college students) than for the high temperature range (24% of middle school, 29% of high school, and 40% of college students). A significant real world model that students seem to evoke is that very high temperatures would not allow life to exist because this is how we kill organisms in our water and how we sterilize medical instruments.

The main conclusion we draw from this data is that students possess an incomplete model of how life is limited by temperature. Student knowledge seems to be piece-wise and inconsistent within age groups. Also, when prompted to consider life at these temperatures, the majority of students often failed to consider non-complex life, particularly microorganisms. With respect to the development of effective astrobiology curricula, this conclusion supports the position that students should be introduced to extremophiles, the specific temperature ranges in which they thrive, and how this relates to the macro world.

3.4. Student Understanding of the Implications of Limiting Environments

Within the past few decades, scientists have made amazing discoveries about the limitations of life. Life has been found on Earth to exist in places that were previously thought to be uninhabitable to any life form. Although inhospitable to human life, these extreme environments are a virtual breeding ground for microbial life. Sulfur hot springs in Yellowstone National Park and the dry, cold tundra of Antarctica are just two examples of areas where scientists are focusing their attention to learn more about the environmental conditions that govern the existence of life.

As was discussed in the previous sections, we found that many students correctly identify sunlight, water, and temperature as having significant impact on the existence of life. However, these are individual and specific environmental conditions. In order to elicit student ideas about the limitations on life in general, another portion of our written student surveys required students to reason about environments that prohibit life on Earth. This question did not prompt the students to consider any *one* particular environmental condition. Rather, we wanted to elicit students' beliefs about what conditions might prohibit the existence of life. To do this, we asked students to describe an environment on Earth that would *not allow any* form of life to exist, to cite specific examples, and to explain why these environments cannot support life.

Although the possibility exists for more than one correct response to this question, the most desirable student responses would include environments with no access to liquid water, environments with temperatures above 113°C (the highest temperature currently known to harbor life), environments deep within Earth, and environments with absolutely no energy sources.

As a direct result of the freedom of response this question encourages, we discovered recurrent themes in students' beliefs concerning not only types of environments that prohibit life, but also how the students reason about these environments. In total, 1,036 students were surveyed; 412 were in middle school, 412 were in high school, and 212 were in college. The student-supplied response categories are shown in Table 8.

Table 8. Student understanding of the implications of limiting environments

Limiting Environment Question (N=1036):

Describe an environment on Earth that would *not allow any* form of life to exist. Cite specific examples and explain why these environments cannot support life.

Student-Supplied Response Categories	**Middle School (N=412)**	**High School (N=412)**	**College (N=212)**
Environment with extreme temperatures	42%	*34%	42%
No water	20%	19%	21%
Volcanoes/core of the Earth	*30%	*20%	*9%
No oxygen/air	16%	25%	21%
No such environment exists	*6%	*12%	*18%
No sunlight	5%	5%	7%
No food/nutrients	7%	4%	8%
Extreme pH	2%	1%	3%
Other/No response	24%	16%	10%

* Designated population demonstrates a difference that is statistically significant at a 95% confidence level from the other two populations.

We considered two of the responses provided to be most consistent with scientific thinking. These include (1) an environment without water and (2) environments within volcanoes or deep within the core of Earth. Currently, most scientists agree that life on Earth cannot exist without intermittent liquid water or within molten lava, which is similar to what most students in the response category labeled "volcanoes/core of Earth" responded. The other response categories we created reveal much about students' beliefs about limiting environments on Earth. These include statements about the need for oxygen/air, sunlight, and food/nutrients, among other things.

In addition to citing temperature as a limiting factor, some students (16% of middle school, 25% of high school, and 21% of college) responded that life cannot exist without oxygen or "air" to breathe. Again, this exemplifies students' apparent tendency to consider only complex organisms when asked to reason about life in general. Namely, they seem to be primarily thinking only about the types of life that can be seen with the naked eye. Furthermore, microorganisms are categorized as non-living or "alternate" life forms by some students. As a prime example, one student responded that no *life* can exist without oxygen, but that organisms such as bacteria and viruses could. When considering the development of astrobiology curriculum materials on life, this response category alerts us to the fact that anaerobic organisms should be addressed or reintroduced to the students.

Finally, it is important to note that less than three percent of all students surveyed cited pH as a limiting factor. This small percentage is a concern because it indicates that students largely fail to identify the importance of pH in dictating whether life can exist in an environment.

3.5. Student Understanding of the Basic Elements for Life

In addition to probing students' reasoning and beliefs concerning life-limiting environmental conditions, we also designed a question to elicit responses on the basic elements for life. The previous survey questions presented were designed to elicit a response about how different environments are able to hinder or promote life. However, the initial questions neglected to ask students what the organism, or life in general, *requires* for survival. In contrast to probing students' reasoning and beliefs concerning life-limiting environmental conditions, we wanted to gain a better understanding into what students feel is necessary for life. As a result, we asked students what elements are the most important for the existence of life.

A total of 1,013 students were surveyed, 412 middle school, 425 high school, and 176 college. The four most common responses across all age groups were water, Sun, oxygen, and a food/energy source. These, as well as the less common response categories, can be seen in Table 9.

Table 9. Student understanding of the basic elements for life

Basic Elements for Life Question (N=1013):

What elements are the most important for the existence of life? Explain your reasoning.

Student-Supplied Response Categories	Middle School (N=412)	High School (N=425)	College (N=176)
Water	57%	61%	*49%
Oxygen/air	*45%	54%	56%
Energy source/nutrients	32%	*41%	35%
Sun	*16%	20%	*25%
Carbon	*7%	17%	19%
Hydrogen	*5%	*25%	*13%
Nitrogen	1%	7%	10%
Temperature of planet	3%	8%	11%
Plants	7%	4%	1%
Other/No response	11%	13%	16%

* Designated population demonstrates a difference that is statistically significant at a 95% confidence level from the other two populations.

Although subject to much debate, two requirements for life as we know it on Earth are an energy source and the presence of liquid water in at least small amounts. Consequently, the most "correct" student responses are those including statements similar to this.

Many of the response categories derived from this question serve to reinforce the results of the other survey questions. For example, roughly half of all students contest that water is necessary for life, a result that parallels the results from our student-supplied response question on water. Also, a considerable percentage of students again cited that oxygen/air is a necessary element.

4. CONCLUSIONS

Our research on students' pre-instructional beliefs focused on five key astrobiology-related topics: sunlight, water, temperature, limiting environments, and necessary elements for life. Following the distribution and careful analysis of a series of student-supplied response questions, we identified several prevalent themes in student beliefs about these astrobiology-related topics. Most students correctly identify that life can exist without sunlight or in extreme temperatures and that life requires at least intermittent liquid water. Although they possess many correct beliefs about life and its limitations, a high proportion of students also provided responses that illustrate several pre-instructional beliefs that include, but are not limited to, the following:

1. Many students believe that life cannot exist without oxygen.
2. When prompted to reason about extreme environmental conditions, students largely failed to cite high concentrations of salt, extreme pH, or extreme cold temperatures as limiting conditions for life.
3. When asked to consider life in *extreme* environments, students most often cited complex organisms

(such as plants, animals, and humans) rather than the more ubiquitous microorganisms.

Work in physics and astronomy education and beyond has shown that students' initial ideas can interfere with learning and the acquisition of new knowledge. The results from this research project underscore the position that students do in fact have important pre-instructional beliefs and knowledge structures about astrobiology topics, ideas that may or may not interfere with the effectiveness of instruction.

From our analysis of student responses from questions concerning the role of sunlight on life, we conclude that the majority of all students surveyed correctly identified that life can exist without sunlight. However, in the context of teaching astrobiology, it is important to note that students often cited more complex organisms such as bats, fungi, and fish in the ocean rather than the microorganisms that play center stage in astrobiology. Some students also responded that all life in some way depends on sunlight as a result of the food chain. Again, most students neglect microorganisms such as chemolithotrophs, which utilize an energy source other than organic carbon or photosynthesis in their food chain model.

Many scientists agree that one essential requirement for life as we know it on Earth is liquid water. A large majority of students surveyed also correctly identified that water is necessary for life. However, it is critical that students understand the properties of water that make it significant to the existence of life. Once prompted, students were able to cite several reasons as to why water is important to life. None of these reasons included the chemical properties of water, such as polarity, its ability to hydrogen bond, and specific heat, that distinguish water from other solvents. It is quintessential for students to understand the properties of water if they are to successfully comprehend scientists' search for water in the universe.

Another example of how students' pre-instructional beliefs may interfere with learning stems from our results from questions eliciting student responses about temperature. Environmental descriptions of extreme cold may evoke images of penguins and polar bears rather than the microorganisms we intend. Similarly, environmental descriptions of high temperatures may evoke images of desert terrain or be in conflict with students' existing ideas about sterilization of medical equipment or purification of drinking water.

In general, a recurring theme in responses was the manner in which students reasoned about life. Many students categorized complex life forms and microorganisms separately, while some students failed to consider microorganisms at all. When asked to reason about life from an astrobiology perspective, it is imperative that students be able to reason about microorganisms as well as more complex organisms. Before we can expect students to be able to reason about the possibility of life in the extreme environments of our solar system and universe, we must ensure that they can identify and conceptualize living organisms in the extreme environments found on Earth. Our results from all the survey questions described above are encouraging in that an increase in age generally accompanied an increase in the number of students who cited that microorganisms are able to thrive in the extreme environments of Earth.

A constructivist approach to instruction prescribes that our curriculum materials be sensitive to the pre-instructional beliefs that students bring into the astrobiology classroom. This preliminary study was designed to determine the range of possible student ideas in the context of the conditions necessary for life on Earth. The research results presented here strongly suggest that a majority of students do in fact harbor well- articulated ideas related to astrobiology-ideas that are often at odds with scientifically accurate conceptions. This points to the need for carefully designed curricular materials that take these ideas into account, challenge existing student concepts, and help students resolve differences. Further, these results reinforce the idea that astrobiology students should not be treated as "blank slates," because their ideas have the possibility of interfering with and positively or adversely impacting the effectiveness of instruction.

As noted, the results from this preliminary research study into students' general pre-instructional beliefs are unprecedented. The results discussed in this paper will serve as a framework for future research that deeply probes student understanding and reasoning difficulties of the concepts identified here, as well as new research into other astrobiology concepts. Undoubtedly, this and future research will contribute significantly to the current bank of science education literature from an astrobiology perspective.

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