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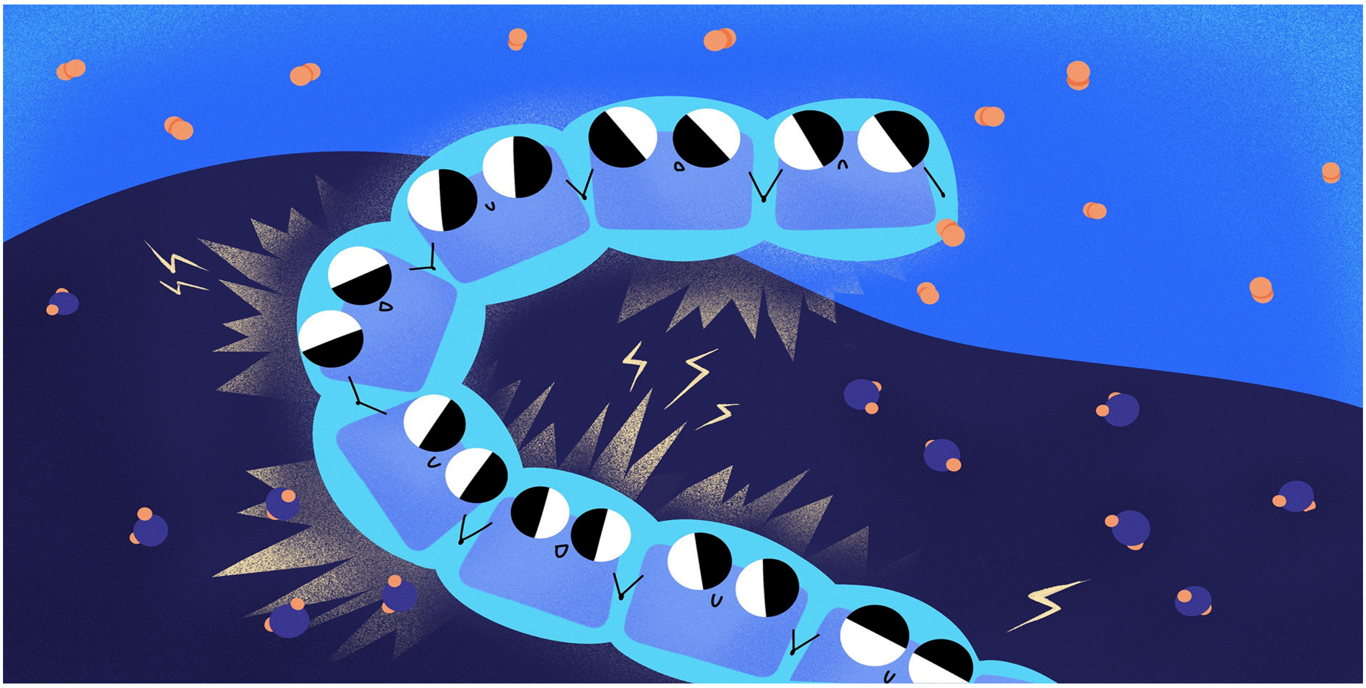
Published: 06 December 2023
doi: 10.3389/frym.2023.978226



CABLE BACTERIA GET ENERGY THROUGH ELECTRICAL TEAMWORK

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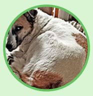

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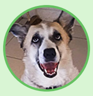

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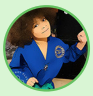

SORA
AGE: 8

Cable bacteria are very different from most other bacteria. First of all, they are multicellular, and each cable bacterium has tens of thousands of cells connected in a chain called a filament that can be several centimeters long. What makes cable bacteria really special is the way they get the energy they need for living: the cells within a filament have to work together to generate energy, and this involves electricity! In this article, we will describe these fascinating bacteria and tell you about recent research that shows how the cells within a filament work together.

WE ALL GET ENERGY FROM ELECTRONS

Animals need to eat and breathe oxygen to keep their **metabolism** going and stay alive. In your body, part of the food you eat turns into

METABOLISM

All chemical processes necessary for an organism to stay alive, including the conversion of food to energy required for running cellular processes.

glucose, a special kind of sugar that provides energy to your cells. You basically have millions and millions of little power plants inside the cells of your body. In your cells, glucose **molecules** give away electrons, which are eventually given to oxygen molecules. This process gives you the energy you need to breathe, think, run, jump, and do all the other things you like to do.

Inside your cells, electrons are transferred from one place to another and, by doing so, **electricity** is generated. Electricity is simply the movement of electrons. In all living cells, electrons are transferred from molecules that give electrons away (like glucose) to molecules that take electrons (like oxygen), so you can say that cells generate electricity (Figure 1). In most living cells, electricity is generated on a very small scale. Electrons travel across very small distances of only a few nanometers (nm; one nanometer is one million times smaller than a millimeter).

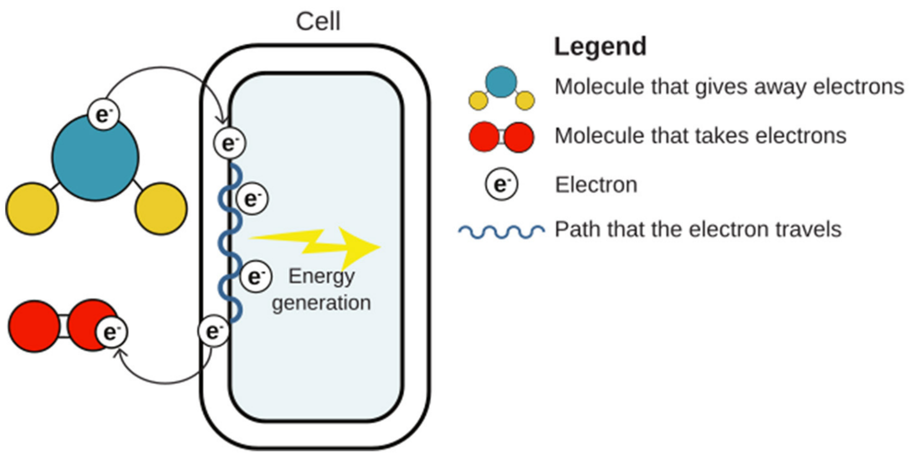

Figure 1

For a long time, biologists thought that all living cells took care of their own energy demands. They also believed that electrons in cells could only travel across very short distances [1]. However, these ideas were challenged by the discovery of cable bacteria and their strange metabolism, back in 2012.

WHAT ARE CABLE BACTERIA?

Bacteria live just about everywhere on Earth, including the air, soils, rivers, lakes, oceans, seafloor, as well as in and on the bodies of animals, including humans. Cable bacteria are a unique kind of bacteria that live in the **sediment** at the bottom of oceans and lakes. Cable bacteria are different from most bacteria in three ways:

MOLECULE

A molecule is the smallest unit of a substance that has all the properties of that substance. For instance, each glucose molecule has the same properties.

ELECTRICITY

Electricity is a form of energy where tiny charged particles called electrons move around. When electrons move, they carry energy from one place to the another.

Figure 1

In most cells, electrons are taken from a molecule that can give away electrons (such as glucose), transported within the cell across short distances (about 10 nanometers), and ultimately given to another molecule that can take these electrons (such as oxygen). This is how these cells generate energy. In this way, each cell takes care of its own energy needs.

SEDIMENTS

Naturally occurring solid material found at the bottom of lakes and oceans.

Cable Bacteria Are Multicellular and Very Long

While most bacteria have only one cell, cable bacteria have thousands of cells connected to each other in a long chain called a **filament**. Cable bacteria are therefore multicellular, meaning that they have multiple cells that work together. A cable bacteria filament can be up to a few centimeters long, which is enormous for bacteria. However, because the filaments are very thin, between 1 and 5 micrometer (μm; a micrometer is one thousand times smaller than a millimeter), we must use specialized microscopes to spot them (Figures 2A–C).

FILAMENT

Long string of cells that are attached to one another, thus forming a multicellular bacterium.

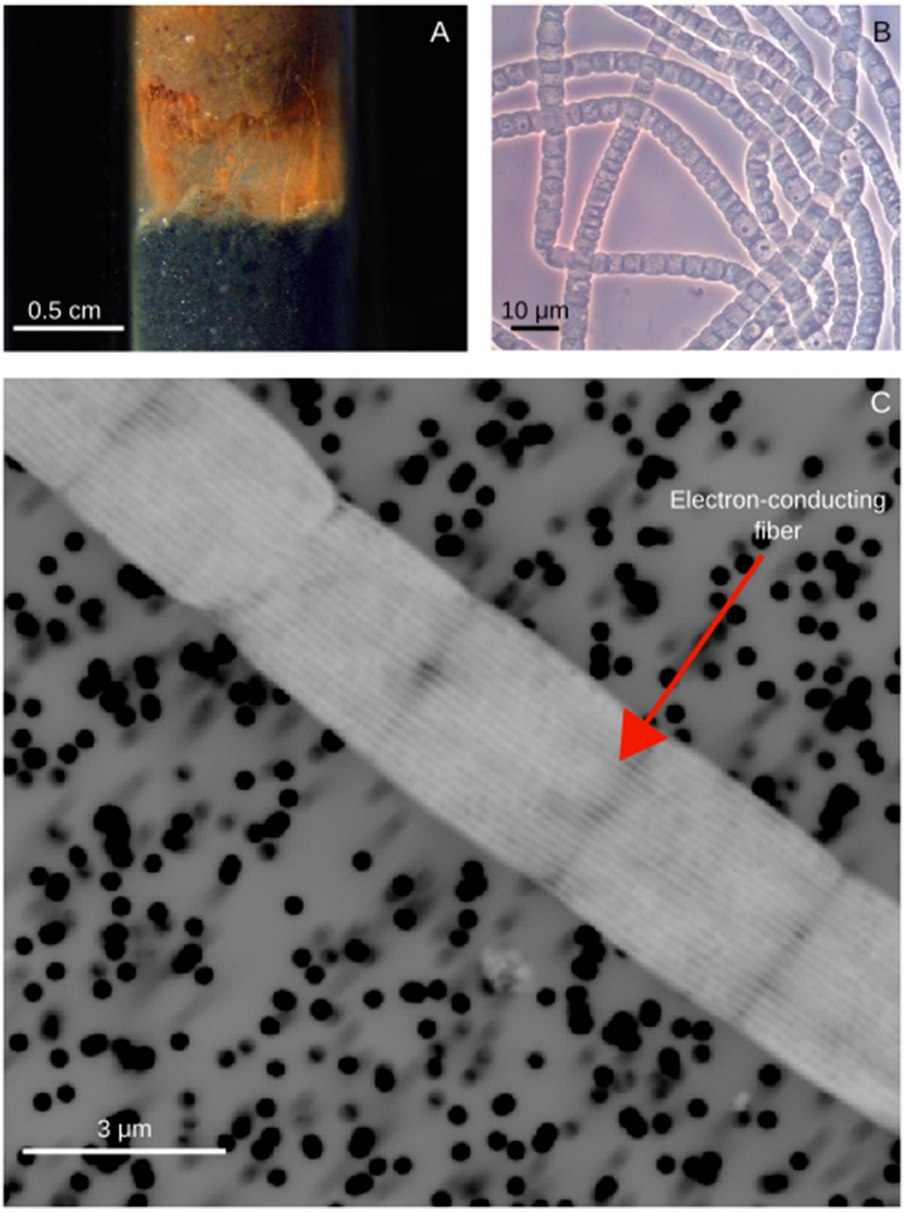

Figure 2

Figure 2

(A) Filaments of cable bacteria stretching between sediment layers that are separated from each other. **(B)** Image taken with a light microscope, showing a bundle of cable bacteria filaments. **(C)** Image taken with an electron microscope showing the electricity-conducting fibers. The red arrow points to an electron-conducting fiber [Images were kindly provided by Nils Risgaard-Petersen and Lars Peter Nielsen **(A)** and Silvia Hildalgo-Martinez **(B)**].

Cable Bacteria Transport Electrons Over Long Distances

When using a light microscope like those that you may have at school, cable bacteria look like a cable (Figure 2B). However, by using an

ELECTRON MICROSCOPE

A microscope that uses a beam of electrons to see tiny objects like bacteria.

RESOLUTION

Within microscopy, the term resolution is used to describe the ability of a microscope to zoom in and see tiny details of the things you are looking at.

HYDROGEN SULFIDE

An energy-rich molecule that cable bacteria use as "food" to get energy for living and growing. Hydrogen sulfide can give electrons to the fibers in cable bacteria filaments.

electron microscope, which has a higher **resolution**, we can see parallel fibers running along each filament and connecting the cells to each other (Figure 2C) [1, 2]. These fibers serve as wires transporting electrons among the cells within the filament [3]. Because cable bacteria can be several centimeters long, they can transport electrons across distances that are more than 10 million times larger than in other bacteria [2]. This ability makes them the world champions of electron transport in the microbial world. How amazing is this?

We still do not know what the fibers transporting the electrons are made of. We do know, however, that they transport electrons very rapidly and efficiently, like a copper wire. These properties raised the attention of many scientists who are now investigating cable bacteria. So, maybe in the future, we can use cable bacteria to make environmentally friendly electronic devices [3].

Cable Bacteria Have Cells That Work Together

In most living cells, the transfer of electrons happens within a single cell and not across multiple cells. So normally, each cell is responsible for its own energy generation to survive and grow, even in multicellular organisms. It was a big surprise for biologists when they found that cells in cable bacteria must work together to generate energy! Like us, cable bacteria use oxygen, but they do not eat the same food we do. Instead of using glucose as their source of energy, cable bacteria use a molecule called **hydrogen sulfide**. In the sediment where cable bacteria live, hydrogen sulfide and oxygen are not present at the same location. The hydrogen sulfide is buried in the sediment, away from the oxygen that is present at the top of the sediment.

In cable bacteria, the electrons are taken from hydrogen sulfide. Then, the electrons are given to the electricity-conducting fibers, and they then move upward via these fibers to cells that are in contact with oxygen in the surface of the sediment. These surface cells take the electrons and give them to oxygen (Figure 3).

UNIQUE ENERGY GENERATION

What is so unique about cable bacteria is that all cells within a filament must work together to generate energy [2]. This sort of "electrical teamwork" between cells has not been observed before, not even in other multicellular organisms. This teamwork gives cable bacteria an advantage, because it allows them to live in an environment where the resources are separated in space [1, 2]. Therefore, cable bacteria are found in many locations around the world and when they are present, there are a lot of them. For example, there can be up to 20,000 km of cable bacteria filaments per square meter of sediment [1].

Although cells within a cable bacteria filament must work together, the energy generated by this teamwork is not divided equally. Surprisingly,

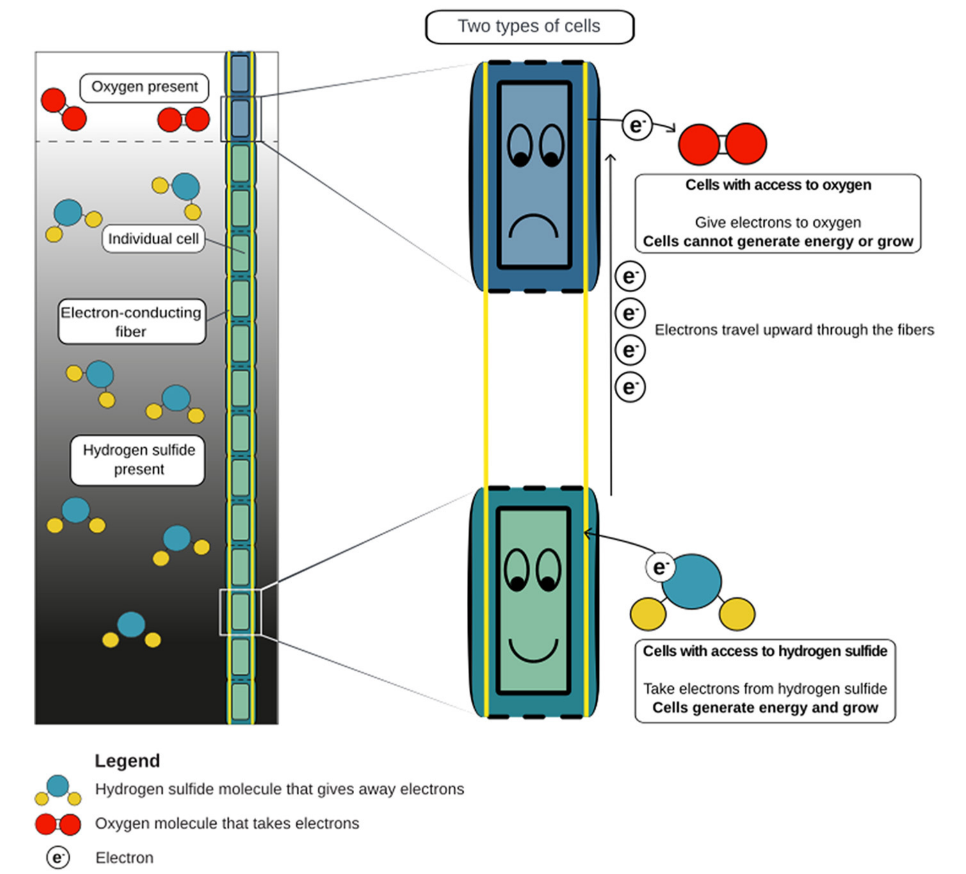

Figure 3

Figure 3

Cable bacteria filaments position themselves in the sediment so 90% of the cells have access to hydrogen sulfide. These cells take electrons from hydrogen sulfide and put them onto the electron-conducting fiber. The rest of the cells have access to oxygen and transfer the electrons to oxygen molecules. The cells must work together to get energy. However, the energy generated by this "teamwork" is not divided equally. Cells that take electrons from hydrogen sulfide get much more energy so they can grow. The cells that give electrons to oxygen do not get enough energy to grow.

only the cells that take electrons from hydrogen sulfide can grow, whereas the cells that give the electrons to oxygen cannot grow. This happens because most of the energy is generated when the electrons are taken from hydrogen sulfide. When the electrons reach the oxygen, the electrons have no or only very little energy left (Figure 3). If a cell cannot generate enough energy, it will eventually die. However, if the cells at the top of the filament cannot give electrons to oxygen, the cells in the rest of the filament cannot take any electrons from hydrogen sulfide. This means that the entire filament cannot get any energy. Therefore, the reaction with oxygen is essential to keep the rest of the filament alive and able to grow. The activity of the oxygen-using cells can be thought of as a kind of "community service" to the filament.

FUTURE RESEARCH

Currently, there is still a lot that we do not know. Do the oxygen-using cells "sacrifice" themselves for the greater good of the rest of the cable bacteria? If they keep giving electrons to oxygen without getting any energy, they will eventually die. It could also be that cells within a filament only stay in contact with oxygen for a while, and then another part of the filament takes over. If this is true, then the "community service" would only be temporary. Nevertheless, just like the "electrical teamwork", the concept of "community service" within a multicellular organism is a new discovery in biology that requires more research to be better understood. Maybe someday you will be the one making exciting discoveries by studying the unique cable bacteria ... or you might even figure out how to use cable bacteria to make environmentally friendly electronic devices!

ACKNOWLEDGMENTS

NG was supported by the Netherlands Organisation for Scientific Research (NWO PhD grant 023.005.049). JM was supported by the Ministry of Education via the Netherlands Earth System Science Centre. The NanoSIMS facility was partly supported by and NWO large infrastructure subsidy to JM (175.010.2009.011). FM was financially supported by the Netherlands Organization for Scientific Research (VICI grant 016.VICI.170.072), the Research Foundation Flanders (FWO grant G038819N) and University of Antwerp (TopBOF program).

ORIGINAL SOURCE ARTICLE

Geerlings, N. M. J., Karman, C., Trashin, S., As, K. S., Kienhuis, M. V. M., Hidalgo-Martinez, S., et al. 2020. Division of labor and growth during electrical cooperation in multicellular cable bacteria. *Proc. Natl. Acad. Sci. U. S. A.* 117:5478–85. doi: 10.1073/pnas.1916244117

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SUBMITTED: 29 January 2023; **ACCEPTED:** 13 November 2023;
PUBLISHED ONLINE: 06 December 2023.

EDITOR: David Hiller, Yale University, United States

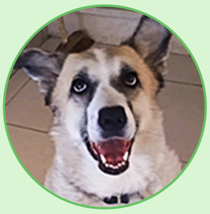
SCIENCE MENTORS: Hadas Nahman-Averbuch and Jannell V. Bazurto

CITATION: Geerlings NMJ, Middelburg JJ, Polerecky L and Meysman FJR (2023) Cable Bacteria Get Energy Through Electrical Teamwork. Front. Young Minds 11:978226. doi: 10.3389/frym.2023.978226

CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

DANIEL, AGE: 9
I like to read long chapter books like Harry Potter (so far, I am on the fifth). I like dogs and would like to visit Paris, Rome, Amsterdam, Venice, and Manchester (I would like to visit Manchester because Manchester United play there and they are my favorite team in the premier soccer league).



LIOR, AGE: 9
I like Harry Potter, and I finished the series.

SORA, AGE: 8
I love playing football, watching football, all the football! American football that is! I have seen highlights of all of the Bulldogs football games since I was alive. I also love biking and playing most of the sports, and playing video games. My favorite is Zelda. One time I went to Yellowstone National Park and it was very beautiful and I got to see bison, bears, and a wolf trying to hunt some bison! My favorite fast food is McDonalds!

AUTHORS

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Dr. Nicole Geerlings currently works as a postdoc at the Division of Microbial Ecology (DoME) at the University of Vienna. She used to work as a PhD student at Utrecht University where she studied how cells in a cable bacteria work together and has also worked as a chemistry teacher at a high school. She is very interested in how bacteria work together and uses methods where single cells and their activity can be visualized. Besides doing research, she loves being outdoors in nature, climbing, and reading. *nicole.geerlings@univie.ac.at

JACK J. MIDDELBURG

Dr. Jack Middelburg is an Earth Sciences Professor at Utrecht University, the Netherlands. He is working at the interfaces of chemistry, geology, ecology, microbiology, limnology, and oceanography. His research is curiosity driven, meaning that he alternates among topics depending on his passion at that moment. He aims to unravel how natural systems are functioning, and his research bridges space and time scales from micrometer observations on microbial communities to the global carbon cycle, from small streams to the deep sea, and from polar to tropical ecosystems. Jack has two sons (identical twin) and two lovely grandsons. He lectures a first-year class Chemistry for Earth Sciences and a master class on Biogeochemical Cycles.

LUBOS POLERECKY

Dr. Lubos Polerecky is an assistant professor at Utrecht University and head of the NanoSIMS facility there. He develops and applies micro- analytical methods and approaches to study the activity of microbes. His primary aim is to contribute to mechanistic understanding of how microbes interact with their environment and impact element cycling on Earth through processes such as photosynthetic and chemosynthetic carbon fixation, nitrogen fixation, methanotrophy, organic matter degradation, plastic degradation, or iron oxidation. The study of carbon and nitrogen assimilation by cable bacteria at the level of individual cells and filaments is an illustrative example showcasing the capabilities of the methods he develops.

FILIP J. R. MEYSMAN

Dr. Filip Meysman is a professor in the Department of Biology at the University of Antwerp, where he leads the GeoBiology research team and the Excellence center on Microbial Systems Technology. His research team is curious about what happens in the seafloor ecosystems at the bottom of the ocean. This is also how he first encountered the fascinating cable bacteria that produce long-range electricity. When investigating some smelly, stinky sediments in the North sea area, his team observed centimeter long tiny threads that were conducting electrical currents through the seafloor. This intriguing finding changed his career and sent him on a scientific journey to discover how this magical electrical life works. In recent years, this research has led to a series of wonderful insights into these electrifying bacteria (www.microbial-electricity.eu). Cable bacteria truly discovered the benefits of electricity way before Alessandro Volta! *filip.meysman@uantwerpen.be