

Kingdoms Archaea and Bacteria

The Story of Life, Part 2:

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Prologue: Classification Systems

How many kingdoms of life were there when you went to school? Just plants and animals? Maybe fungi, as well? How about bacteria or the Monera or the Protists? The latest scheme I've read about has over forty kingdoms. Even in the relatively simple approach adopted for this series of essays there are six kingdoms and two domains. Just what are the life sciences up to?

Like all the sciences, the rate of research and discoveries in the field of biology has greatly accelerated in the last few decades. A whole new group of micro-organisms, the Archea, was only recognized in the 1970s when microbiologists began looking in the steaming hot springs of Yellowstone National Park. More far-reaching has been the discovery that the DNA and RNA molecules that pass on the genetic instructions from generation to generation also contain a form of 'genetic history' that can be analyzed to tease out the evolutionary relationships between different species. Finally, just the sheer numbers of species being discovered is astounding. One thing is certain, whichever life classification scheme one chooses today, it will be vastly modified in the not too distant future. What matters most to us is not which scheme is more 'correct' than the others, but that it provide a reasonable vehicle for exploring the great variety of life in this International Biodiversity Observation Year.

The scheme that we will follow is most similar to that proposed by biologists Lynn Margulis and Karlene Schwartz, as expounded in their fascinating book, *Five Kingdoms: An Illustrated Guide to the Phyla of Life on Earth*, with the exception that I have accredited the Archaea full Kingdom status, thus arriving at six kingdoms in lieu of their five. I also recognize the deep division of life at the cellular level into two domains.

Domains	Kingdoms
Prokarya	Archaea (Archaebacteria) Bacteria (Eubacteria)
Eukarya	Protoctista (Protista) Animalia Fungi Plantae

The remaining part of this essay and the ones that follow it present my own idiosyncratic tour of life. We'll begin with the two kingdoms that comprise the Domain Prokarya. Unless otherwise attributed, the descriptions of kingdoms, domains, phyla, and of specific species is taken from *Five Kingdoms*.

Kingdom Archaea

Kingdom Archaea consists of micro-organisms that until a few years ago were classified as bacteria (the archaebacteria). However, as microbiologists and biochemists have looked more closely at this group, it has become increasingly clear that the archaea are fundamentally different from the much larger group that comprises the Kingdom Bacteria. Although neither group possesses the nucleus and chromosome structures characteristic of the larger and more complex eukaryotic cell, in details of biochemistry and ultra-structure the archaea are actually more closely related to eukaryotic animal cells than they are to bacteria. Based on these fundamental characteristics, most systematists seem to lean toward granting Kingdom status for the archaea.

Kingdom Archaea is best known for containing many species that live in extreme environments that were believed to exist on the early Earth. Thus these organisms are also sometimes called 'extremophiles'. Their lack of structural complexity and the fact that their exterior forms match those of ancient microfossils, leads many biologists to believe that the archaea may represent a direct lineage from the earliest life forms (hence archae-bacteria = 'ancient'-bacteria). Interestingly, none of the Archaea appear to be pathogenic, or disease-causing, in the plant and animal kingdoms, unlike many of their distantly-related bacterial cousins.

GLOSSARY

Genus (Genera, pl): A collection of species sharing one or more characteristics common to each other.

Phylum (Phyla, pl): A collection of genera. In our scheme, phyla are grouped under one of six kingdoms of life. Biologists, microbiologists, zoologists, botanists, and paleontologists, however, often group phyla into other categories, such as orders, sub-orders, sub-phyla, tribes, classes, etc., to reflect their particular areas of research.

Bacteria/Eubacteria/Archaea: Kingdom Bacteria formerly included a group of unicellular organisms that were called archaebacteria. Biomolecular research revealed that the archaebacteria are as different from the 'true' bacteria as we are, resulting in them being assigned their own Kingdom Archaea, leaving only the true, or eubacteria in Kingdom Bacteria.

Protoctista/Protista/Protists: Kingdom Protoctista is a 'catch-all' grouping consisting of organisms that don't fit into any of the other classical kingdoms. It is also referred to as Kingdom Protista.

Autotroph: A primary producing organism that synthesizes all the organic molecules it needs for growth and for energy from inorganic compounds, either by utilizing energy from sunlight as a **phototroph** (photoautotrophy, or photolithoautotrophy) or by oxidizing inorganic compounds as a **chemotroph** (chemoautotrophy, or chemolithoautotrophy).

Heterotroph: An organism that obtains its food from the organic molecules produced by other life forms, as opposed to an autotroph.

Aerobe/Anaerobe: An aerobic organism that requires free molecular oxygen in its metabolic cycle is called an aerobe, as opposed to an anaerobe, which requires the absence of free oxygen.

Anoxic/Anoxygenic/Anaerobic: The absence of free oxygen, as opposed to an oxygenic environment.

Motile: Possessing the quality of self-movement.

Organelles: The distinct intracellular bodies ("little organs"), such as the nucleus, mitochondria, and chloroplasts, among others.

Mitochondria: Organelles that transfer the chemical energy contained in organic compounds (food molecules) to a form that can be used by the rest of the cell, namely the ATP molecule (adenosine tri-phosphate). Oxygen is always required; hence the presence of mitochondria implies obligate oxygen respiration.

Chloroplasts: Organelles in which photosynthesis take place.

Kingdom Archaea is divided into only three phyla: the Euryarchaeota, consisting of methanogens, which as their name suggests produce methane as a product of their metabolisms, and the salt-loving halophils; the Crenarchaeota, which are broadly classed as thermoacidophils (heat- and acid-loving organisms); and the mysterious Koryarchaeota, which have never been directly observed or isolated but are known to exist from analysis of DNA samples.

Phylum Euryarchaeota: There are at least 25 genera within this phylum that can be characterized as methanogens, meaning that their metabolic pathways lead to the generation of methane, a powerful and explosive greenhouse gas.¹ These microbes are ubiquitous around the world, being found in sewage, muds and sediments, and as ordinary inhabitants of the intestinal tracts of animals, most particularly those that

¹ Prescott, Chapter 20 notes.

deal with the digesting of cellulose such as ruminants and wood-eating insects.

The methanogens are critical in maintaining the world's carbon cycle. Methane (CH₄), or "marsh gas" comprises more than 90 percent of all natural gas. Ceaselessly working in swamps, estuaries, bogs, and sewage treatment plants around the world, these microbes break down the organic products of other life forms and thus prevent carbon from being irretrievably buried in the ground. They also prevent the Earth from exploding and burning from spontaneous combustion. For every carbon atom combined into the products of photosynthesis, two atoms of oxygen are released. If these photosynthate products were buried instead of recycled by the methanogens, the excess atmospheric O₂ would rise to the level at which plants and animals would self-combust due to their oxidizing metabolisms alone. Fortunately, most methane spontaneously reacts with oxygen to form CO₂ or is utilized by methylotrophic eubacteria to form cell material or CO₂, thus completing the familiar oxygen-carbon dioxide cycle. All the methanogens are intolerant of the presence of free oxygen and are thus said to be anaerobic.

The nine genera of Halophils,² the other major group within the Euryarchaeota, live in extremely salty or alkaline, environments (*halo*: salt), where they feed on a variety of carbon compounds. Until the advent of modern molecular sequencing techniques the close relationship between the halophils and methanogens was unknown. Unlike the methanogens, all halophils respire oxygen. The triangular and square-shaped forms in genus *Haloarcula* seem to take their form from the alkaline and salt minerals in which they abide. The cell walls of halophils are quite different from other microbes, having modified proteins that enable them to function at high salt concentrations when other cells would burst.³

Phylum Crenarchaeota: At least 12 genera make up this phylum,⁴ which is characterized by single-celled organisms that live in the extremely hot and/or acidic environments around the world. The crenarchs have the distinction of living and reproducing at some of the highest temperatures known (some live at temperatures above the boiling point of water). The whole class of thermoacidophils was virtually unknown until microbiologists began looking in the hot springs of Yellowstone in the 1970s. Since then, they have been found in the geysers of Iceland, around submarine vents such as the 'black smokers' found at deep ocean spreading centers, "and other habitats with conditions far too hot, too acidic, and too sulfur rich and oxygen poor for the far more familiar eubacteria."⁵

Species in the genus *Sulfolobus*, first isolated in culture in 1972, live in 90 degC water with a pH value of 1 to 2 (the acidity of concentrated sulfuric acid). As can be imagined, the cell walls of *Sulfolobus* and other crenarchs are greatly modified in order to survive such environments. Living cells of *Sulfolobus* can be seen adhering to crystals of elemental sulfur when viewed by fluorescence microscopy. Some of the *Sulfolobus* literally freeze to death at temperatures below 55C (human body temperature is 37C).

Thermoplasma, contains a species, *T. acidophilum*, that is known only from hot coal refuse piles (waste tailings from coal mines) and from hot springs in Yellowstone. Their optimum growing conditions are at 60C and pH values of 1 to 2. They make an excellent laboratory culture, in that no other organisms can coexist in this extreme environment and thus the culture remains pure. Like *Sulfolobus*, they freeze to death at relatively high temperatures, which makes them difficult to observe in life, since microscopes and their users are not normally equipped to maintain samples at such high temperatures. Not only can *Picrophilus*,

another thermoplasma, survive in nearly pure acid, it even grows at or near pH 0.⁶

Deep ocean volcanic hot springs have yielded several new genera of thermoacidophils in recent years. One of them, *Pyrodictum*, grows at a temperature as high as 110C, thus rivaling the eubacterium *Pyrolobus* which grows at the hottest temperature known (113C). The recently discovered *Methanopyrales*, which also grows at a temperature of 100C, has been isolated from the same marine hydrothermal vents and "evidence suggests that they may be among the first living organisms to have developed."⁷

Phylum Koryarchaeota: The koryarchs have never been isolated and cultured or otherwise identified as a particular organism or set of organisms. They are only surmised to exist, probably as thermophils, from peculiar characteristics of DNA analyzed from the wild.⁸

Kingdom Bacteria

Since I have excluded the Archaea from Kingdom Bacteria, all bacteria now fall within the Eubacteria (*Eu* = true). The true bacteria encompass a huge class of organisms, many of which are familiar to us as agents of disease and decay, but many others of which are highly beneficial and even necessary to our existence. Under the Margulis/Schwartz scheme, they are divided into 12 phyla.

Phylum Proteobacteria: These organisms are classified by a combination of their RNA molecular sequences, by morphologies, and by their metabolisms. Analysis of RNA from thousands of bacterial species has divided the Proteobacteria into four major lineages, designated by the Greek letters alpha, beta, gamma, and delta. The array of morphologies and metabolisms among the proteobacteria is incredibly varied, as exemplified by a small selection of genera:

Group	Genus	Morphology	Metabolism
Alpha	<i>Agrobacterium</i>	Motile rod	Crown gall-forming heterotroph
	<i>Nitrobacter</i>	Short budding rod	Ammonia & nitrate oxidizer
	<i>Rhizobium</i>	Symbiotic with root nodules	Nitrogen fixer
	<i>Rhodobacter</i>	Flagellated rod	Purple nonsulfur phototroph
Beta	<i>Alcaligenes</i>	Motile rod	Hydrogen oxidizer
	<i>Sphaerotilus</i>	Filament	Iron oxidizer
	<i>Thiobacillus</i>	Motile rod	Sulfide oxidizer
Gamma	<i>Chromatium</i>	Motile rod, sulfur globules in cells	Purple sulfur phototroph
	<i>Escherichia</i>	Motile rod, peritrichous flagella	Heterotroph
	<i>Salmonella</i>	Motile rod	Heterotroph
	<i>Vibrio</i>	Motile comma-shaped bacterium	Heterotroph
Delta	<i>Bdellovibrio</i>	Motile, tiny curved rod	Heterotroph-Predator
	<i>Desulfovibrio</i>	Motile rod, polar flagella	Sulfate reducer

Enterics are bacteria that inhabit intestines and have long been known for their pathogenic effects on humans, plants, and other animals. Among the more familiar genera are *Escherichia*, *Salmonella*, and *Yersinia (Pasteurella)*. The enterics are widespread in the environment, having been cultured from water samples taken from around the world. According to Margulis, "it is not too extreme to assert that most life on

² Prescott, Chapter 20 notes.

³ Our own Owens Lake beside Highway 395 just south of Lone Pine, plays host to species of halophils which produce bright pink carotenoids giving its salt-encrusted surfaces their characteristic pink and red coloration.

⁴ Prescott, Chapter 20 notes.

⁵ Margulis, p. 60.

⁶ Prescott, Chapter 20 notes.

⁷ Prescott, Chapter 20 notes.

⁸ On Koryarchaeota, see Tudge, p. 123. There's a doctorate in it for anyone who first cultures and identifies the particular organism(s) for which a phylum has already been set aside.

Earth takes the form” of this class of organisms, and “at the base of microbial food webs, they provide food for innumerable prototists and other organisms.”⁹

The species *Escherichia coli*, the familiar sewage-related contaminant of Santa Monica Bay, is easily and universally cultivated in laboratories and has thus been studied more than any other organism in the world.

Several species of the genus *Salmonella* are notorious pathogens.

Many, such as *S. agona*, *S. typhimurium* and *S. enteritidis*, reside on poultry and eggs or in meat and dairy products and are the cause of classic food poisoning.¹⁰ *S. typhi* is less common but more serious, being the organism responsible for typhoid fever.¹¹

The comma-shaped microbes of the enteric vibrios include several members in the genus *Vibrio* that are associated with cholera.¹² Other vibrios, such as *Photobacterium* and *Xenorhabditis*, are bioluminescent and live within pockets called light organs on certain tropical fish.

Yersinia pestis is infamous as the microbe that caused the Black Death (Bubonic Plague), and in the form of plague is still with us today. One of our Natural Science Section meetings had to be moved from Eaton Canyon Nature Center due to an outbreak of plague-infected ground squirrels. The rodents had to be exterminated to eliminate the remote possibility of transfer of the *Y. pestis* bacterium via fleas jumping from the affected animals to humans.

Some Proteobacteria, such as *Sphaerotilus*, aggregate together and can be recognized under the microscope by the metal-rich clumps of manganese- and iron- oxides that form as a byproduct of their metabolic activities. They are the source of the dark patina, or ‘desert varnish’, that forms on desert rock surfaces exposed to the atmosphere for long periods of time.

Bacteria of the genus *Neisseria* are notorious as the cause of the sexually transmitted disease gonorrhea and of one form of bacterial meningitis.

More than thirty species of *Legionella* are now known to exist since first discovered after an outbreak of a severe form of pneumonia was traced to an American Legion convention in Philadelphia in 1976. The genus name and the popular term “Legionnaires’ disease derive from this occurrence. At least 19 varieties can cause pneumonia in humans. It is an unusual pathogen in that it cannot be spread person-to-person.

⁹ Margulis, p. 66.

¹⁰ Salmonella in all its pernicious varieties, is a world wide problem. There are over 2, 200 known species and strains (Biddle, p. 125). Many are named after the place where they were originally discovered, usually in some outbreak of food poisoning. “So, running from *S. aba* and *S. abadina* to *S. zuielen* and *S. zwickau*, we have *S. adamstown* and *S. birmingham*. There is a *S. cambridge* and a *S. denver*, a *S. elizabethville* and a *S. fremantle*. Countries commemorated in this way include *S. gambia*, *S. india*, and *S. kenya*, while U.S. states range from *S. kentucky* to *S. tennessee*. Less-familiar locales are represented by the likes of *S. fischerstrasse* and *S. mishmar-haemek*, *S. onderstepoort* and *S. wilhelmsburg*. There is a *S. wedding* and a *S. oysterbeds*, a *S. infantis* and a *S. banana*.” (Dixon, p. 120) Salmonella may yet be one of the great benefactors of mankind. In a press release dated 1/11/01, Yale University research scientists announced that genetically modified Salmonella have been successfully used in combination with radiation as a new and promising anti-cancer therapy. (see website: <http://www.sciencedaily.com/releases/2001/01/010111074337.htm>).

¹¹ Over fifty strains of *S. typhi* exist, all so closely tied to the human species that they can grow only in the human digestive system. Typhoid fever is a so-called ‘filth disease’ spread through fecal contamination. It is thus rarely encountered in the U.S., but is still a common ailment in the Third World. My father, who is retired and lives in Baja California, contracted it from his local environment, so my wife and I have obtained vaccinations for our future visits. See Biddle, pp. 152-154.

¹² Cholera is a ‘filth disease’ spread through contaminated water and food. At least seven pandemics have occurred in parts of the world since cholera first rampaged out of India’s state of Bengal in 1817. It can spread quickly through contaminated water and kill thousands through fluid loss from severe diarrhea. The current seventh pandemic began in Indonesia in 1961 and is still operating in scattered pockets around the world, having reached epidemic proportion in parts of South America during the early 90s. See Biddle, pp. 36-43 for more on what should be a fully controllable disease.

Instead, it must be taken into the lungs by breathing a fine mist containing the organisms. *L. pneumophila*, the specific agent active in the Philadelphia outbreak, killed 34 of 221 people who had inhaled bacteria that had taken up residence in the hotel’s air conditioning cooling towers.¹³

Gluconobacter and *Acetobacter* bacteria oxidize ethanol to acetic acid, converting wine to vinegar.

The minute rickettsias are also members of the Proteobacteria. Like viruses, they can only grow inside other living cells. They are the source of tick-borne Rocky Mountain spotted fever and of flea- and lice-borne typhus.¹⁴

After so much death and destruction, it is good to know that many chemolithoautotrophs are found in this phylum. Chemolithoautotrophy is any metabolic lifestyle that functions without sunlight and without preformed organic compounds. Chemolithoautotrophs represent “the pinnacle of metabolic achievement,” living on “air, salts, water, and an inorganic source of energy. Provided with nitrogenous salts, oxygen, carbon dioxide, and appropriate reduced compounds to use as an energy source, they make all of their own nucleic acids, proteins, and carbohydrates and derive their energy from oxidation of the reduced compound. . . Chemolithoautotrophic bacteria are crucial to the cycling of nitrogen, carbon, and sulfur throughout the world because they convert gases and salts unusable by animals and plants into usable organic compounds. The maintenance of the biosphere depends on such metabolic virtuosity, yet chemolithoautotrophy is strictly limited to bacteria.”¹⁵

Although soil-dwelling nitrate oxidizers of the genera *Nitrobacter* and *Nitrosomonas* are essential in recycling nitrogen and making it available for plants, they are also implicated in the destruction of stone monuments and buildings through their metabolic conversion of ammonia to nitrous acid and the further conversion of nitrous acid to nitric acid. Thus architectural stone ‘infected’ with these bacteria end up with a built-in form of acid rain.¹⁶

Among the delta-group of the Proteobacteria are some of the strangest members of the bacterial world in that they actually form colonies that can clump together and act as one organism to glide off to find a new food source. The deltas also include some of the most athletic organisms ever to be encountered, the bdellovibrios, which prey upon other bacteria. Colin Tudge describes how they “attack their hosts like guided missiles, rushing into them at 100 cell-lengths per second—which is equivalent to a 30-centimetre-long rabbit running about 110 kilometres an hour, or a man at half the speed of sound. The attacking *Bdellovibrio* then attaches by its flagellar end and bores its way in by spinning at more than 100 revolutions a second.”¹⁷

¹³ *Legionella* bacteria have “also been found in shower heads and faucet pipes. *L. pneumophila* can survive in room temperature tap water for more than a year. Streams, ponds, and plain old mud may harbor them. Hot tubs, humidifiers, vegetable stand misters, decorative fountains—the list of possible habitats is unsettling. Chlorination may not remove the threat if the concentration of organisms is high.” The information on *Legionella* was derived from Biddle, pp. 85-87.

¹⁴ The name Rickettsia commemorates American scientist Howard T. Ricketts, who first discovered these tiny bacteria in 1907 and who later died from contracting *R. prowazekii*, the agent of epidemic typhus (Biddle, p. 121). The same disease claimed Czechoslovakian bacteriologist Staniltau von Prowazek (Dixon, p. 14). Bacteriologists still play tag with death, especially those who travel to the ‘hot zones’ to investigate emerging diseases. Typhus has been the great destroyer of armies. As much credit should be given to typhus in spoiling Napoleon’s attempted conquest of Russia as to the Russian armies and the infamous winter weather. Not much had improved in preventing this lice-transmitted disease by World War I, when epidemic typhus caused two to three million deaths among the troops. See Dixon, pp. 14-16.

¹⁵ Margulis, p. 70.

¹⁶ The ‘infection’ of several great European cathedrals by nitrifying bacteria is discussed in Dixon, pp. 60-63.

¹⁷ On *Bdellovibrio*, see Tudge, p. 119.

Phototrophic proteobacteria come in a wide range of colors from pink through green and typically grow in layers according to each species' growth requirements. These bacteria are key members of the bacterial mats that form in anoxic sediments around the world. Some types are also capable of 'fixing' nitrogen. Most notable in this respect, however, are the free-living aerobic (oxygen-respiring) soil nitrogen-fixers *Azobacter* and *Beijerinckia*. Only bacteria are able to convert inert atmospheric nitrogen molecules (N₂) into organic compounds, i.e., to 'fix' nitrogen into amino acids and ammonium radicals, that other organisms, such as plants, are then able to use. In the old growth forests of the Pacific Northwest, this is accomplished by bacteria living symbiotically with fungi in lichens growing high in the forest canopy. When branches or pieces of lichen fall to the forest floor, the nitrogen compounds then become available for tree roots to absorb.¹⁸ Other close relatives to the free-living nitrogen fixers are the plant root symbionts, such as the *Rhizobium* and *Bradyrhizobium*, often found in the root nodules of leguminous plants.

Phylum Spirochaetae. The spirochetes look like tightly coiled snakes under the microscope. This phylum contains a number of groups that can result in disease in humans. They may be found in water, mud, the gastrointestinal tracts of animals and elsewhere. The arrangement of from 2 to 200 flagella (whip-like appendages) by which they propel themselves, and which is probably responsible for their corkscrew shapes, is what distinguishes the spirochetes from all other bacteria.

Certain members of the genus *Leptospira* reside in the kidneys of animals, from which they may be carried with the urine and passed into water supplies. From there the floating bacteria may enter the human bloodstream through contact with cuts or abrasions in the skin, causing the disease leptospirosis. These bacteria are so small and difficult to see even with a microscope that the disease is often misdiagnosed. More infamous is *Treponema pallidum*, the agent of syphilis as well as yaws, a debilitating tropical eye disease.

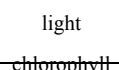
Members of four genera—*Pillotina*, *Hollandina*, *Diplocalyx*, and *Clevelandina*—are found in close association with other microbes in the hindgut of wood-eating cockroaches and termites. It is believed that the spirochetes themselves lack the enzymes that initiate the breakdown of wood, but instead live on the by-products of other microbes that accomplish this important task via their cellulase enzymes.

Lyme Disease is a debilitating but usually non-fatal disease that Sierra Club hikers should be aware of, since the spirochetes of *Borrelia burgdorferi* are transmitted via ticks.¹⁹

Phylum Cyanobacteria. This phylum of organisms was once included in the plant kingdom when the many species were lumped together as the blue-green algae. Although physiologically similar to algae and plants—they all respire oxygen and perform photosynthesis—they are now classified as bacteria. Because of their photoautotrophic ('light-feeding') metabolisms and their dominance in the environment, the cyanobacteria, along with algae and plants, are one of the primary producers upon which almost all other organisms depend. The chloroplast bodies that accomplish photosynthesis in algae and plant cells are believed to have evolved from an ancient time when cyanobacteria became permanent symbionts in these organisms.

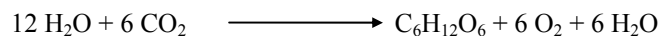
The cyanobacteria are divided into two large classes: the Class Coccogoneae, which are the coccoid (spherical) forms, and the Class Hormogoneae that stay attached as they grow into linear chains (filamentous cyanobacteria).

Most cyanobacteria photosynthesize the same way as algae and plants, combining water with carbon dioxide (reducing the CO₂) to form sugar, oxygen and water, as shown in the chemical equation:

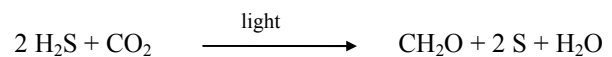


¹⁸ The critical role of the nitrogen-fixing lichen *Lobaria oregana* in old growth forests is wonderfully told by Luoma, see especially p. 52.

¹⁹ Lyme Disease and its spread due to human-induced ecological changes is covered in Biddle, pp. 26-29.



However, under high sulfide conditions many cyanobacteria can perform photosynthesis using hydrogen sulfide instead of water as the hydrogen donor, thus depositing sulfur instead of releasing oxygen:



The cyanobacteria dominated the landscape during much of the Proterozoic, from 2,500 million to 600 million years ago, and are generally credited for converting Earth's early carbon dioxide-dominated atmosphere into the oxygen-nitrogen mixture of today. Petrified remains of their layered communities (called stromatolites) from this time period are found around the world. As the primary oxygen producer during the long Precambrian time period, they are also believed to have pumped oxygen into the oceans where it combined with dissolved iron to form insoluble iron oxides that precipitated out as the banded iron formations (BIFs) from which more than 90 percent of the world's supply of iron has been extracted.

Although only small relict populations of living stromatolites are found today, there are still thousands of living types of cyanobacteria.²⁰ Those of us living in the American Southwest can see examples of cyanobacteria on almost any trip to a desert area where they form the so-called cryptogamic or cryptobiotic crust often encountered on the surface of arid soils.

The grass-green cyanobacterium *Prochlorococcus*, a free-floating ocean species, is probably one of the most common bacteria in the world.²¹

Phylum Saprospirae. Informally called 'fermenting gliders', the saprospirae are divided into two major subgroups. The genus *Bacteroides* and its relatives are anaerobic fermenters. The flavobacterium subgroup are oxygen respirers that are able to 'glide' about their environments. The fermenting bacteria cannot synthesize certain metal- and nitrogen-containing ring compounds called porphyrins, as can all photosynthesizing and respiring organisms. Hence they must derive these constituents from preformed compounds through the fermentation of organic materials in their environment. Some species are invaluable in participating in the breakdown of the tough organic molecules contained in wood (cellulose) and insect exoskeletons (chitin).

Members of the genus *Bacteroides* are a normal complement of our intestinal flora, which they inhabit in great numbers.

Phylum Chloroflexa. Known as the green nonsulfur phototrophs, the chloroflexa were only discovered in the 1960s, growing in hot springs and microbial mats. There are only four known species distributed among three genera. Being phototrophs ('light-feeders'), they require light in order to metabolize. Previously lumped with the Chlorobia (see next phylum description), there were hints in their tolerance of oxygen and their independence from sulfur that they were fundamentally different. This has since been confirmed through the technique of genetic nucleotide sequencing analysis, which finally resulted in these organisms being placed in their own phylum. The two species of the genus *Chloroflexus* are found in hot springs where they associate with species of filamentous cyanobacteria.

²⁰ The cyanobacteria constitute the most diverse group of photosynthetic bacteria. They are also the photosynthetic partner in most lichens. See Prescott, Chapter 21.

²¹ There's always something new showing up, even in the world of pond scum and sea mud. In December 2000 researchers announced the discovery of a potent neurotoxin, called kalkitoxin, isolated from a species of marine cyanobacteria harvested from the ocean floor near Venezuela. This new drug promises to be of great help in the area of nerve function research, which "could someday lead to new treatments for pain, epilepsy and possibly stroke." The discovery of kalkitoxin was announced by lead investigator William Gerwick, Ph.D., a pharmacy professor at Oregon State University in Corvallis.

Phylum Chlorobia. This phylum is comprised of the anoxygenic green sulfur bacteria. They are all phototrophic, i.e., deriving their basic energy from sunlight, which they store in various chemical ‘batteries’ (molecular compounds) through a ‘light reaction’ and their suite of metabolic pathways. Members of Chlorobia require sulfur to do this, and so are found only in sulfide-rich, sunlit habitats—typically in the dark-colored sulfur-smelling anaerobic muds located in beach areas or in ponds and lakes over sulfur-rich rock.

With their intolerance of oxygen, the chlorobia end up at or near the bottom layers of microbial mats, beneath the cyanobacteria and other oxygen-producing or oxygen-tolerant microbes. The large genus *Chlorobium* contains strains that are tolerant of extremely high or extremely low temperatures or salinities.

Phylum Aphragmabacteria. Called ‘mycoplasmas’, the aphragmabacteria comprise a remarkable set of organisms, some of which are pathogenic to humans and other animals, and some of which “probably do represent minimal life on this planet and are truly primitive in the sense that their ancestors never had [cell] walls. Among them are the smallest organisms known. Most bacteria have from 3000 to 6000 genes.”²² *Mycoplasma genitalium*, on the other hand, has ten times less DNA than most other bacteria, which is contained in fewer than 500 genes with which it manufactures fewer than 500 proteins.

In *Aphragmabacteria*, the cell wall common to most bacteria is totally absent, although they still retain their identity by means of the cell membrane. They are thus resistant to penicillin and other drugs that work through inhibiting cell wall growth. Their small size enables these organisms to live inside the cells of their hosts as normally benign symbiotrophs. However, they may be found in large numbers in diseased mammals and birds. They are also found in insects and plant tissues.

Members of the genus *Spiroplasma* have been isolated from the leaves of citrus plants suffering from the disease called ‘stubborn’, but it has not been determined with certainty that they are the direct agents of the malady. Members of *Ehrlichia* cause tick-borne diseases.

Phylum Endospora. This huge collection of bacteria is characterized by the habit of many species to form specialized reproductive bodies (endospores) within their ‘mother’ cells that are resistant to heat and desiccation that are harmful to the normal growing cells. There are thousands of species, a number of which are familiar to us as agents of disease.

Many members of the Endospora are involved in the stages of breaking down tough organic molecules such as pectin, polysaccharides, cellulose and lignin. The rare ability to perform this feat among living organisms explains the persistence of these materials as forest litter, petroleum, coal and peat. Some species are psychrophils, i.e., cold-lovers, growing optimally at three degrees Centigrade below the freezing point of water. Others are thermophils, growing in hot springs at temperatures above 47C.

Among the endospore-forming bacteria the genus *Bacillus* is so large that entire volumes are required to characterize all of its species, and the term ‘bacillus’ has become synonymous with ‘bacteria’ in the common tongue. Many of its members are animal symbionts, including strains of *Bacillus anthracis* that are responsible for the disease anthrax.²³

A large subgroup is classified as lactic acid bacteria for the acid they produce as a byproduct of their metabolisms. Among them are the *Lactobacillus*, *Streptococcus*, and *Leuconostoc*, all “rod-shaped organisms famous for their ability to ferment sugar, in particular that in milk, and to produce lactic acid as well as acetate, formate, succinate,

²² Margulis, p. 91.

²³ Anthrax is a zoonotic disease (Greek *zo-*: life or animal, and *nosos*: disease), meaning a disease that people can catch from animals and not from other people. Anthrax may be contracted from cattle, sheep, horses, pigs, or goats. The form transmitted through cuts in the skin is not fatal, but another rare form whose spores can be inhaled is extremely deadly and one of the most feared of potential biological warfare agents. See Biddle, pp. 20-22. One strain has been put to beneficial use in controlling populations of alien rabbits that had overrun portions of Australia.

CO₂, and ethanol.” These microbes can tolerate oxygen but do not use it for metabolism. In the role of fermenting milk, one species of *Streptococcus* is responsible for giving yogurt its creamy taste. Strep, as it is commonly called, is most famous as the cause of sore throats and childhood ear infections.²⁴

The genus *Clostridium* is a large family that produces spores that are found in dirt all over the world. They are all anaerobes, of which the most famous is *C. botulinum*, producer of one of the most toxic poisons known, which due to the heat resistance of the spores can survive home-canning operations. Only pressure cookers can achieve the 250F temperature required to guarantee their destruction. *C. tetani*, source of tetanus or ‘lock-jaw’ is another rightfully feared member of this family, but is a rare problem nowadays due to effective vaccines. One member of the clostridium family wears a white hat, however. *C. pasteurianum* is a common nitrogen-fixing inhabitant of agricultural soils, and thus fundamental to world food production.²⁵

Phylum Pirellulaceae. This phylum represents a relatively new grouping based primarily on the biochemical analysis of their RNA. Several genera have unique cell walls closer to eukaryotic organisms than most of the bacteria (prokaryotes), making them insensitive to penicillin and other wall-inhibiting drugs.

The most infamous genus is *Chlamydia*, some strains of which are responsible for a sexually transmitted disease that can cause a host of problems in the human reproductive systems. *C. psittaci* is identified with a parrot-transmitted pneumonia-like disease of humans, while *C. trachomatis*, the “most prevalent of all sexually transmitted organisms,”²⁶ is the cause of trachoma-type blindness. As obligate symbiotrophs living inside host cells, *Chlamydia* are much smaller than typical bacteria. No means of metabolic production of energy molecules has been discovered in pure cultures of these organisms, so they are assumed to be energy parasites, robbing energy-rich molecules from their hosts.

Gemmata obscuriglobus independently evolved a double-layered nucleoid membrane that encloses its bacteria-type DNA, thus superficially resembling the true nuclei of eukaryotic cells. In microstructure this membrane is quite different, and in no other way does *G. obscuriglobus* resemble a eukaryotic organism.

Phylum Actinobacteria. In appearance and growth habits many of the members of this grouping appear very similar to fungi, an entirely different kingdom composed of eukaryotic cells in which this group was first mistakenly classified as the actinomycetes. The filamentous colony-forming actinobacteria have stringy extensions or threads that look like the mycelia of true fungi. However, these organisms, united by their morphology, physiology, and more importantly, their RNA genetic sequencing codes, are now properly grouped with the bacteria.

²⁴ Margulis, pp. 92-93. *Streptococcus pneumoniae* is the culprit behind classic lobar pneumonia, which affects an entire lobe of the lungs rather than more localized regions. It is often the last disease that the aged and infirm encounter, hence its sobriquet “the friend of the aged.” According to Biddle, “the prevalence of pneumococcal strains highly resistant to penicillin increased by a factor of sixty between the late 1970s and early 1990s. See Biddle, pp. 110-111. The so-called strep-A strain took the life of Muppets creator Jim Henson in 1990, and this variety’s potential to cause severe skin infections has since been sensationalized by the press as the “flesh-eating” disease. Strep throat, when accompanied by rash and fever, is known as scarlet fever. Strep infections often settle in the tonsils, and it was mistakenly believed at one time that removing these innocent glands would save children from recurring bouts of strep throat. I had mine removed at a young age and can still vividly recall the fearful trip to the hospital and the subsequent reward of consuming vast amounts of soothing ice cream. See Biddle, pp. 136-140.

²⁵ The information on *Clostridium* comes from Biddle, pp. 43-47. He also relates how injections of *C. botulinum* are used in the beauty industry to paralyze certain facial muscles to remove wrinkles. Sounds kind of gross, doesn’t it? However, injections of the botulism toxin have been successfully administered to thousands of people to relieve symptoms of uncontrollable muscle spasms (Dixon, pp. 173-176).

²⁶ Chlamydia as most prevalent STD, see Biddle, p. 34.

The many members of the genus *Frankia* are plant symbionts, living in and around the roots where they induce nodules in which they carry out nitrogen fixation, a function that plants alone cannot perform.

Some species of *Dermatophilus* form pathogenic lesions on human skin; others are found in soils. Much more serious are the members of the genus *Micobacterium*, agents of leprosy, or Hansen's disease, and tuberculosis.²⁷

More than 500 species of *Streptomycin* have been identified, among them the species used to produce powerful antibiotics, including streptomycin.

A species from genus *Corynebacterium*, *C. diphtheria*, is responsible for the associated diphtheria disease in humans. Curiously, the diphtheria bacterium is but an innocent tool of destruction under the genetic control of a bacteriophagic virus that infects the bacterium with a gene that directs the production of the powerful exotoxin responsible for poisoning its victims. A sister organism, *C. glutamicum* is used to manufacture monosodium glutamate, the ubiquitous MSG that is a flavor enhancer often used by Chinese restaurants and which causes allergic reactions in some people.²⁸

Phylum Deinococci. Members of the two genera that make up this phylum, *Deinococcus* and *Thermus*, are recently discovered microbes famous for their radiation and heat resistant qualities. Their status as a separate phylum is based primarily on their unique RNA gene sequences. All deinococci require oxygen for growth.

As indicated by their genus name, *Thermus* thrive in water at temperatures of 60C to 80C. *Thermus aquaticus*, discovered by Thomas Brock when he examined the microflora of hot springs in Yellowstone, is one of the most famous micro-organisms in the bioengineering field, as the source of the Taq polymerase. The heat stability of this molecule is what enables the polymerase chain reaction (PCR) process to work as an everyday process in laboratories around the world sequencing DNA for scientific, legal and industrial applications. (In the PCR process, small amounts of pieces of DNA are replicated many times over, thus amplifying their chemical signatures in analytic processes.)

Deinococci are famous also, due to their ability to withstand extreme doses of ionizing radiation—up to 3,000,000 rads. Most bacteria die when exposed to only 100 rads. For comparison, the lethal dose for humans is about 500 rads. Such high levels of radiation do not occur anywhere in the natural environment, so the radiation resistance of these microbes is believed to be an accidental side effect of their adaptations to resist desiccation and ultraviolet light rather than evolution through natural selection. “The remarkable resistance of *Deinococcus* to mutagenic chemicals, radiation, and other treatments that generate genetic change in most bacteria has led to failure to induce stable mutations. The genetics of these organisms is poorly understood, although it is clear that excellent enzyme repair systems for DNA lead to highly efficient recovery from attempts to induce heritable damage.”²⁹ *Deinococcus* can be isolated from meat, feces, air, and fresh water, but their natural habitat is still not known.³⁰

Phylum Thermotogae. As with the Deinococci, the members of this family are newly discovered and have unique RNA gene sequences that

warrant placement in their own phylum. The four genera in this grouping are all thermophilic fermenters. Genus *Thermotoga* and genus *Thermosipho* live in and immediately adjacent to hot volcanic vents in the deep ocean where temperatures exceed 90C. As anaerobic fermenters, they are not chemolithoautotrophic organisms, rather they must obtain their nutrients from molecules generated by other life forms. Undoubtedly many other species and genera remain to be isolated from the deep ocean vents, since culturing and observing them under simulated heat and pressure conditions in the laboratory remains a difficult obstacle.

In 1995, a new species of *Thermotoga*, *T. subterranea*, was discovered inhabiting a deep, continental oil reserve in the East Paris Basin of France, becoming the fourth recognized species in this genus. The nether regions of the planet are sure to yield many other relatives.

The Archaea and Bacteria, along with the Protoctists and Fungi (subjects of future essays) comprise the “little things that run the world.” It is only in the last 250 years that we have begun to gain some appreciation of their impact and import upon the world and our own well-being. It's exciting to think about how little we know about these organisms and about the wonderful discoveries that lie ahead.

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Next Installment: Kingdom Fungi

²⁷ On tuberculosis, see Biddle, pp. 146-152, who states that this bacterium infects half the world's human population. Interestingly, one of the most powerful drugs with which to combat this scourge is derived from other members of the same phylum Actinobacteria, from the genus *Streptomycin*.

²⁸ George Washington may have died from diphtheria, which can result in sore throats so badly swollen that the victims can't breathe (as well as poisoning the heart and other vital organs). The name diphtheria is derived from the Greek word for a piece of leather, diphtheria, “referring to the tough, gray, mucousy membrane of dead cells that may block the victim's throat.” See Biddle, pp. 54-57 for a further discussion of diphtheria, and Biddle, pp. 33-34 for *C. glutamicum*'s contribution to Chinese cuisine.

²⁹ Margulis, p. 100. Deinococci may thus be the most stable information medium known in the Universe—orders of magnitude better than the best hard disk drive or other memory repository of any computer.

³⁰ Prescott, Chapter 21.