November 28, 2005

Genome sequencing aids investigation of an ancient and mysterious life-form

By Emily Saarman

UCSC researchers are using the latest in genetic technology to investigate an ancient form of life--the poorly understood microorganisms known as Archaea.

Many species of Archaea thrive in extreme environments, such as hot springs.
Photo: W. B. Hamilton

Many Archaea live in hostile environments, from salt lakes to acidic hot springs, but they can be very difficult to grow and study in the laboratory. So UCSC researchers were thrilled when their proposal to sequence the complete genomes of five species of Archaea was approved earlier this year by the Community Sequencing Program of the U.S. Department of Energy's Joint Genome Institute (JGI). JGI will carry out the sequencing and make the results publicly available.

"Having complete genome sequences will be enormously helpful to our research," said Todd Lowe, an assistant professor of biomolecular engineering.

Lowe and Chad Saltikov, an assistant professor of environmental toxicology at UCSC, teamed up with Sorel Fitz-Gibbon of UCLA and Christopher House of Pennsylvania State University to submit the Archaea proposal to the Community Sequencing Program. The five species they proposed for sequencing are closely related heat-loving Archaea found in various hot springs from Iceland to the Philippines. These species belong to a unique group of Archaea that can use sulfur compounds and toxic metals such as arsenic and selenium to power their cells. They use these compounds in much the same way that our own cells use oxygen, Lowe said.

One of Lowe's goals is to identify the genes and metabolic pathways that enable the Archaea to thrive at extremely high temperatures and make use of toxic compounds. His lab investigates the unique biology of Archaea using a combination of laboratory experiments and computational techniques for genetic analysis.

Superficially, Archaea look much like bacteria. It wasn't until about 25 years ago that genetic techniques enabled scientists to see beyond the cell surface and recognize the differences between Archaea and bacteria.

"Archaea are as different from bacteria as bacteria are from us," Lowe said. "They account for a third of the biodiversity on the planet and they've hardly been studied."

Scientists now divide all known organisms into three distinct domains: the eukaryotes, which include all plants, animals, and fungi; the bacteria; and Archaea.

"We're studying a third group of life that we know very little about and that may tell us about the origin of life, how life works, and geochemical processes. It's really exciting," said Aaron Cozen, a graduate student in Lowe's lab.

Archaea have already yielded some useful products, such as heat-resistant enzymes used in laundry detergents. Other practical benefits are likely to emerge from ongoing research on the unusual metabolism and genetics of these organisms, said Saltikov, who is focusing on their metabolic use of arsenic.

The use of naturally occurring arsenic by Archaea and certain types of bacteria has serious consequences in some parts of the world, because the process converts the arsenic to a more toxic form that is also more likely to remain dissolved in water. In Bangladesh, many people have been poisoned by drinking water that is laden with this toxic form of arsenic. Saltikov and others have already found the bacterial gene involved in arsenic respiration, but they have not found a match for this gene in Archaea.

"Archaea may have the same gene, but the sequence is so different that it's not recognizable. Or they may have a completely different metabolic pathway, or an older pathway that leads us to greater understanding of the bacterial mechanism," Saltikov said.

For now, the biggest challenge for Lowe and Saltikov is learning how to grow

Archaea and experiment with them in the lab. Many Archaea are poisoned by oxygen and have to be grown in special airtight containers. The heat-loving Archaea that Lowe is studying can only live at near-boiling temperatures and have to be grown in ovens. Keeping the conditions just right can be difficult and expensive, which limits the kinds of experiments researchers can do.

"These Archaea are more difficult than bacteria to grow and keep happy, so there are fewer ways we can assault them to learn about how they respond," Lowe said. He hopes that at least one of the five species chosen for genome sequencing will be easy to grow so it can become a model system for him and other scientists studying Archaea.

DNA microarrays (sometimes called "gene chips") are among the most powerful tools that Lowe is using to study Archaeal biology. Microarrays can provide a comprehensive view of gene activity in cells, revealing which genes are turned on and off in response to different conditions. Lowe's lab has already developed DNA microarrays based on the full genome sequences of two species of Archaea, and he plans to do the same for the five new species that will be sequenced by JGI. Using this "whole genome" approach to study Archaeal biology, he hopes to uncover the secrets that enable these organisms to live at the extreme limits of life on Earth.

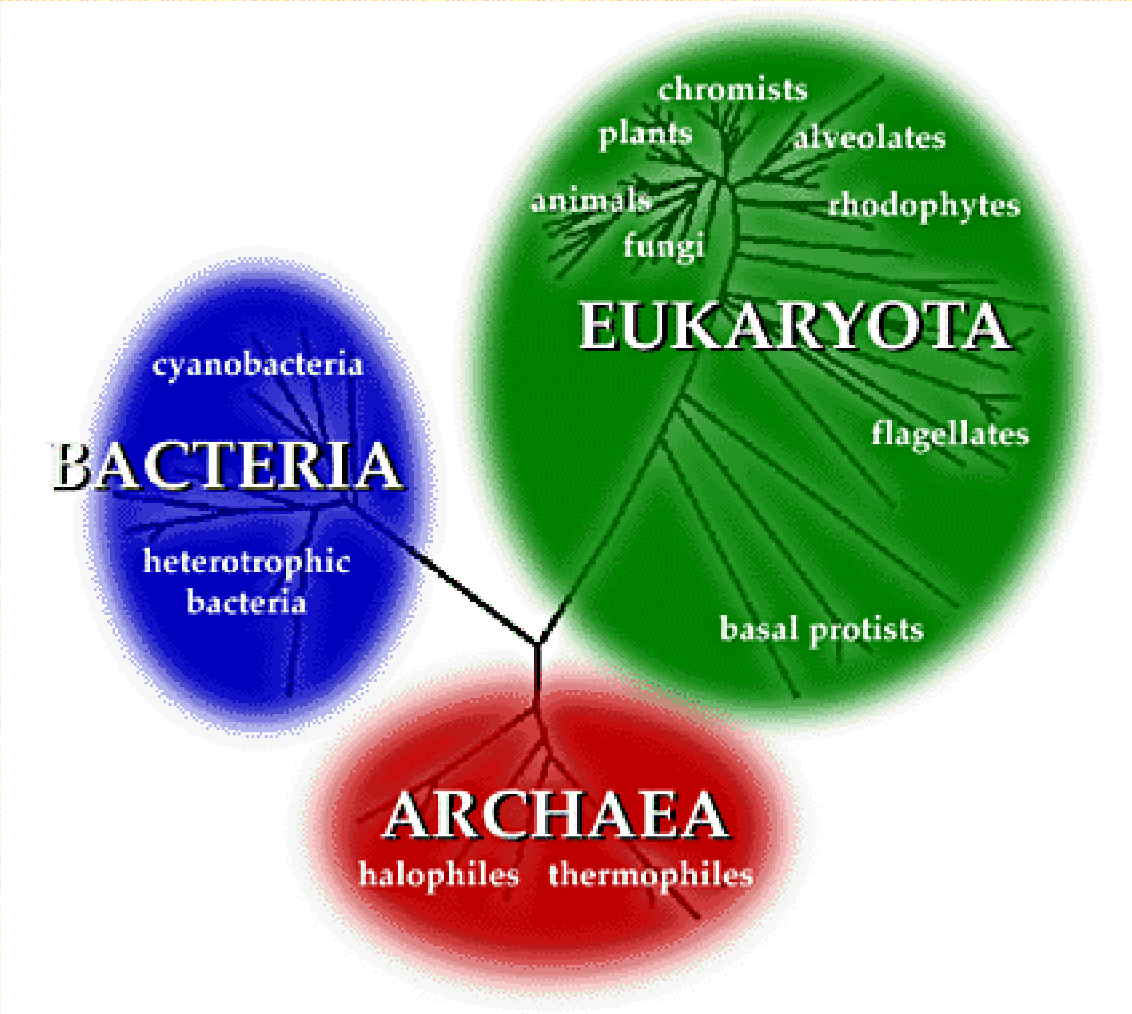
"It’s really exciting to know that you are the first person to understand something," Lowe said. "It's the potential for discovery of new biology that keeps me in this field."

This hot spring, known as Hot Creek, is on the Eastern Sierra Nevadas near Mammoth Mountain.

Photo: Chad Saltikov

ARCHAEA research in University of Helsinki.

Tree of life



Infomation source: Introduction to the Archaea (http://www.ucmp.berkeley.edu/archaea/archaea.html)

Until comparatively recently, living organisms were divided into two kingdoms: animal and vegetable, or the Animalia and the Plantae. In the 19th century, evidence began to accumulate that these were insufficient to express the diversity of life, and various schemes were proposed with three, four, or more kingdoms. The scheme in widest current use divides all living organisms into five kingdoms: Monera (bacteria), Protista, Fungi, Plantae, and Animalia. This coexisted with a scheme dividing life into two main divisions: the Prokaryotae (bacteria, etc.) and the Eukaryotae (animals, plants, fungi, and protists).

Recent work, however, has shown that what were once called "prokaryotes" are far more diverse than anyone had suspected. The Prokaryotae are now divided into two domains, the Bacteria and the Archaea, as different from each other as either is from the Eucaryota, or eukaryotes.

Archaea

The Domain Archaea wasn't recognized as a major domain of life until quite recently, largely through the work of Dr. Carl Woese and his colleagues at the University of Illinois. Archaeans don't look that different from most bacteria under the microscope; since most of them are extremely difficult to culture, their unique place among living organisms long went unrecognized. However, biochemically and genetically, they are as different from bacteria as you are. Although many books and articles refer to them as "Archaebacteria," they aren't bacteria - they're archaea. Archaeans include inhabitants of some of the most extreme environments on the planet. Some live near rift vents in the deep sea at temperatures well over 100 degrees Centigrade. Others live in hot springs, in extremely alkaline or acid waters, or in extremely saline water.

- Archaeans may be the only organisms that can live in extreme habitats such as thermal vents or hypersaline water. They may be extremely abundant in environments that are hostile to all other life forms. However, archaeans are not restricted to extreme environments; new research is showing that archaeans are also quite abundant in the plankton of the open sea, exist in soils, freshwater and almost everywere!

Phylogenetic diversity Archaea

Phylogenetic diversity in the domain Archaea is subdivided into two main lineages: Euryarchaeota and Crenarcheaota. The traditional view of the diversity of Archaea has been that the kingdom Euryarchaeota is a physiologically variable group including halophiles, thermophiles and methanogens. On the other hand, diversity in the the kingdom Crenarchaeota has been thought to be more homogenous, consisting exclusively of sulfur-dependent, extreme thermophiles. This view, however, has been based primarily on cultivation studies and has subsequently provided a biased picture of crenarchaeal diversity due to the difficulty of cultivating most organisms. In analysis of crenarchael diversity, researchers use a comparative analysis of small-subunit ribosomal RNA (SSU rRNA) genes obtained directly from the environment, allowing for microbial communities to be characterized without cultivation.

Lectures about Microbial Diversity at the Department of Microbiology - North Carolina State University by James W. Brown (really good, easy to read material, lots of photos)

Publications about Archaea isolated from soil

Novel Group within the Kingdom Crenarchaeota from Boreal Forest Soil (German Jurgens and Aimo Saano), Applied and Environmental Microbiology, Feb. 1997, p. 803-805, Vol. 63, No. 2. (FULL TEXT in pdf format)

Diversity of soil *Archaea* in boreal forest before, and after clear-cutting and prescribed burning. Jurgens, G. and Saano, A., 1999. FEMS Microbiology Ecology, Vol.29 (June), No.2, pp. 205-213. (FULL TEXT in pdf format)

Molecular phylogeny of Archaea from soil (Scott B. Bintrim, Timothy J. Donohue, Jo Handelsman, Gary P. Roberts, and Robert M. Goodman), Proc. Natl. Acad. Sci. USA Vol. 94, pp. 277-282, Jan. 1997. (FULL TEXT in HTML and pdf formats)

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Wide diversity of Crenarchaeota (Karen L. Hershberger, Susan M. Barns, Anna-Louise Reysenbach, Scott C. Dawson, Norman R. Pace), Nature, vol.384, 5 Dec. 1996.

Elämän puu kolmihaarainen (Teija Peltoniemi), Publications about Archaea isolated from freshwater

> **Jurgens, G., Glöckner, F.-O., Amann, R., Saano, A., Montonen, L., Likolammi, M. and Münster, U. 2000. Identification of novel *Archaea* in bacterioplankton of a boreal forest lake by**

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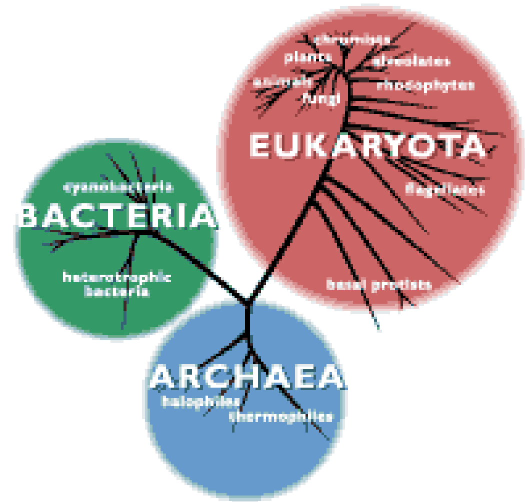

Introduction to the Archaea

Life's extremists. . .

The Domain Archaea wasn't recognized as a major domain of life until quite recently. Until the 20th century, most biologists considered all living things to be classifiable as either a plant or an animal. But in the 1950s and 1960s, most biologists came to the realization that this system failed to accomodate the fungi, protists, and bacteria. By the 1970s, a system of Five Kingdoms had come to be accepted as the model by which all living things could be classified. At a more fundamental level, a distinction was made between the **prokaryotic** bacteria and the four **eukaryotic** kingdoms (plants, animals, fungi, & protists). The distinction recognizes the common traits that eukaryotic organisms share, such as nuclei, cytoskeletons, and internal membranes.

The scientific community was understandably shocked in the late 1970s by the discovery of an entirely new group of organisms -- the Archaea. Dr. Carl Woese and his colleagues at the University of Illinois were studying relationships among the prokaryotes using DNA sequences, and found that there were two distinctly different groups. Those "bacteria" that lived at high temperatures or produced methane clustered together as a group well away from the usual bacteria and the eukaryotes. Because of this vast difference in genetic makeup, Woese proposed that life be divided into three **domains**: Eukaryota, Eubacteria, and Archaebacteria. He later decided that the term Archaebacteria was a misnomer, and shortened it to Archaea. The three domains are shown in the illustration above at right, which illustrates also that each group is very different from the others.

Further work has revealed additional surprises, which you can read about on the other pages of this exhibit. It is true that most archaeans don't look that different from bacteria under the microscope, and that the extreme conditions under which many species live has made them difficult to culture, so their unique place among living organisms long went unrecognized. However, biochemically and genetically, they are as different from bacteria as you are. Although many books and articles still refer to them as "Archaebacteria", that term has been abandoned because they aren't bacteria -- they're Archaea.

Finding Archaea : The hot springs of Yellowstone National Park, USA, were among the first places Archaea were discovered. At left is Octopus Spring, and at right is Obsidian Pool. Each pool has slightly different mineral content, temperature, salinity, etc., so different pools may contain different communities of archaeans and other microbes. The biologists pictured above are immersing microscope slides in the boiling pool onto which some archaeans might be captured for study.

Archaeans include inhabitants of some of the most extreme environments on the planet. Some live near rift vents in the deep sea at temperatures well over 100 degrees Centigrade. Others live in hot springs (such as the ones pictured above), or in extremely alkaline or acid waters. They have been found thriving inside the digestive tracts of cows, termites, and marine life where they produce methane. They live in the anoxic muds of marshes and at the bottom of the ocean, and even thrive in petroleum deposits deep underground.

Some archaeans can survive the dessicating effects of extremely saline waters. One salt-loving group of archaea includes *Halobacterium*, a well-studied archaean. The light-sensitive pigment **bacteriorhodopsin** gives *Halobacterium* its color and provides it with chemical energy. Bacteriorhodopsin has a lovely purple color and it pumps protons to the outside of the membrane. When these protons flow back, they are used in the synthesis of ATP, which is the energy source of the cell. This protein is chemically very similar to the light-detecting pigment **rhodopsin**, found in the vertebrate retina.

Archaeans may be the only organisms that can live in extreme habitats such as thermal vents or hypersaline water. They may be extremely abundant in environments that are hostile to all other life forms. However, archaeans are not restricted to extreme environments; new research is showing that archaeans are also quite abundant in the plankton of the open sea. Much is still to be learned about these microbes, but it is clear that the Archaea is a remarkably diverse and successful clade of organisms.

Click on the four buttons below to learn more about the Archaea.

For even more archaeal information :

- An impressive set of links to all things Archaean may be found at Life in Extreme Environments: Archaea on the Astrobiology Web.
- Get a general introduction to the major groups of prokaryotes from Kenneth Todar at the University of Wisconsin--Madison.
- The Microbe Zoo features several methane-producing organisms, including some Archaea.
- For more information on Halobacteria, including lesson information for teachers, go to The HaloEd Project.

Images of Yellowstone springs courtesy of Norman Pace at the University of Colorado, Boulder.

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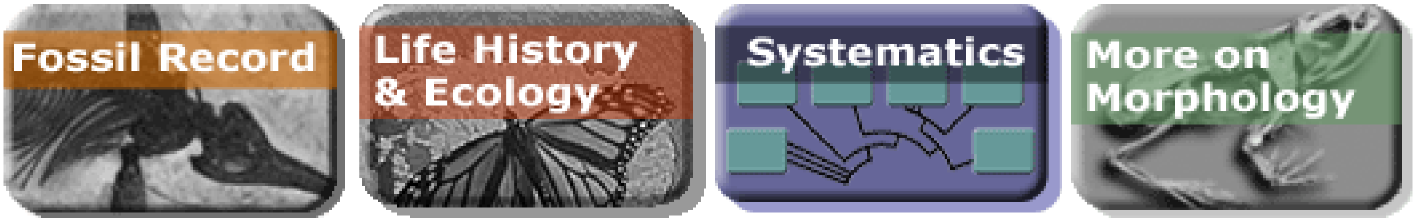
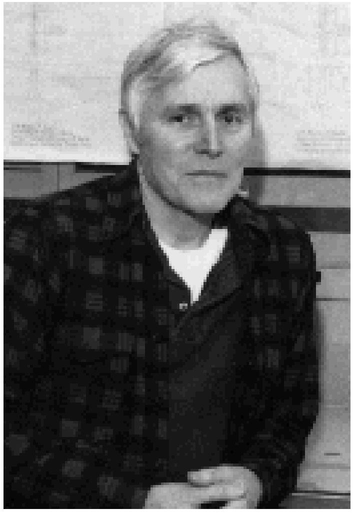


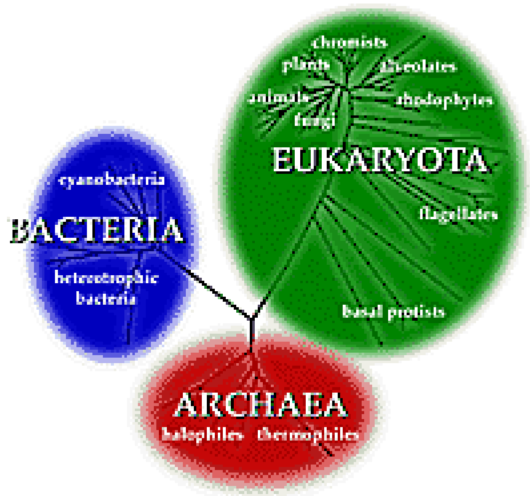
Archaea: Systematics

The Archaea constitute one of the three domains into which all known life may be divided. There are two other domains of life. One of these is the Eukaryota, which includes the plants, animals, fungi, and protists. Except for the protists, these organisms have been known and studied since the time of Aristotle, and are the organisms with which you are most likely familiar. The second domain to be discovered was the Bacteria, first observed in the 17th century under the microscope by people such as the Dutch naturalist Antony van Leeuwenhoek.

The tiny size of bacteria made them difficult to study. Early classifications depended on the shape of individuals, the appearance of colonies in laboratory cultures, and other physical characteristics. When biochemistry blossomed as a modern science, chemical characteristics were also used to classify bacterial species, but even this information was not enough to reliably identify and classify the tiny microbes. Reliable and repeatable classification of bacteria was not possible until the late 20th century when molecular biology made it possible to sequence their DNA.

Molecules of DNA are found in the cells of all living things, and store the information cells need to build proteins and other cell components. One of the most important components of cells is the **ribosome**, a large and complex molecule that converts the DNA message into a chemical product. Most of the chemical composition of a ribosome is **RNA**, a molecule very similar to DNA, and which has its own sequence of building blocks. With sequencing techniques, a molecular biologist can take apart the building block of RNA one by one and identify each one. The result is the **sequence** of those building blocks.



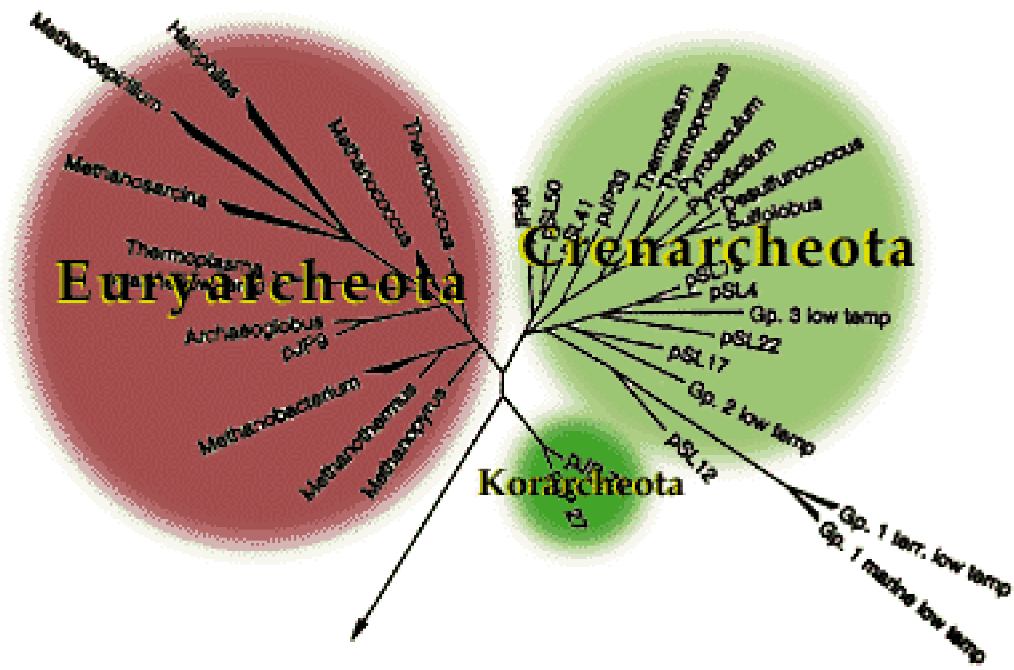


A New Domain : In the late 1970s, Dr. Carl Woese (pictured above at left) spearheaded a study of evolutionary relationships among prokaryotes. Instead of physical characters, he relied on RNA sequences to determine how closely related these microbes were. He discovered that the prokaryotes were actually composed of two very different groups -- the Bacteria and a newly recognized group that he called **Archaea**. Each of these groups is as different from the other as they are from eukaryotes. These three groups are now recognized as three distinct **domains** of life, as shown above at right.

Because ribosomes are so critically important is the functioning of living things, they are not prone to rapid evolution. A major change in ribosome sequence can render the ribosome unable to fulfill its duties of building new proteins for the cell. Because of this, we say that the sequence in the ribosomes is **conserved** -- that it does not change much over time. This slow rate of molecular evolution made the ribosome sequence a good choice for unlocking the secrets of bacterial evolution. By comparing the slight differences in ribosome sequence among a wide diversity of bacteria, groups of similar sequences could be found and recognized as a related group.

In the 1970s, Carl Woese and his colleagues at the University of Illinois at Urbana-Champaign began investigating the sequences of bacteria with the goal of developing a better picture of bacterial relationships. Their findings were published in 1977, and included a big surprise. Not all tiny microbes were closely related. In addition to the bacteria and eukaryote groups in the analysis, there was a third group of methane-producing microbes. These **methanogens** were already known to be chemical oddities in the microbial world, since they were killed by oxygen, produced unusual enzymes, and had cell walls different from all known bacteria.

The significance of Woese's work was that he showed these bizarre microbes were different at the most fundamental level of their biology. Their RNA sequences were no more like those of the bacteria than like fish or flowers. To recognize this enormous difference, he named the group "Archaebacteria" to distinguish them from the "Eubacteria" (true bacteria). As the true level of separation between these organisms became clear, Woese shortened his original name to **Archaea** to keep anyone from thinking that archaeans were simply a bacterial group.



Archaean Phylogeny : The phylogeny of archaeans is based on molecular sequences in their DNA. The analysis of these sequences reveals three distinct groups within the Archaea. The **Euryarcheota** are probably the best known, including many methane-producers and salt-loving archaeans. **Crenarcheota** include those species that live at the highest temperatures of any known living things, though a wide variety have recently been discovered growing in soil and water at more moderate temperatures. The **Korarcheota** are only known from their DNA sequences -- nothing more is known about them yet since they have only recently been discovered.

Since the discovery that **methanogens** belong to the Archaea and not to the Bacteria, a number of other archaeal groups have been discovered. These include some truly weird microbes that thrive in extremely salty water, as well as microbes that live at temperatures close to boiling. Even more recently, scientists have begun finding archaea in an increasing array of habitats, such as the ocean surface, deep ocean muds, salt marshes, the guts of animals, and even in oil reserves deep below the surface of the Earth. Archaea have gone from obscurity to being nearly ubiquitous in only 25 years!

Archaeans have increasingly become the study of scientific investigation. In many ways, archaeal cells resemble the cells of bacteria, but in a number of important respects, they are more like the cells of eukaryotes. The question arises whether the Archaea are closer relatives of the bacteria or our our group, the eukaryotes. This is a very difficult question to answer, because we are talking about the deepest branches of the tree of life itself; we do not have any early ancestors of life around today for comparison. One novel approach used in addressing the question is to look at sequences of **duplicated genes**. Some DNA sequences occur in more than one copy within each cell, presumably because an extra copy was made at some point in the past. There are a very few genes known to exist in duplicate copies in all living cells, suggesting that the duplication happened before the separation of the three domains of life. In comparing the two sets of sequences, scientists have found that the Archaea may actually be more closely related to us (and the other eukaryotes) than to the bacteria.

For more information :

- For current and additional information about the phylogeny of the archaeans visit the root pages of the Tree of Life, housed at the University of Arizona.
- Eight complete archaeal genomes have been sequenced as of April, 2001, and they are available on-line at The Institute for Genomic Research (TIGR).
- Get a general introduction to the major groups of prokaryotes from Kenneth Todar at the University of Wisconsin--Madison.
- Professor Karl Stetter has created a rich gallery of archaean images on-line at the University of Regensburg's Department of Microbiology.
- More pictures of living archaeans can be seen at the Picture Gallery of the Department of Microbiology, University of Nijmegen, in the Netherlands.

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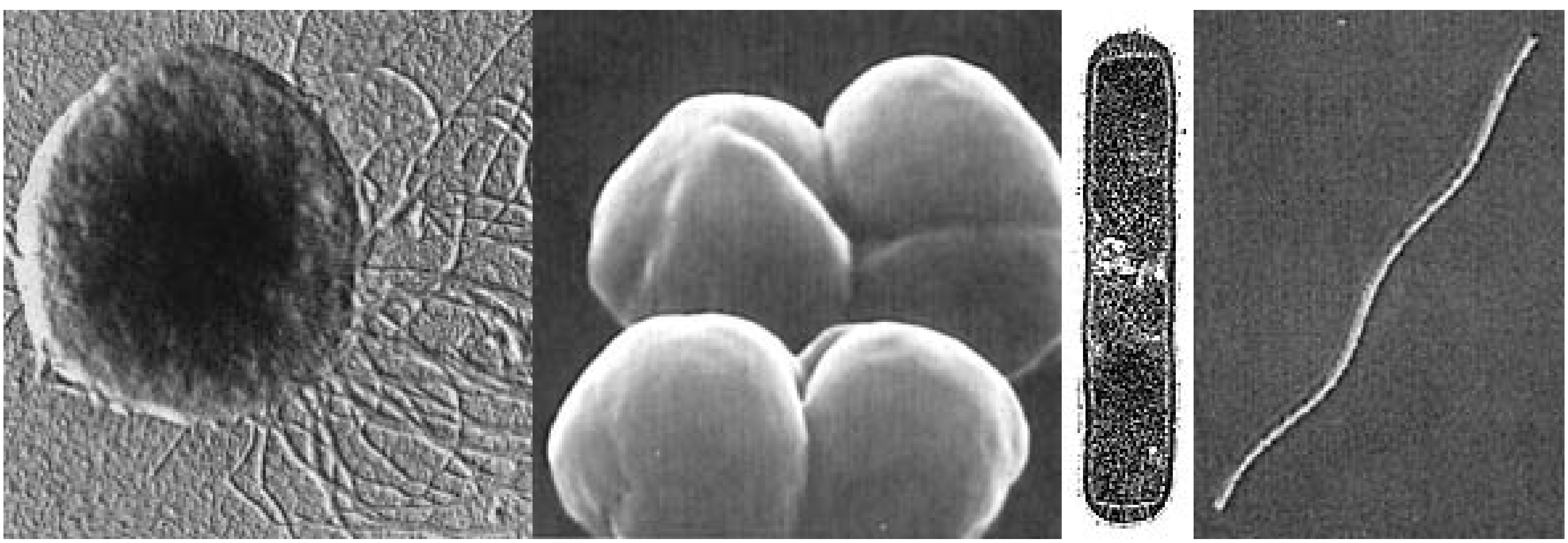
Archaea: Morphology

Archaea are tiny, usually less than one micron long (one one-thousandth of a millimeter). Even under a high-power light microscope, the largest archaeans look like tiny dots. Fortunately, the **electron microscope** can magnify even these tiny microbes enough to distinguish their physical features. You can see archaean images below, made using a variety of micrographic techniques.

You might think that organisms so small would not have much variety of shape or form, but in fact archaeal shapes are quite diverse. Some are spherical, a form known as **coccus**, and these may be perfectly round or lobed and lumpy. Some are rod-shaped, a form known as **bacillus**, and range from short bar-shaped rods to long slender hair-like forms. Some oddball species have been discovered with a triangular shape, or even a square shape like a postage stamp!



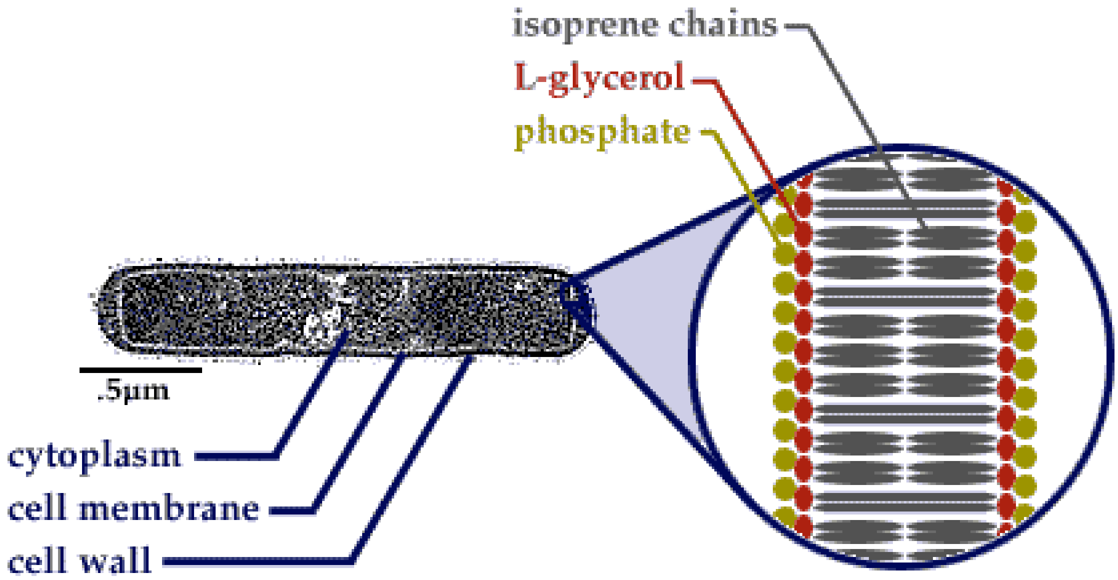
Basic Archaeal Shapes : At far left, *Methanococcus janaschii*, a **coccus** form with numerous flagella attached to one side. At left center, *Methanosarcina barkeri*, a lobed coccus form lacking flagella. At right center, *Methanothermus fervidus*, a short **bacillus** form without flagella. At far right, *Methanobacterium thermoautotrophicum*, an elongate bacillus form.

Structural diversity among archaeans is not limited to the overall shape of the cell. Archaea may have one or more **flagella** attached to them, or may lack flagella altogether. The flagella are hair-like appendages used for moving around, and are attached directly into the outer membrane of the cell. When multiple flagella are present, they are usually attached all on one side of the cell. Other appendages include protein networks to which the cells may anchor themselves in large groups.

Like bacteria, archaeans have no internal membranes and their DNA exists as a single loop called a **plasmid**. However, their tRNAs have a number of features that differ from all other living things. The **tRNA** molecules (short for "transfer RNA") are important in decoding the message of DNA and in building proteins. Certain features of tRNA structure are the same in bacteria, plants, animals, fungi, and all known living things -- except the Archaea. There are even features of archaeal tRNA that are more like eukaryotic critters than bacteria, meaning that Archaea share certain features in common with you and not with bacteria. The same is true of their **ribosomes**, the giant processing molecules that assemble proteins for the cell. While bacterial ribosomes are sensitive to certain chemical inhibiting agents, archaeal and eukaryotic ribosomes are not sensitive to those agents. This may suggest a close relationship between Archaea and eukaryotes.

As with other living things, archaeal cells have an outer **cell membrane** that serves as a barrier between the cell and its environment. Within the membrane is the **cytoplasm**, where the living functions of the archeon take place and where the DNA is located. Around the outside of nearly all archaeal cells is a **cell wall**, a semi-rigid layer that helps the cell maintain its shape and chemical equilibrium. All three of these regions may be distinguished in the cells of bacteria and most other living things, but when you take a closer look at each region, you find that the similarities are merely structural, not chemical.

In other words, Archaea build the same structures as other organisms, but they build them from different chemical components. For instance, the cell walls of all bacteria contain the chemical **peptidoglycan**. Archaeal cell walls do not contain this compound, though some species contain a similar one. Likewise, archaea do not produce walls of cellulose (as do plants) or chitin (as do fungi). The cell wall of archaeans is chemically distinct.



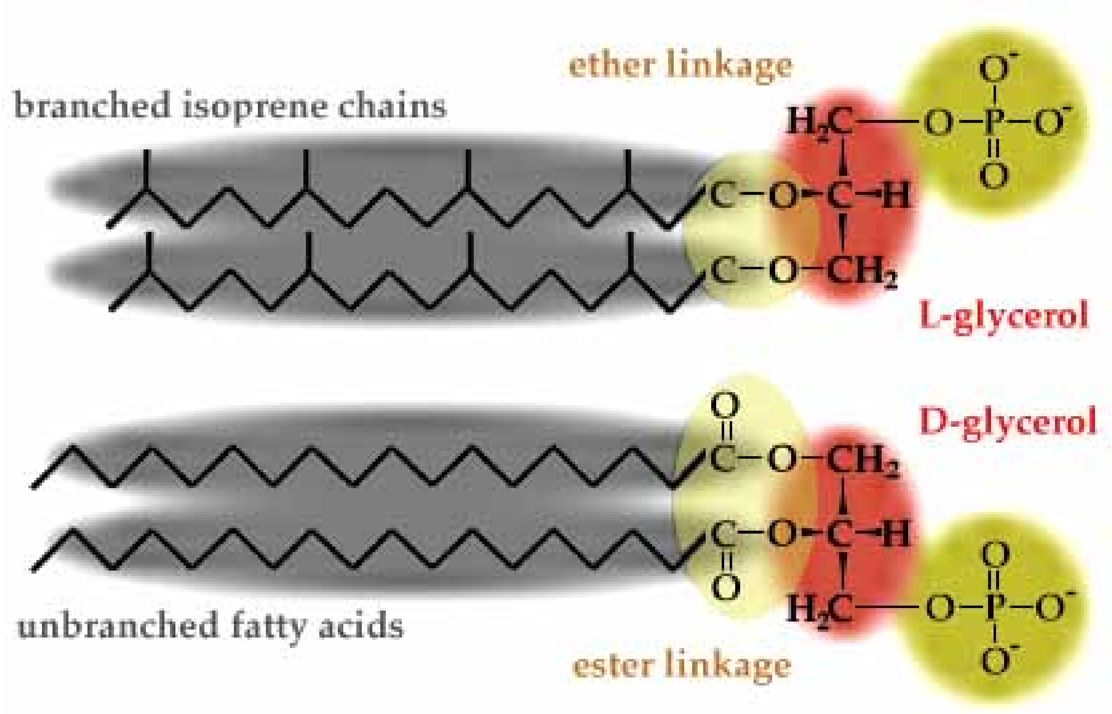
Basic Archaeal Structure : The three primary regions of an archaeal cell are the cytoplasm, cell membrane, and cell wall. Above, these three regions are labelled, with an enlargement at right of the cell membrane structure. Archaeal cell membranes are chemically different from all other living things, including a "backwards" glycerol molecule and isoprene derivatives in place of fatty acids. See text below for details.

The most striking chemical differences between Archaea and other living things lie in their cell membrane. Their are four fundamental differences between the archaeal membrane and those of all other cells: (1) chirality of glycerol, (2) ether linkage, (3) isoprenoid chains, and (4) branching of side chains. These may sound like complex differences, but a little explanation will make the differences understandable. The header for each explanation is color-coded to match the relevant portion of the diagram below.

(1) Chirality of glycerol : The basic unit from which cell membranes are built is the **phospholipid**. This is a molecule of glycerol which has a phosphate added to one end, and two side chains attached at the other end. When the cell membrane is put together, the glycerol and phosphate end of the molecules hang out at the surface of the membrane, with the long side chains sandwiched in the middle (see illustration above). This layering creates an effective chemical barrier around the cell and helps maintain chemical equilibrium.

The glycerol used to make archaeal phospholipids is a **stereoisomer** of the glycerol used to build bacterial and eukaryotic membranes. Two molecules that are stereoisomers are mirror-images of each other. Put your hands out in front of you, palms up. Both hands are oriented with fingers pointing away from you, wrists toward you, and with palms upwards. However, your thumbs are pointing different directions because each hand is a mirror image of the other. If you turn one hand so that both thumbs point the same way, that one will no longer be palm-up.

This is the same situation as the stereoisomers of glycerol. There are two possible forms of the molecule that are mirror images of each other. It is not possible to turn one into the other simply by rotating it around. While bacteria and eukaryotes have **D-glycerol** in their membranes, archaeans have **L-glycerol** in theirs. This is more than a geometric difference. Chemical components of the cell have to be built by **enzymes**, and the "handedness" (**chirality**) of the molecule is determined by the shape of those enzymes. A cell that builds one form will not be able to build the other form.



(2) Ether linkage : When side chains are added to the glycerol, most organisms bind them together using an **ester linkage** (see diagram above). The side chain that is added has two oxygen atoms attched to one end. One of these oxygen atoms is used to form the link with the glycerol, and the other protrudes to the side when the bonding is done. By contrast, archaeal side chains are bound using an **ether linkage**, which lacks that additional protruding oxygen atom. This gives the resulting phospholipid different chemical proerties from the membrane lipids of other organisms.

(3) Isoprenoid chains : The side chains in the phospholipids of bacteria and eukaryotes are **fatty acids**, chains of usually 16 to 18 carbon atoms. Archaea do not use fatty acids to build their membrane phospholipids. Instead, they have side chains of 20 carbon atoms built from **isoprene**.

Isoprene is the simplest member of a class of chemicals called **terpenes**. By definition, a terpene is any molecule bilt by connecting isoprene molecules together, rather like building with Lego® blocks. Each isoprene unit has a "head" and a "tail" end (again like a Lego® block), but unlike their toy counterparts, isoprene blocks can be joined in many ways. A head can be attached to a tail or to another head end, and tails can be similarly joined. The immense variety of terpene compounds that can be built from simple isoprene units include beta-carotene (a vitamin), natural and synthetic rubbers, plant essential oils (such as spearmint), and steroid hormones (such as estrogen and testosterone).

(4) Branching of side chains : Not only are the side chains of achaeal membranes built from different components, but the chains themselves have a different physical structure. Because isoprene is used to build the side chains, there are side branches off the main chain (see diagram above). The fatty acids of bacteria and eukaryotes do note have these side branches (the best they can manage is a slight bend in the middle), and this creates some interesting properties in archaeal membranes.

For example, the isoprene side chains can be joined together. This can mean that the two side chains of a single phospholipid can join together, or they can be joined to side chains of another phospholipid on the *other side* of the membrane. No other group of organisms can form such **transmembrane** phospholipids.

Another interesting property of the side branches is their ability to form **carbon rings**. This happens when one of the side branches curls around and bonds with another atom down the chain to make a ring of five carbon atoms. Such rings are thought to provide structural stability to the membrane, since they seem to be more common among species that live at high temperatures. They may work in the same way that **cholesterol** does in eukaryotic cells to stabilize membranes. It's interesting to note that cholesterol is another terpene!

For more information :

- An impressive set of links to all things Archaean may be found at Life in Extreme Environments: Archaea on the Astrobiology Web.
- Or get a general introduction to the major groups of prokaryotes from Kenneth Todar at the University of Wisconsin--Madison.
- Professor Karl Stetter has created a rich gallery of archaean images on-line at the University of Regensburg's Department of Microbiology.
- More pictures of living archaeans can be seen at the Picture Gallery of the Department of Microbiology, University of Nijmegen, in the Netherlands.

Images of *Methanobacterium* and *Methanosarcina* courtesy the Dept. of Microbiology, University of Nijmegen, and used with permission. Images of *Methanococcus* and *Methanothermus* kindly provided by Dr. Karl O. Stetter at the University of Regensberg, Germany.

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