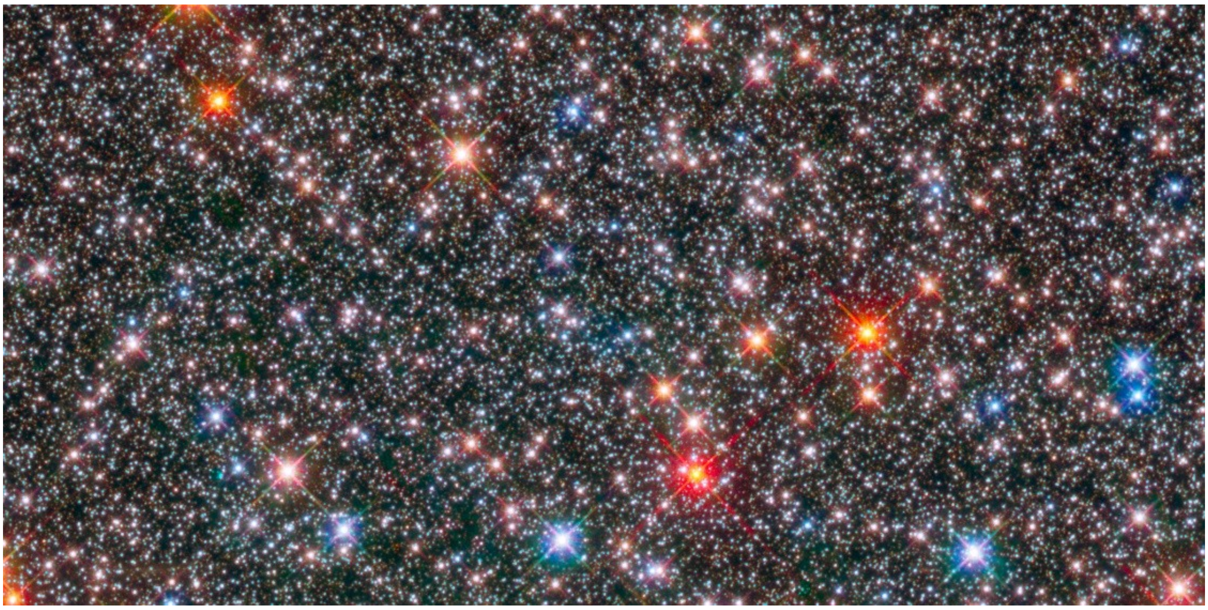
A child-centric microbiology education framework

Extremophilic Microorganisms

Daddy, do you think life is possible on distant planets?



The heart of the Milky Way Galaxy, which houses our solar system and planet Earth,
as imaged by the Hubble Space Telescope. Credit: NASA and the Space Telescope Science Institute.

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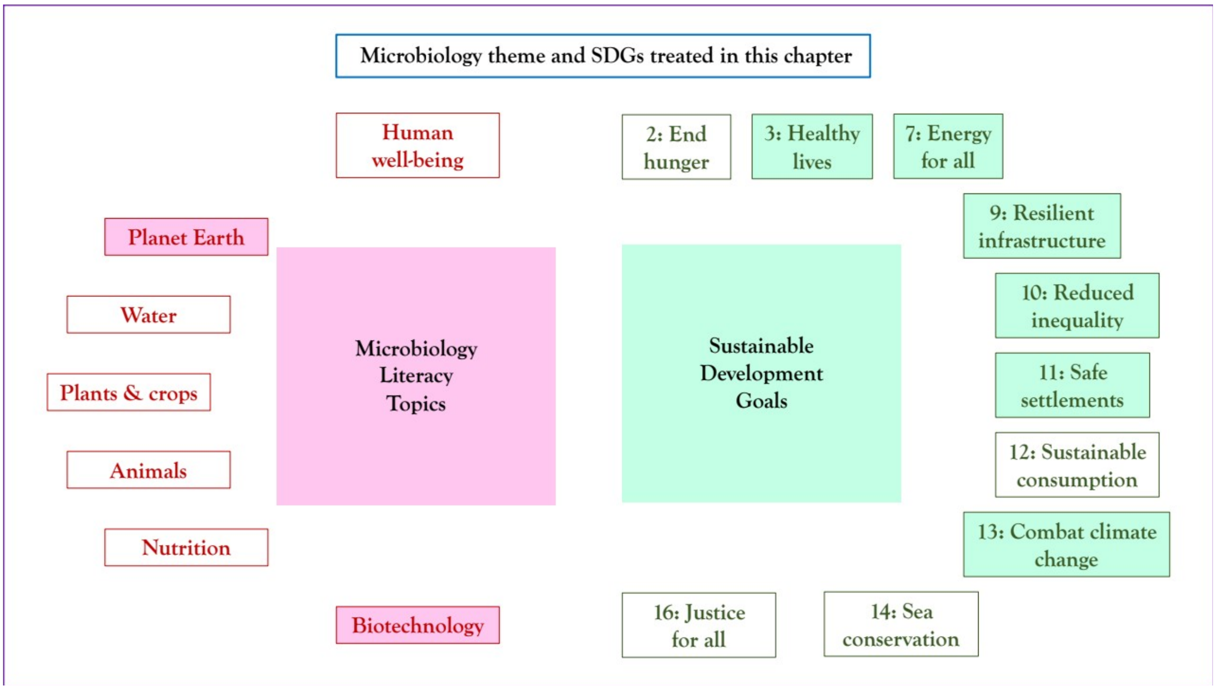
Extremophiles

Storyline

Microorganisms inhabit some of the most exotic environments on the planet, including those that are intolerable to human life and that we consider to be extreme. Yet, the microbial life we find in these extreme environments (termed extremophiles) not only tolerate the extreme conditions, they thrive in them. This includes extremophiles that inhabit boiling hot springs with water that is as acidic as battery acid or that is as alkaline as household bleach, extremophiles that thrive at depths of 10 km (about 6 miles) in Earth's subsurface where the pressure is 1000 times higher than at the surface, and extremophiles that grow in deserts that receive less than 1 mm of rainfall annually. Such exotic environments and their extremophilic microbial inhabitants can also be found in less exotic environments, such as in our acidic stomachs, on our salty and dry skin, and in our home hot water heaters. It is little surprise then that extreme environments and their extremophilic microbial inhabitants continue to fascinate microbiologists and are attractive targets for engaging children in the science of microbiology. This lesson focuses on the unique properties of extremophiles, including those that are being harnessed for biotechnology, biofuel, and human health applications. Studies of extremophiles are also shedding light on the limits of life on Earth, and the environmental context of extremophiles is guiding our search for habitable environments on other planetary bodies.

The Microbiology and Societal Context

The Microbiology: extremophiles; biodiversity; human microbiome; desiccation. *Societal Context*: human health and disease; environmental health; life on other planets; origin of life; biotechnology; innovation; polymerase chain reaction; forensic DNA testing; COVID testing.



Extremophiles: The microbiology

1. ***Humans invest considerable resources to create a rather constant environment.*** Our environment dictates whether we as humans feel comfortable and our own experiences of what defines comfort forms our conception of what types of environments are conducive for life. We might define our level of comfort based on temperature which, if too cold, might motivate us to turn on our furnace or put on a coat. Likewise, if a beverage that we are drinking is too warm, we might allow that drink to cool before we consume it. Alternatively, our level of comfort might be related to hunger or thirst, in which case we might seek to consume food or water. Yet, the truth of the matter is that the conditions that define comfort for us as humans are very narrow compared to the range of conditions that are possible in nature. For example, we desire environmental temperatures near 20 degrees Celsius (~20°C or ~68° Fahrenheit) and require a steady supply of food and water to survive. We desire our body temperature to be relatively stable, and work to ensure that this is possible by controlling environments through heating and cooling. We require our water to be highly pure with low salt concentrations, near neutral pH (defined as a solution with similar numbers of protons and hydroxide ions (**Fig. 1**)), and our food to have high calorie and nutritional content.

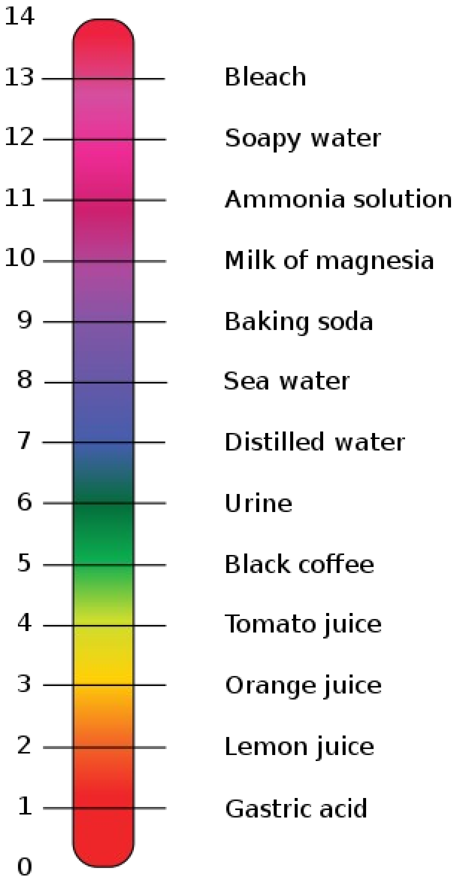


Figure 1. The pH scale illustrating the relative amounts of protons (H^+, acidic) and hydroxide ions (HO^-, basic) in representative solutions. The more acidic a solution is, the lower its pH. The more basic a solution is, the higher its pH. Image credit: Wikipedia under CC-by-SA 3.0 Unported and GFDL (author: Edward Stevens)

To meet these needs, humans continue to develop and build water treatment facilities and expansive agricultural systems to ensure that our need for safe drinking water and nutrition are met. In fact, most of the life that we are familiar with, whether it be plants and animals, live within a very similar set of environmental conditions as humans require (**Fig. 2**). However, if we step outside of these narrow conditions that we require to maintain comfort, is life possible?

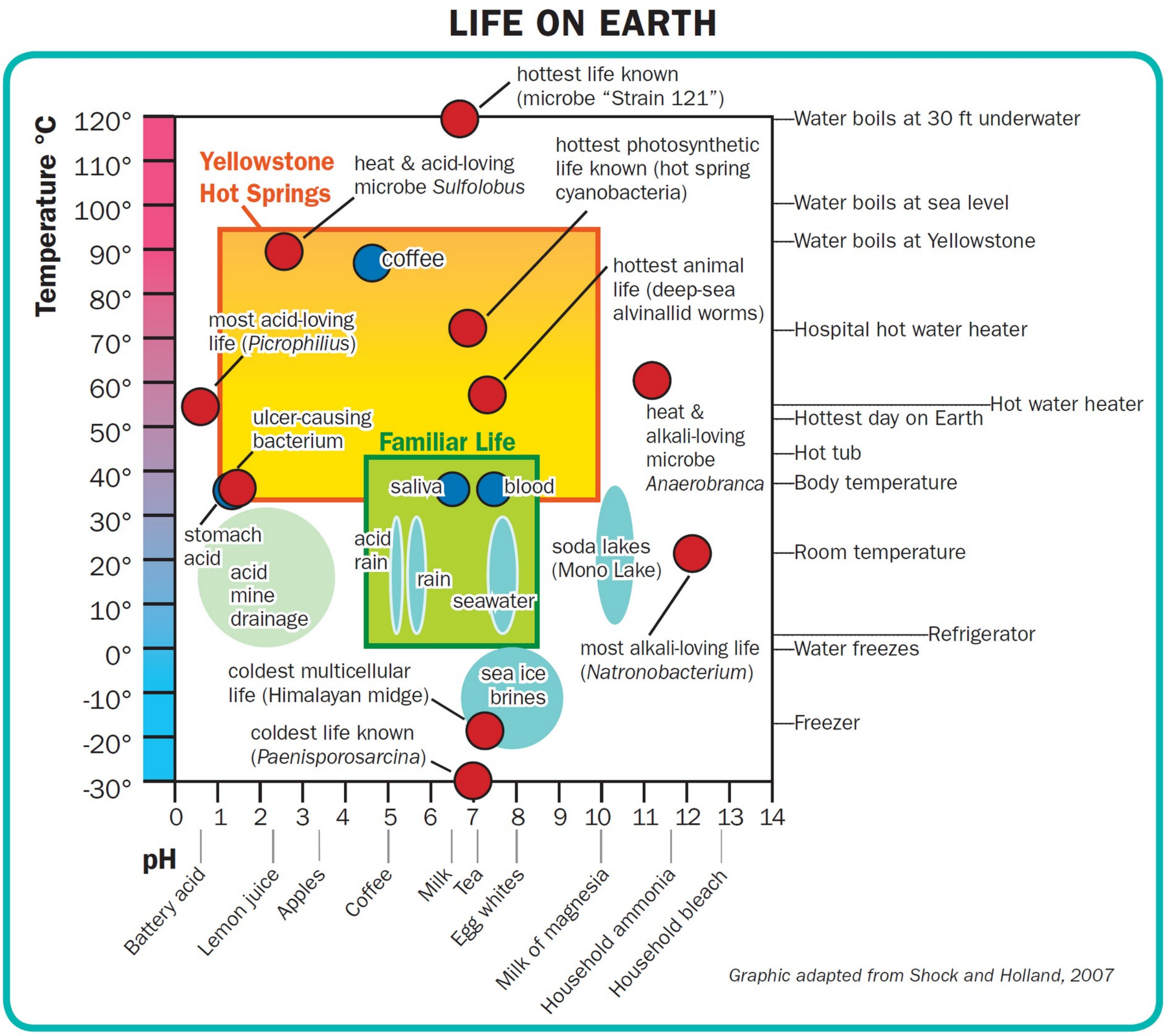


Figure 2. A plot of temperature vs pH values that characterize habitable environments found on Earth. Examples of solutions with pH value ranges are provided in the plot and various temperature dependent processes or thresholds are also provided on the right. Overlaid on the plot are examples of familiar Earth environments and their biological components, as are the pH and temperatures where they are found. Examples of extremophiles that thrive at various pH and temperatures are also shown. Image adapted from Shock and Holland, 2007 (Astrobiology, 2007, volume 7, pages 839-851; doi: 10.1089/ast.2007.0137).

2. ***What are extreme environments and extremophiles?*** When we contemplate the various types of environments on Earth, we quickly come to realize that there is a vast array of environments that we humans would consider "extreme" (**Fig. 2**). This includes hot springs with temperatures as high as over the boiling point of water (>100°C, 212°F), icy environments where temperatures can be below the freezing point of water (<0°C, 32°F), acidic or alkaline pools with pH values near to that of battery acid or household bleach, respectively (**Fig. 1**), salt-saturated brines, desert environments that receive less than 1 mm of rainfall per year, and the vast subsurface rocky environment habitat beneath our feet. Ironically, while these

environmental conditions are clearly extreme, we can find many similar extreme environments associated with our own body. Yet, we rarely consider our bodies to be extreme! For example, the human stomach is as acidic as the most acidic hot springs, our skin is dry like a desert, and our own body fluids (e.g., blood and urine) are saltier than the waters that we ingest. It is therefore incredibly intriguing to realize that many of these "extreme" environments on or in our bodies host robust microbial communities. These are not alien forms of microbial life but are genetically related to more familiar forms of life. We call these microorganisms "extremophiles" and we study them to better understand the environmental limits of life on Earth, to guide our search for the possibility of life on other planets, to develop technologies to improve human conditions, and to maintain environmental, human, and animal health. Now, let's explore these extreme environments and their extremophilic inhabitants.

3. Microorganisms have adapted to grow in nearly every conceivable environment on Earth's surface and shallow subsurface. Microbial life first appeared on Earth sometime between 3.5 and 3.8 billion years ago. For comparison, the earliest human ancestors were first present on Earth 2 million years ago (or roughly 2,000 times shorter than that of microbial life!). The extraordinary amount of time that microorganisms have inhabited Earth have allowed them to adapt to and thrive in nearly all conceivable surface environments, in addition to those in the shallow subsurface. This has occurred through a process called evolution. To understand evolution, it is first important to know that the molecules and metabolic processes that an organism need to survive are encoded in its DNA (i.e., its genome) that represents a so-called blueprint for what a cell can do. However, when an organism grows, it must replicate its genome so that each daughter cell receives a copy. When replicating genomic DNA, mistakes are often made. Most of the time, these mistakes have very little impact on the organism and its ability to survive. However, in some instances, these mistakes are harmful to an organism and it can no longer successfully compete for resources (nutrients or food) or space in its environment and will die. Yet, at other times, these mistakes result in an organism that is even more competitive than its close relatives at obtaining resources. Alternatively, these genomic changes might lead to the production of slightly different cell components (e.g., enzymes) that function better under slightly different environmental conditions like increased or decreased temperature, pH, or pressure. This process, whereby DNA is replicated, mistakes are made, and opportunities arise to inhabit slightly different environments has taken place continuously over the past >3.5 billion years that microbial life has been present on Earth and has resulted in the incredibly diverse organisms that populate Earth today. This includes microorganisms that inhabit "extreme" environments, both in nature and in our human bodies.

4. ***Extremophilic microorganisms are not so alien after all.*** The orange color that we see in the outflow channels of the near boiling hot spring, Grand Prismatic, Yellowstone National Park, U.S.A., the pink color that we see on the cold surface of snow on Mount Ritter, U.S.A., and the black color that we see on dry desert soils in Natural Bridges National Monument, U.S.A. are due to photosynthetic pigments produced by Cyanobacteria (**Fig. 3**).

Figure 3. Cyanobacteria inhabiting Grand Prismatic hot spring, Yellowstone National Park, U.S.A. (orange colors; **A**), the snow surface on Mount Ritter, U.S.A (pink colors; **B**), and desert soils in Natural Bridges National Monument, U.S.A. (grey to black colors; **C**) as examples of extremophiles inhabiting extreme environments. Image credits: **A**, Eric S. Boyd; **B**, Wikipedia under Creative Commons Attribution 2.0 Generic (author: Pacific Southwest Region 5); **C**, Wikipedia under CC-by-SA 3.0 Unported and GFDL (author: Nihonjoe).

These Cyanobacteria are not terribly different from their cyanobacterial relatives that grow in more "normal" environments like on rocks as lichens, that color ponds green, and that are the major producers of oxygen in Earth's oceans. Cyanobacteria are just one example of how seemingly non-extremophilic organisms have adapted to thrive in extreme environments. Extremophilic microorganisms are also known to inhabit boiling waters, sulfuric acid hot springs, the deepest depths of our oceans (>10,000 meters), deep sea hydrothermal vents, and waters flowing from rocks collected in mines that are 5,000 meters deep. These organisms have evolved elaborate approaches to not just tolerate the extreme conditions of their habitats, but to thrive in those habitats such that they are not even able to survive outside of the extreme conditions of their preferred habitats. These adaptations include building more robust cell membranes that better separate the conditions of the outside environment from their inner cell environments where their metabolisms take place, more rigid protein structures that can tolerate higher temperatures, and producing proteins that bind and stabilize genomic DNA to keep it from degrading under extreme conditions. But are all extreme environments where we find microbial life as exotic as hot springs, deep ocean trenches, or deep within Earth's rocky crust? In other words, might extreme environments and extremophiles live closer to home?

It would surprise many of us to know that extreme environments are ever-present in our houses and even in and on our own bodies. As an example relevant to most all of us – the water that we use to bathe and wash our hands is heated by hot water heaters (**Fig. 4**). The temperatures of those water heaters are ~60°C (~140ºF), a temperature close to the temperature of many hot springs and hydrothermal vents. Hot springs with temperatures near ~60°C are home to numerous thermophilic (heat-loving) microorganisms, including those related to Eukarya, Archaea, Bacteria, and their viruses. In some ways, it may not be terribly surprising to learn that our hot water heaters are also home to thermophilic microorganisms, many of which are close relatives of those that we find in hot springs and hydrothermal vents.

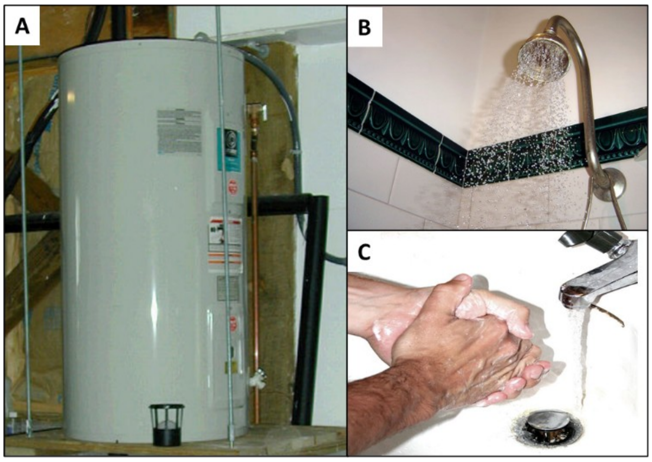


Figure 4. A hot water heater used to keep water temperatures near ~60°C (~140°F) (**A**), a shower head used to bathe our bodies (**B**), and a bathroom faucet used to clean our hands (**C**) are all home to thermophilic microbial life. Image Credits **A**): Wikipedia under Creative Commons CC0 License (author: Dave Saville, Federal Emergency Management Agency), **B**): Wikipedia under the Creative Commons CC0 (author: DO'Neil), **C**): Wikipedia under the Creative Commons CC0 (author: Lars Klintwall Malmqvist).

An interesting question that follows is how thermophilic microorganisms "find" these high temperature "island-like" environments, despite being surrounded by environments with much cooler temperatures. It turns out that microorganisms can be readily dispersed through the air, similar to how the virus that causes COVID19 is spread through aerosols. As another example, the pH of our stomach is maintained at ~1.0, which is as acidic as the most acidic hot springs and is near the acidity of concentrated battery acid. Our bodies evolved stomach acidity as a mechanism to enhance the breakdown of the food that we eat and to keep us healthy. Our own stomach cells have evolved many mechanisms to tolerate that acidity, and some of these adaptations are similar to those utilized by microbial acidophiles to thrive in naturally acidic conditions (e.g., ion pumps to maintain ionic homeostasis on the interior of the cell). The acidity of our stomach kills most pathogenic organisms that might be present in the foods we eat and acts as a filter for those that can ultimately make it to our gut, where they perform important functions that allow us to absorb nutrition from our food. Yet, if we are unlucky, our stomach can become colonized by the acidophilic microorganism, *Helicobacter pylori,* that causes stomach ulcers if left untreated by antibiotics. Oftentimes, humans experience acid reflux or indigestion, forms of discomfort caused by the acidic nature of stomach fluids. To treat this condition, some of us will take antacid medication. These medications contain bicarbonate that reacts with acid, helping to neutralize the pH of our stomach. For reasons mentioned above, neutralizing stomach acid could have unintended consequences, including a decreased ability to digest certain foods and a decreased ability for the acidity of the stomach to kill pathogenic organisms that may be present in the foods that we eat.

The stomach is not the only extreme environment that we humans host. Also consider the skin, the largest organ in our body. The skin is a dynamic ecosystem comprising diverse habitats that support a wide range of microorganisms. Much of our skin environment is dry and salty, while other areas, such as our armpits, are moister. The organisms found in dry skin environments often have similar adaptations as organisms inhabiting deserts or evaporated saltern environments. The low moisture content (dryness) of skin and its high levels of salt select for a group of beneficial organisms that act as a barrier to pathogenic organisms by outcompeting them for resources. Thus, over the 2 million years that humans have been on

Earth, we have evolved alongside our microbial inhabitants, often by creating extreme environments that favor the growth of good bacteria at the expense of those that can cause infection or disease.

5. ***Extremophiles and the search for life on other planets***. The most compelling questions guiding scientific discussions today focus on the distribution of life in the Universe. Is Earth unique in its ability to support life? Could similar life exist on other planetary bodies with conditions like those that support life on Earth? Answers to these questions are being sought by an international group of astrobiologists, or scientists that seek to understand the distribution of life on Earth to guide our search for life on other planets. These scientists are motivated by the fact that the conditions on planets close to Earth (or those that can be reasonably studied) exhibit environmental extremes. For example, the average temperature of Mars hovers around -63°C (~-81°F), although warmer temperatures are often encountered during the day depending on location. The average temperature on Mars is as cold as temperatures recorded on the highest mountains in Antarctica. Further, most of Mars' near surface water is locked up as ice. For life to exist on Mars, it would need to be capable of growth under extremely cold conditions with limited water availability. Given these considerations, astrobiologists are busily working to determine if life can exist under these conditions by using Earth environments such as the icy and mountainous environments in Antarctica and the dry desert environments of the Atacama Desert in Chile, as analogous extreme environments.

On Earth, a temperature gradient is observed as we probe deeper into the subsurface. A similar gradient exists on Mars and it is therefore likely that higher temperatures exist in the Martian subsurface where liquid water might be present. Given this likelihood, astrobiologists are searching deep environments on Earth by accessing them through deep mines and drilled boreholes to determine the extent of life in these extreme environments. Current research indicates the presence of viable and active microbial cells in waters naturally flowing out of rock fractures in mines that reach depths of nearly 5 km! These microbial extremophiles are living off of the minerals in rocks as their source of food, and many have been isolated from the surface of Earth for millions of years. This information is now being used to assess the likelihood that similar environments on Mars might host microbial life and what that microbial life might be capable of eating.

6. ***Societal Benefits of Extremophiles***. We have already discussed several examples of how extremophiles help maintain our health, including protecting our skin and guts from invasion by pathogens. But there are other examples of how our understanding of microbial extremophiles have improved social conditions. Just a few of the more important ones include:

a. *PCR*. If you have been tested for COVID-19 by means of the "gold standard" PCR test, you have been directly impacted by technologies that were developed from extremophilic bacteria. The COVID-19 test is based on the use of an enzyme (protein) that was obtained from the bacterium, *Thermus aquaticus*. *T. aquaticus* was originally isolated from Mushroom Pool, a high temperature (90°C, ~194°F), alkaline (pH 8.5) hot spring in Yellowstone National Park, U.S.A. (**Fig. 5**) by the famous American microbiologist, Dr. Thomas Brock and colleagues.

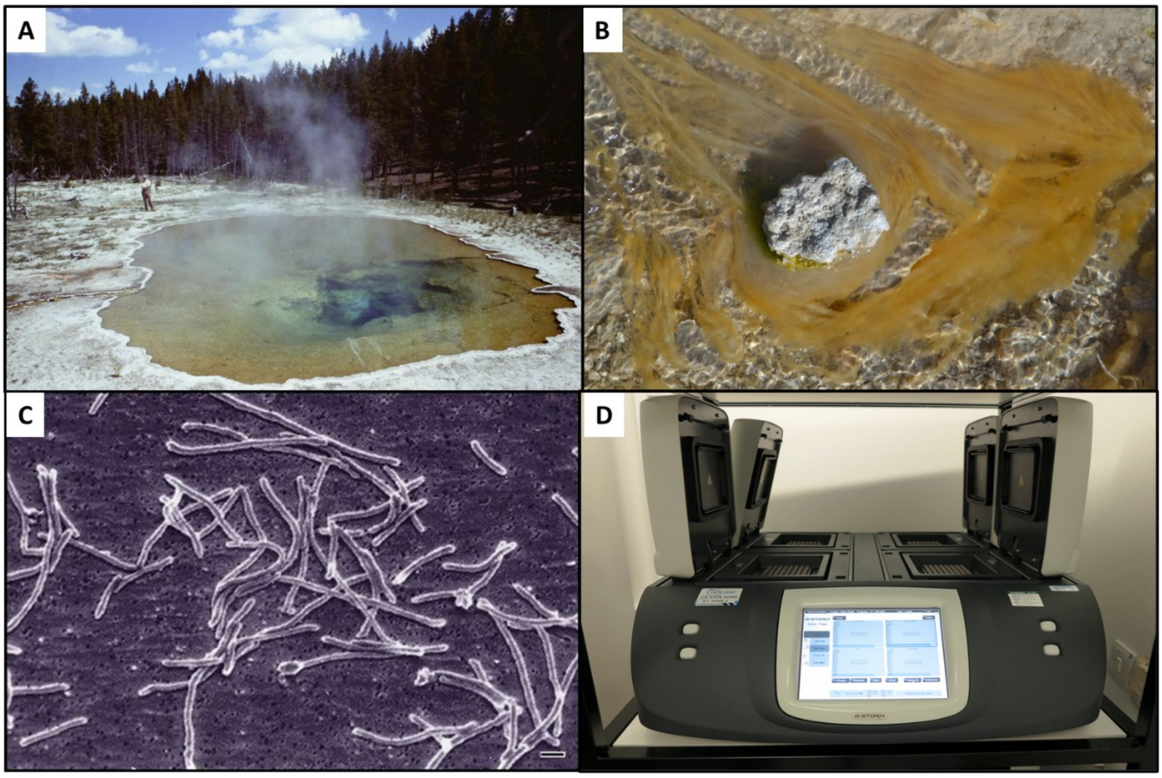


Figure 5. Mushroom Pool, Yellowstone National Park, U.S.A, as it looked on June 23, 1967, with Thomas D. Brock in the background (**A**). Typical "streamer" like microbial filament structures that are common in alkaline hot springs (~90°C, pH 8.5) and that typically comprise the bacterium *Thermus aquaticus* growing in close association with the bacterium *Thermocrinus ruber* (**B**). Microscopic image of a culture of *T. aquaticus* on a membrane filter, scale bar = 1 μm or about 100 times smaller than the diameter of a human hair (**C**). Modern day thermocycler that is used to replicate DNA molecules using *Taq* polymerase (**D**). Image Credit: **A)** self-published "A Scientist in Yellowstone National Park" by Thomas D. Brock, 2017; **B)** E.S. Boyd; **C)** Wikipedia under Creative Commons CC0 License (author: Diane Montpetit of the Food Research and Development Centre, Agriculture and Agri-Food, Canada); **D)** Wikipedia under Creative Commons CC0 License (author: Rror).

Taq is used in a process called polymerase chain reaction (PCR) that replicates (amplifies) tiny amounts of DNA to levels that can be detected using scientific instruments. To efficiently run this reaction, many cycles of heating (~90°C) and cooling (~50°C) are needed, requiring an enzyme that can maintain its function under such dynamic and high temperature conditions. The thermophile, *T. aquaticus*, and its collection of enzymes, naturally evolved the ability to not only withstand high temperatures but to thrive under these conditions. In the case of the COVID-19 test, tiny amounts of viral DNA that are sampled from our nasal passages are replicated by *T. aquaticus* (also known as *Taq*) polymerase so that they can be accurately detected (or hopefully not!) as an indication of exposure or infection to the COVID-19 virus. In addition to COVID-19 testing, PCR and *Taq* polymerase are commonly used to produce many of the medicines and antibiotics that keep us healthy and are the basis of a biotechnology industry that is worth tens of billions of U.S. dollars every year. This process is also used in forensic investigations and allows the identification of the source of DNA when only tiny amounts of it can be obtained from a crime scene. Ironically, our understanding of the diversity of life on Earth has also been revolutionized by the development of PCR applications for environmental samples. Small amounts of DNA obtained from the environment can now be PCR-amplified, allowing it to be sequenced and their host organisms to be identified. This approach has increased the number of organisms known to exist on the planet by several orders of magnitude and has better allowed scientists to more accurately predict their roles in the functioning of ecosystems that support animal, plant, and human health. Clearly, the cultivation of *T. aquaticus* and the development of PCR using *Taq* have had a profound and positive influence on the human condition and our understanding of how the world that sustains us operates.

b. *Biomining.* Extremophiles and the cellular molecules that they produce are commonly used in other aspects of our daily lives. For example, many of the metals that we use in our modern lives are recovered using extremophiles in the production process. More specifically, much of the copper that we use in electrical wires that power our homes and much of the gold that we use in the production of jewelry or that we base our monetary systems on are mined with the help of microorganisms. This process is termed bio-mining or bio-leaching and results in the separation of target metals (e.g., copper and gold) from components of the rocks that are mined (ores). Bio-leaching is much more environmentally friendly than other approaches that use cyanide, a potent toxin that is problematic for environmental and animal/human health. At the heart of ore bio-leaching is the ability of many microorganisms to oxidize inorganic sulfur and iron compounds and generate acid as a byproduct. This form of metabolism, where microorganisms literally are eating rocks, is a newly identified process and is very similar to what microbial extremophiles that thrive deep within Earth's subsurface are doing. The production of acid required the identification of acidophiles (extremophiles that tolerate acid) that are also capable of eating sulfur or iron. The most commonly used acidophilic microorganisms in bio-leaching processes are the bacterium, *Acidithiobacillus*, and the archaeon, *Ferroplasma*. These organisms were isolated from acidic environments, where they evolved naturally to thrive under these conditions, making them ideal for bio-leaching applications.

c. *Fuels.* As a final example, there is an urgent need to identify more environmentally friendly ways to provide power for our daily lives, whether this be electricity to power our homes or liquid/gaseous fuels to power our vehicles. Burning of fossil fuels is how we have powered our lives and economies for >150 years, but these activities are polluting our environments with toxic metals like mercury and is also responsible for increased concentrations of carbon dioxide (CO_2) in our atmosphere, a phenomenon that is driving climate change. For these reasons, we desperately need to transition from fossil fuel-based technologies to renewable fuel-based technologies. Much of the effort towards achieving this goal in recent years has focused on producing combustible liquid forms of fuel from abundant and renewable plant materials like cellulose and lignin. These chemical conversion processes are enhanced by high temperature and alkaline or basic pH. Several extremophiles have been isolated from natural environments that can covert cellulose and lignin into alcohols, including ethanol that can be substituted for gasoline in automobile fuels. In addition, several microorganisms including the bacteria *Thermoanaerobacterium* and *Caldicellulosiruptor* have been isolated from high temperature and alkaline pH environments and can enhance the conversion process. Extremophiles are also being investigated for their ability to produce hydrogen gas, or rocket fuel, from water using light energy (photosynthesis) and to produce bioelectricity. While these topics are perhaps a bit too complicated to discuss in this chapter, they are mentioned with the purpose of illustrating just how diverse and applicable extremophiles are to our current and future well-being on Earth.

Relevance for Sustainable Development Goals and Grand Challenges

A child-centric microbiology education framework

Extremophilic microorganisms relate to several Sustainable Development Goals (SDGs). Where overlap among applications is apparent, the SDGs are combined and addressed together. This includes:

- **Goal 3: healthy lives.** Our bodies comprise nearly as many microbial cells as they do our own cells. These organisms help to fight off pathogenic bacteria that can make us sick and help us digest foods. In many cases, our health depends on maintaining a careful balance between the extreme conditions we require and the extremophilic bacteria that these environments host. In the case of the skin, maintaining dry and salty conditions promotes the development of bacterial communities that can outcompete pathogenic bacteria that can cause infections. However, shifts in diet can promote oily or moist skin that can allow for pathogenic bacteria to grow. In another example, our acidic stomachs help breakdown food and acts as a filter against pathogenic bacteria that may be present in the foods that we digest. Identifying diets and lifestyles that promote healthy skin and gut microbial flora, and thus healthy lives, is a key goal of ongoing microbiology and dietary research.

- **Goal 7: affordable and clean energy**
- **Goal 13: climate action.** Microorganisms are being harnessed for their metabolic versatility including the efficient conversion of non-economic plant debris (cellulose and lignin) into value-added products including alcohols like ethanol that can be used as a source of clean energy. These conversion processes are enhanced by extreme conditions and the activities of extremophilic organisms, requiring identification of microorganisms that can tolerate these extreme conditions. Similarly, extremophiles are being studied for their ability to convert water into hydrogen gas, a fuel that when burned, re-generates water. Future advances in our understanding of the processes that allow extremophiles to survive extreme conditions will continue to advance their use in biofuel production technologies.

- **Goal 9: industry, innovation, and infrastructure**
- **Goal 10: reduced inequities**
- **Goal 11: sustainable cities and communities.** Extremophiles are critical for advancing biotechnology and our search for life outside of Earth. Innovations in biotechnology continue to be driven largely by improvements in our understanding of the metabolisms and physiologies of these unique organisms. Examples of this include the discovery of *Taq* polymerase and the development of the PCR process, applications of extremophiles in bio-leaching or bio-mining practices, and the sustainable development of renewable energy technologies. Many of these processes are low cost and could be readily implemented to improve various industries in developing countries. As such, they have the strong potential to also reduce inequities and to help create sustainable cities and communities.

  Our understanding of the limits of life on Earth also guide our search for life on other planets. Extremophiles live at the limits of habitable environments on Earth and through their investigation, we can identify conditions on other planets that might support life, either today or in the distant pasts of those planets. Astrobiology and the search for life on other planets is a uniquely human endeavor and one that can easily capture the imagination of any child or adult, regardless of income status, gender, or ethnic background. It follows that innovation in this area of research would be greatly enhanced by engaging a global cohort of students and citizen scientists for creative thinking of how life might be discovered and, the associated question, what that life might look like.

Pupil Participation

1. Class discussion of what constitutes an extremophilic form of life. Can we envision our own bodies as extreme environments? How do these environments resemble or differ from natural environments that we typically consider as extreme? Do these environments exist on other planets and might these planets therefore be expected to host microbial life?

2. Pupil stakeholder awareness

a. Extremophiles comprise diverse microorganisms and inhabit environments with temperatures as low as -20°C (-4°F) to as high as 120°C (248°F), and waters that have pH as low as battery acid (pH <1.0) to as high as household bleach (pH >12.0), and in waters with salt concentrations that are 10 times saltier than seawater (34% sodium chloride or water that is saturated with table salt). They can even live in the deepest parts (10 km, or ~6 miles) of the oceans and at 5 km (or ~3 miles) deep in Earth's crust! These are conditions that no human can survive, at least for long periods of time. Describe why these conditions are considered extreme for humans. Alternatively, describe why extremophiles might consider (if they could think) that conditions required by humans might be extreme to them.

b. All forms of life require a source of energy (food), liquid water, and a stable environment to thrive. Extremophiles are no different and have even evolved to eat rocks as their source of food! Yet, there are even some environments on Earth where even extremophiles cannot persist or exist. These include liquid magma in volcanoes, the inside of a radiator in a car, and in hot springs in Africa that have a combination of near boiling temperature, acidic pH, and extremely high salt concentrations. Thinking about what we know life requires to survive, what is it about these environments that keep extremophiles from inhabiting them?

c. Human health and well-being requires extremophilic microorganisms. What might happen if the extreme conditions on a person's skin or in a person's stomach change, perhaps due to a change in diet, stress, or medication (e.g., antacids)? Would this person become ill or malnourished if these extreme conditions and the organisms that they naturally host change?

d. Space agencies across the globe are constantly learning about the conditions on other planets in our solar system (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune) and their own moons, including Europa (moon orbiting Jupiter) and Enceladus/Titan (moons orbiting Saturn). These environments have extreme temperatures, atmospheric pressures, and limited availability of liquid water. Might these environments host microbial life? If so, what might these microorganisms look like? What types of environments on Earth could we study to gain new understanding of what that microbial life might look like and be eating?

3. Exercises

a. Develop criteria for life. Bring in several objects, including animate (plant) and inanimate (rocks, table salt) objects and have students discuss whether each object meets this list of criteria of being alive.

b. Microorganisms inhabit nearly all near surface environments on Earth. Work in small teams to identify an extreme environment on Earth and how one might try to prove that life exists or does not exist in that environment? How would you be sure that there is no life in that environment? How would you be sure that the life that you detected in that environment is alive?

c. Prepare students with several pictures of extreme environments (hot springs, hydrothermal vents, salterns, deserts, etc.) and ask students to consider what makes each of these environment types extreme for microbial life. Present several images of extreme environments closer to home (hot water heater, salt in your salt shaker, inside of oven, bottle of rubbing alcohol, bottle of vinegar) and ask students whether life might persist in such environments.

d. Present students with images of our galaxy taken from a telescope. Next present students with images of microorganisms taken from a microscope. Our ability to study both of these environments – both macroscale (planets and stars) and microscale (microbial cells) – requires technology in the form of image magnification. Discuss how astronomy and microbiology are both dependent on technological advancements and how these advances have revolutionized our understanding of life in our universe.

The Evidence Base, Further Reading, and Teaching Aids

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4187170/
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