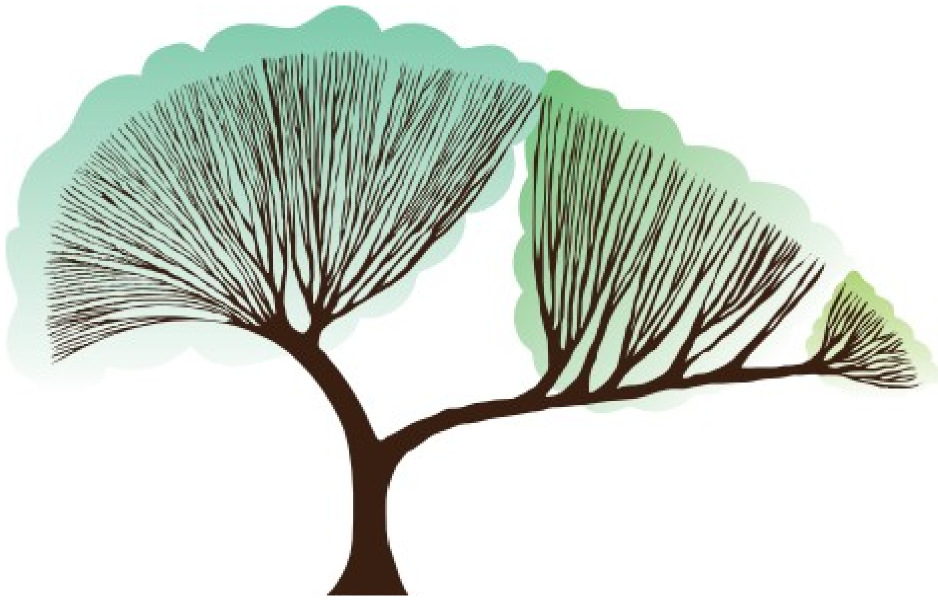
Archaea:
what are and why are they important?

Granny: what is the difference between archaic and archaea?
Do they both mean old?



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Nature Microbiology, 2016 Apr 26;1:16056. doi: 10.1038/nmicrobiol.2016.56.

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Archaea: what are and why are they important?

Storyline

There are three major forms or domains of life on Earth today: the Archaea, Bacteria and Eukaryotes. Of these, the Archaea have been discovered most recently and have traditionally been the least investigated. However, research during the past years has shown that Archaea have played a very important role in the evolution of the life on Earth: indeed, it seems that eukaryotic cells, that is the cells that make up our bodies, have evolved through the close interaction of certain Archaea and Bacteria. In addition, Archaea – originally thought to be restricted to 'extreme' environments – are now known to be widely distributed all around the world and to play important roles in the cycling of nutrients and climate change gases. Finally, it has become clear, that Archaea are living both on and in human bodies; however, their role in human health and disease remains a puzzle to be solved by curious students and scientists. Much has to be learned about the Archaea. So, let's begin.

The Microbiology and Societal Context

The microbiology: living organisms and cells, overview of the different major life forms, the discovery of the Archaea as a separate form or life, the role of Archaea in the origin of eukaryotic life which includes us humans, the role of archaea in their natural environments, the importance of archaea for the production and consumption of climate change gases, the role of Archaea in and on the human body, archaea and human health and disease. *Sustainability issues:* nutrient cycles, green-house gases, environmental pollution and climate change; ruminant contribution to global warming, health and disease, novel enzymes of industrial importance.

Archaea: the Microbiology

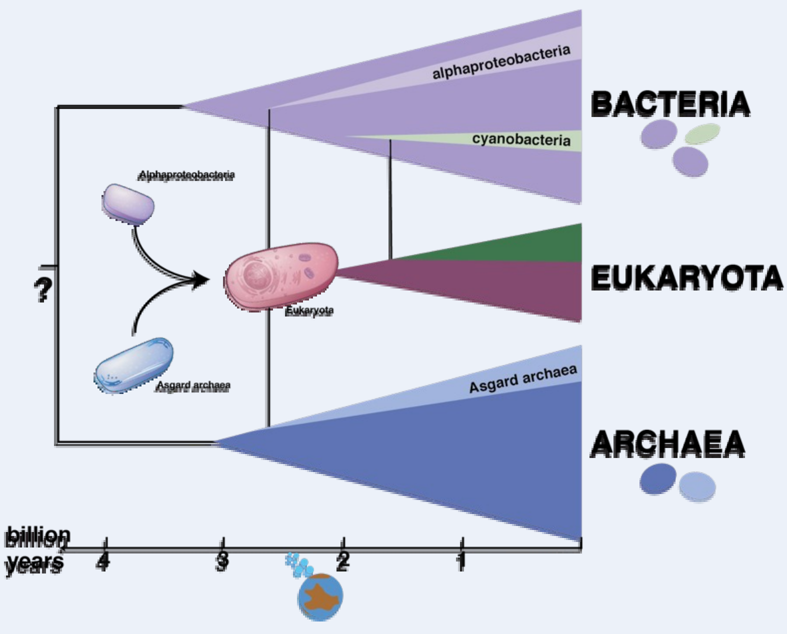
1. ***How do archaeal cells look and which other cells are there?*** Microbial life on our planet, while invisible to our eyes, is extremely diverse. In fact, it is thought that there are more microbial **cells** on Earth than there are stars in the Universe. All of this microbial life has evolved from a common ancestor, but comprises different major lineages. One of these are the **Archaea** (named after the Greek word 'archaía', which means ancient). Archaea are **unicellular** organisms consisting of small cells with genetic material and proteins, that are enclosed by a membrane and sometimes a cell wall. Indeed, under the microscope, archaeal cells look exactly like **Bacteria** and, from their appearance, it is impossible to tell them apart. And yet, Archaea are very different from Bacteria and form their own branch (or domain) in the **tree of life** just like Bacteria do (**Box 1**). So how do they differ? When scientists started to look at archaeal cells more closely, it became clear that the chemical composition of the cell membranes and cell walls of Archaea and Bacteria are distinct. In addition, the cellular machineries for the duplication of chromosomes, the production of **proteins,** and **cell division** differ between Archaea and Bacteria. Curiously, the cellular machineries of Archaea are much more similar to those of eukaryotes. Now you will wonder: but who are the eukaryotes? **Eukaryotes** are organisms that consist of eukaryotic cells and comprise **unicellular** protists and algae but also **multicellular** plants, fungi and animals, including us humans. And all these eukaryotic cells look different from archaeal and bacterial cells because they contain many small sub-compartments (or **organelles**) surrounded by their own membranes. For example, eukaryotic cells have a **nucleus** that encloses the genetic material. They also have so-called **mitochondria**, which fuel the cells with energy and resemble bacterial cells. When you look at eukaryotic cells under the microscope, you can not only see that they are more complex; it even seems as if there are smaller bacterial cells inside the bigger eukaryotic cells.

And yet, many of the molecular machineries of eukaryotic cells are similar to those of the Archaea. How can this be?

2. ***Are we Archaea?*** Have you ever wondered about where humans come from? Because this is not a stupid question: many scientists are trying to understand how humans and other Eukaryotes came to be, that is how the complex eukaryotic cells that, for example, make up our bodies have originated. One of the most common explanations is that at some point in time, probably as far back as 2 billion years ago, there were some archaea (perhaps related to the so called **Asgard archaea**) and some bacteria (related to the **Alphaproteobacteria**) that lived closely together. At some point the archaeal cells might have surrounded the bacterial cells and kept them inside until a new type of cell evolved. This new cell had certain archaeal features, but also harboured tiny bacterial cells that provided energy for growth (**Box 1**). Over time, the bacteria became smaller and formed the **mitochondria** of eukaryotic cells. And the **genome** of the eukaryotic cell became much bigger, had **genes** from both the ancestral Archaea and Bacteria and was surrounded by its own membrane. Some of these eukaryotic cells took up other bacteria (so called blue-green algae or **cyanobacteria**), that helped to use sunlight for energy. And some of the unicellular eukaryotic cells evolved into multicellular organisms including plants, animals and humans. In this way, we humans are a bit “Archaea” and a bit “Bacteria”: our cells contain traces of both organisms. And you can see how important these little microbes have been in the evolutionary history of multicellular life! Without them, we would never have come to be! But microbes have not only been important in the past. Archaea and Bacteria are all around us and inhabit all most environments that you can find on Earth.

Box 1

A depiction of the tree of life.
Archaea and Bacteria from two primary domains of life that evolved from a common ancestor many billion years ago. The cells of both archaea and bacteria are unicellular and do not contain compartments. In contrast, eukaryotes, which include both unicellular protists and algae but also multicellular organisms such as plants, fungi, and animals including us humans have likely evolved later. In fact, the prevailing theory suggests that eukaryotic cells evolved from a symbiosis between an archaeaon or a sister-group of archaea and a bacterium. Therefore, both Bacteria but also the much lesser studied Archaea are very important for our understanding of the evolution of life on Earth.

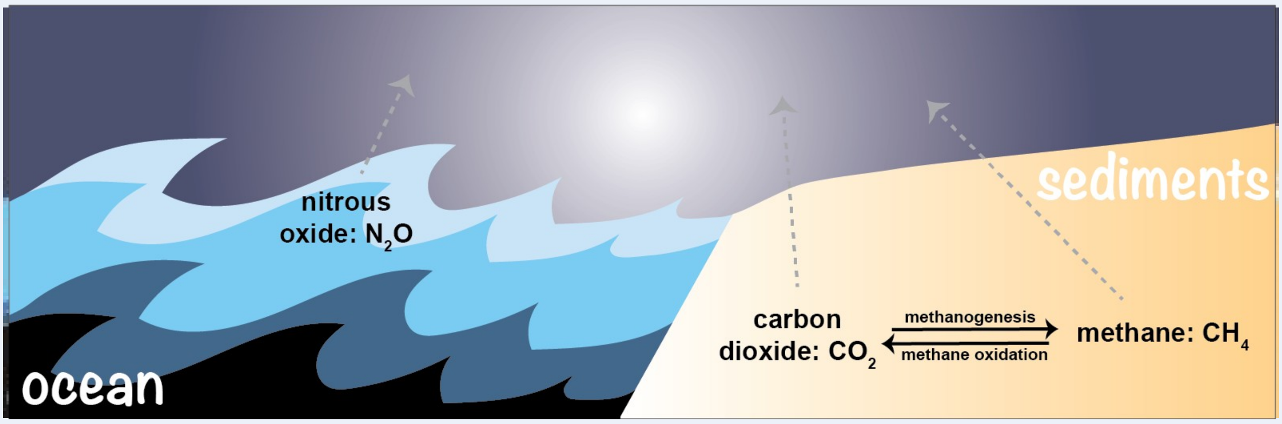


3. ***Where do the Archaea live and what are they doing and eating?*** While Bacteria have been known for a long time, Archaea were only discovered in the 1970’s by Carl Woese and his co-workers. Originally, it was thought that Archaea are not very important because they were often found in environments that may seem extreme to us humans: for example, some of the first described archaea were found in places with very high salinity, such as in salt lakes, while others were found in thermally

heated places including the **hot springs** of Iceland or Yellowstone National Park and **hydrothermal vents** in the deep ocean. For example, some Archaea can only grow at temperatures above 100°C and the archaeal record holder, *Methanopyrus kandleri*, prefers a growth temperature of 122°C. This is extremely curious and led to new insights into the limits of life and the discovery of new enzymes that function at extremely high temperatures and are useful for humans. However, initially it was unclear whether Archaea also occur in 'normal' environments, i.e. the environments that we inhabit and use and, if so, whether Archaea are important players in **nutrient cycles**. The earliest insights into these questions came from the study of the so-called **methanogenic** archaea, i.e. archaea that eat **hydrogen** and **carbon dioxide** and produce the extremely potent climate change gas **methane** (**Box 2**). This type of metabolism is not present in any Bacteria or Eukaryotes and therefore unique to methanogenic Archaea, which occur in most anoxic environments on Earth, including marine and lake water sediments, paddy fields, peatlands, as well as in animals. Did you ever hear that cows contribute to the release of methane and therefore to climate warming? In fact, the cows do not produce the methane themselves – instead, methanogenic archaea living inside the rumen of the cows are responsible for the production and release of methane. During recent years, many more archaea have been discovered in soils, lakes and the ocean, and it has become increasingly clear, that these unicellular organisms play many important roles in the environment: for example, Archaea abundant in marine waters contribute to the cycling of **nitrate** and the production of **nitrous oxide** (**Box 2**), another gas affecting our climate. But not all archaea are "bad": in fact, some archaea in marine sediments, are able to use methane for growth (rather than producing it) and thereby reduce the escape of this climate gas to the atmosphere.

Box 2

A depiction of the role of archaea in the environment. Archaea can be found in almost all environments on Earth and include important players in nutrient cycles by contributing to the production and consumption of climate gases to the atmosphere



4. Can Archaea make us sick? Do you remember your last cold or that nasty flu that made you stay in bed feeling miserable? This was either caused by an infection with bacteria or viruses. As you may have heard, while Bacteria and Archaea are cellular life forms that can live independently, viruses need a **host** cell to survive. In particular, viruses infect either Bacteria, Archaea or Eukaryotes including us humans, and are therefore also referred to as **parasites**. But while Bacteria, Archaea and Eukaryotes can live independently, some Bacteria and Eukaryotes can also be parasitic and make us humans sick. But until today, it is unclear, whether there are real archaeal **parasites** out there. During the past years, archaea have been found to live on human skin as well as inside our bodies. For example, some methanogenic archaea are present in the human mouth and may be involved in the development of tooth decay. Recently, archaea have even been found in the lungs of humans. However, so far we do not know what these archaea are doing and whether they are important for our health or involved in disease. Much has to be learned about these organisms.

Potential Implications for Decisions

What do we not currently know that is important for future policy/behaviour? Recently, many new groups of Archaea have been discovered in all environments on Earth including in soils, sediments, lakes, the ocean as well as associated with plants, animals and humans. Yet, we still know extremely little about the function of all these Archaea: how do they affect other organisms, the cycling of nutrients and climate change? And are there true archaeal **pathogens** out there: Archaea that make us sick? It is already clear that archaea living in the rumen of cows negatively affect our climate due to the production of large amounts of methane, while others help to reduce the release of methane to the atmosphere. Some of the examples described above, as well as the lack of knowledge regarding archaea, make clear that we all need to pay much more attention to this relatively little investigated domain of life! Archaea have not only been important in the past and in the origin of eukaryotes but play important roles in the environment: they are all around us and we need to understand what they are doing so that we can make better choices for us and our planet.

The evidence base, further reading and teaching aids

Videos:
Archaea and the tree of life: < https://www.youtube.com/watch?v=hw-ij3822DY>
Education:
What is a cell? <https://www.nature.com/scitable/topicpage/what-is-a-cell-14023083/>
Archaea and the meaning of life: <https://microbiologysociety.org/publication/past-issues/what-is-life/article/archaea-and-the-meaning-of-life-what-is-life.html>
The Two Empires and Three Domains of Life in the Postgenomic Age:
<https://www.nature.com/scitable/topicpage/the-two-empires-and-three-domains-of-14432998/>
Literature
Offre, P., Spang, A. and Schleper, C. Archaea in biogeochemical cycles. *Annu Rev Microbiol*. 2013;67:437-457. doi:10.1146/annurev-micro-092412-155614
Spang, A., Caceres, E.F. and Ettema, T.J.G. Genomic exploration of the diversity, ecology, and evolution of the archaeal domain of life. *Science. 2017;357(6351):eaaf3883*. doi:10.1126/science.aaf3883

Glossary

Asgard archaea. A recently discovered group of Archaea, which is more closely related to eukaryotes than any other so far known archaeal lineage. It is possible that Asgard archaea once interacted with Alphaproteobacteria and together gave rise to eukaryotes.
Alphaproteobacteria. A group of Bacteria which is thought to have given rise to the mitochondria, the small organelles within eukaryotic cells that are responsible for providing energy for growth.
Carbon dioxide, CO_2. An important trace gas in the atmosphere. Can be used as food source by some organisms (e.g. by plants, algae and certain Archaea and Bacteria,), while it is a waste product of other organisms (e.g. Archaea, Bacteria, animals including us humans, etc).

Cells. Are the small structural units of organisms. All cellular life is comprised of cells that contains genetic material with the information for growth and replication. See also: <https://www.nature.com/scitable/topicpage/what-is-a-cell-14023083/>
Cyanobacteria. A group of Bacteria whose members are able to get energy for their living from sunlight through the process called photosynthesis. Some early eukaryotic cells have taken up cyanobacterial cells, that allowed these eukaryotes to use sun light for growth as well. For examples, algae and plants, which live from the energy of sunlight, have tiny remnants of cyanobacteria within their cells.
Genes. A DNA sequence that encodes the information of a gene product, i.e. RNA or a protein. Proteins consist of amino acids, carry out metabolic reactions in the cell, and are responsible for the functions characterizing an organism.
Hydrogen, H_2. A gas which represents an important food source for microbial organisms, especially in environments with little or no oxygen such as in sediments.
Hydrothermal vents. Crack or fissure in the seafloor with up-flow of thermally heated water/fluids.
Hot springs. Springs filled with thermally-heated groundwater.
Methane. A gas found in traces in the atmosphere, which has a strong greenhouse effect. It can be used as food source by some organisms and represents an important waste product of methanogenic archaea.
Methanogenic. Archaea that can use carbon dioxide and H_2 (or other compounds) as food source while producing methane as waste product.
Mitochondria. Membrane bound organelles/compartments inside eukaryotic cells, which are thought to be derived from Bacteria. They function as the "powerhouse " or engine of eukaryotic cells, i.e. they provide eukaryotic cells with the energy needed for growth.
Multicellular. Organisms consisting of many cells, all with the same genetic information.
Nitrous oxide. Commonly known as laughing gas and an important greenhouse gas besides methane and carbon dioxide. Produced by some Archaea and Bacteria as a waste product.
Nucleus. Another membrane-bound organelle of eukaryotic cells, which contains the genetic material in form of a genome. Most eukaryotic cells have one nucleus (but several mitochondria).
Nutrient cycles. The recycling of substances containing certain key elements (such as nitrogen, carbon and sulfur) in the environment. For example, In the carbon cycle, carbon dioxide is converted into organic compounds (e.g. sugars) by the activity of certain organisms (e.g. plants, algae, Bacteria and Archaea). Other organisms can use these organic compounds as food sources and convert them back to CO_2.
Organelles. A specialized subunit or compartment within a cell, which is usually enclosed by a membrane of its own.
Parasite. A symbiont, that has negative effects on its host organism, like for example a virus or bacterium that causes harm for the host organism.
Pathogen. Any parasite that can cause disease.
Protein. Large molecule that consists of different amino acids arranged in a specific sequence that is dictated by its gene. All the genes of the cell are organized in chromosomes and collectively make up the cell's genetic information or genome. The different proteins of an organism determine its function and biology. For example, there are structural proteins that are used to build the cell, while others are enzymes that carry out cellular reactions that metabolise food sources or replicate the genome etc.
Replication. Process in which the genetic material or genome of an organism or virus gets copied. When cells divide, each cell inherits one of the two copies.
Rumen. Part of the first chamber in the digestive tract of certain animals such as cattle and sheep.
Symbiont. An organism living in a symbiotic relationship, i.e. in a long-term interaction with another organism of a different kind. When both partners have a positive effect from the symbiotic interaction,

the relationship is mutualistic. However, if only one partners profits and causes harm to the other partner, the interaction is parasitic.

Tree of life. A tree that depicts the relationship of all living cellular organisms to each other.

Unicellular. Organisms consisting only of one cell