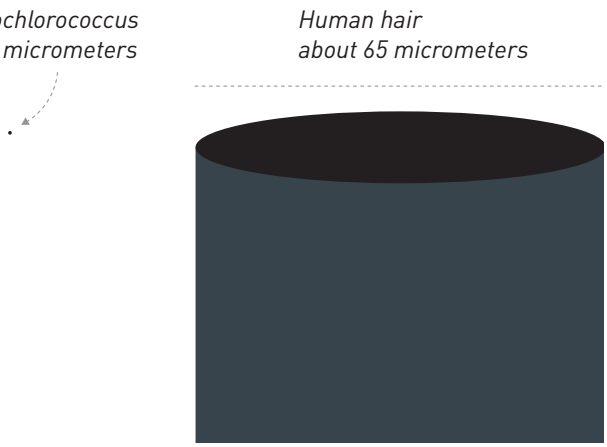
A miniscule organism of huge importance

The most common oxygen-producing organism in the world is also the smallest. This is why it remained undiscovered until the 1980s, despite there being tens of thousands of them in a drop of seawater, and despite estimations that it performs as much photosynthesis as all the Earth's croplands. Sallie Chisholm, from the US, is awarded the Crafoord Prize in Biosciences 2019 for her discovery of and research into the Prochlorococcus cyanobacteria.

Life on Earth is dependent on photosynthesis – the ability of green organisms to absorb solar energy. The oxygen we breathe and the energy in the food we eat come from this process. The more knowledge we have about the plants and microorganisms that perform photosynthesis, the better answers we will have for the most fundamental questions about life on Earth: how it originated, how the ecosystem now works and, not least, the consequences of humanity's impact on the environment and atmosphere for the Earth's climate and all living things.



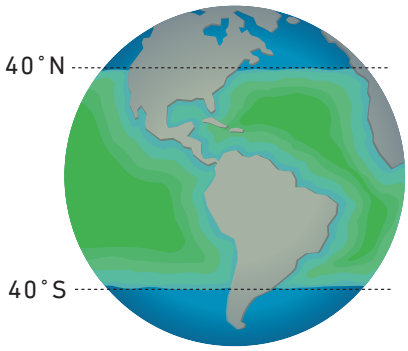
It has long been known that photosynthesis is largely carried out by invisible microorganisms in the oceans, but it was not until the mid-1980s that the most common photosynthesising species was discovered: the *Prochlorococcus* cyanobacteria. The total number of this organism on Earth has been estimated as $3*10^{27}$ (3,000,000,000,000,000,000,000,000,000). In some calculations, this species alone is responsible for as much photosynthesis as all the cropland on the planet – something no other single species comes close to. The reason that *Prochlorococcus* remained undiscovered for so long is that these tiny bacteria are only about half of a micrometre in size – considerably smaller than other oxygen-producing organisms, including other cyanobacteria. *Prochlorococcus* remains the smallest photosynthesising organism ever discovered.

Discovery

American marine biologist Sallie (Penny) Chisholm and her colleagues discovered *Prochlorococcus* in the second half of the 1980s. Her research group at the Massachusetts Institute of Technology, MIT, had come up with the idea of using a flow cytometer to study microorganisms in seawater. This instrument – which had thus far mainly been used for medical research – analyses cells in a fluid as they pass by, one at a time, through a laser beam. After successes on land, the group wanted to investigate whether they could also get this sensitive instrument to work onboard a research vessel, so that analyses could be carried out at sea while all the microorganisms in the water were still alive.

From 1985 onwards, during expeditions in the Atlantic and the Pacific Ocean that used the flow cytometer, the researchers noted a recurring, but very weak, signal in the results from the instrument. The signal was first interpreted as background noise, but eventually the researchers saw that it varied in specific patterns, including with depth, which could indicate that it came from something living. Additional studies confirmed these suspicions. They had found a previously unknown photosynthesising organism – microscopic, but of enormous significance. The discovery was published in Nature in 1988.

Since the discovery of *Prochlorococcus*, Sallie Chisholm has successfully spent a great deal of her research career studying this cyanobacterium in greater detail. It was apparent from an early stage that it is very different to other oxygen-producing organisms – partly because it is so small, but also because it is so abundant. Chisholm's continued research has further strengthened the image of *Prochlorococcus* as both a very strange and very important species. We now know that it is found in all the seas and oceans of the world, and that it is by far the most abundant photosynthesising organism in the World Ocean. It dominates in nutrient-poor and relatively warm water – all the oceans that are far from continents and between the latitudes of 40°N and 40°S (see map). There are few large organisms in these vast areas, but instead they teem with microscopic life – every drop of water in the upper layer of the ocean contains tens of thousands of *Prochlorococcus*. These bacteria do not only live at the surface, but can survive to a depth of a few hundred metres, where only a few per cent of the sun's light reaches. That far down the light is too weak for other photosynthesising organisms, but it is adequate for *Prochlorococcus*.

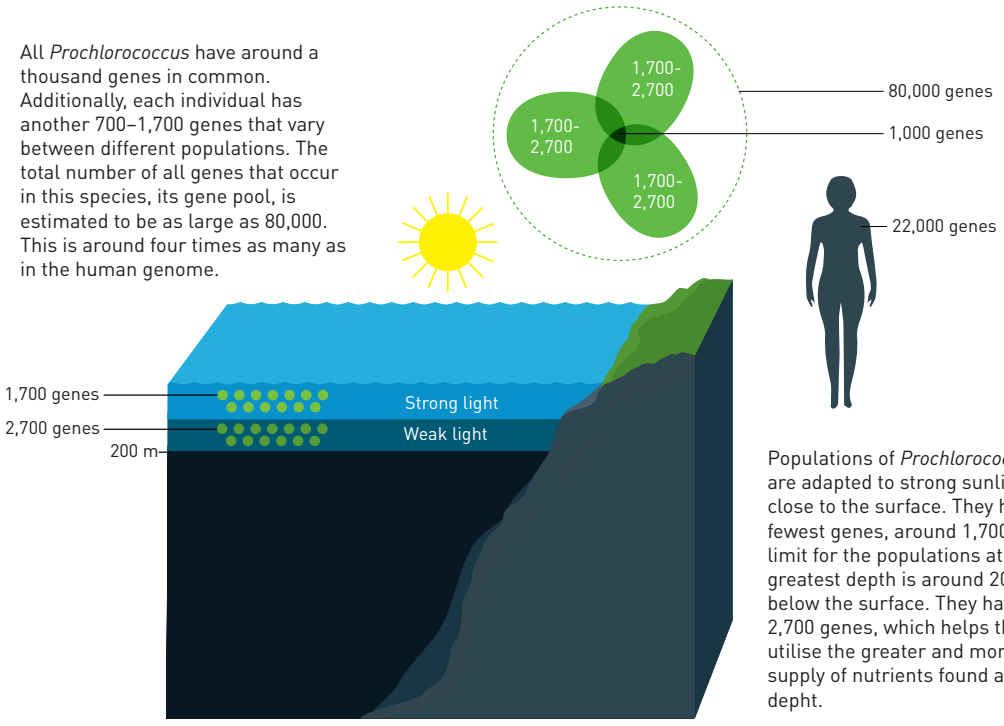


Genetic studies

Sallie Chisholm's research into *Prochlorococcus* has remained at the forefront – not least because she has seen the potential of new research technology. She was quick to use new genetic tools for reading and comparing the entire genetic material of different populations of *Prochlorococcus*.

These genetic analyses show that this type of bacteria has very few genes – but also astoundingly many. The entire DNA of a single *Prochlorococcus* may have as few as 1,700 genes, the smallest number among all known photosynthesising organisms. However, in total, the species is estimated to have around 80,000 genes in its gene pool – four times more than humans do. A thousand or so of these genes are common to all individuals; the others are adaptations to different habitats and only occur in certain populations. There is a particularly large genetic difference between populations close to the surface, which are adapted to strong light, and populations that are specialised in absorbing extremely weak light at great depth. This wide genetic variation is the reason why *Prochlorococcus* thrives in conditions with such varying light, heat and nutrient levels, and thus dominates large areas of the world's seas and oceans.

All *Prochlorococcus* have around a thousand genes in common. Additionally, each individual has another 700–1,700 genes that vary between different populations. The total number of all genes that occur in this species, its gene pool, is estimated to be as large as 80,000. This is around four times as many as in the human genome.

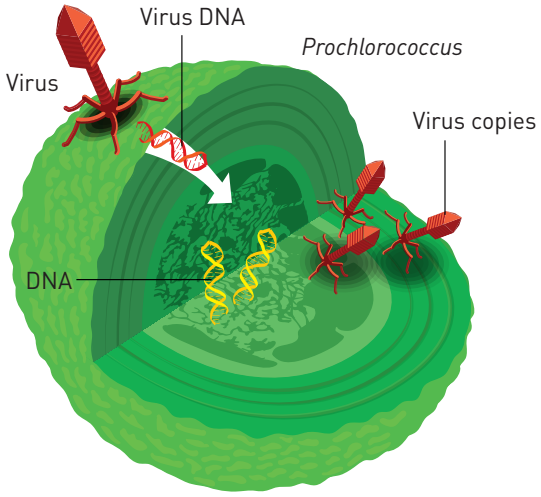


Populations of *Prochlorococcus* that are adapted to strong sunlight live close to the surface. They have the fewest genes, around 1,700. The limit for the populations at the greatest depth is around 200 metres below the surface. They have up to 2,700 genes, which helps them utilise the greater and more varied supply of nutrients found at this depht.

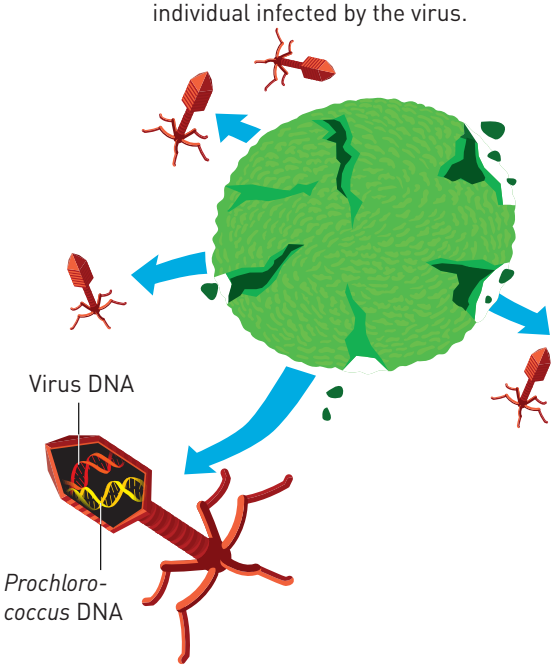
Chisholm's research has helped us to understand the dynamics of the *Prochlorococcus* gene pool – how genetic adaptation is spread, and how different populations vary over time and space in recurring patterns. Viruses that live off *Prochlorococcus* are part of this. They can carry genes from the bacteria and appear to play an important role in the spread of genes and the evolution of its host. This is not least true for genes linked to photosynthesis.

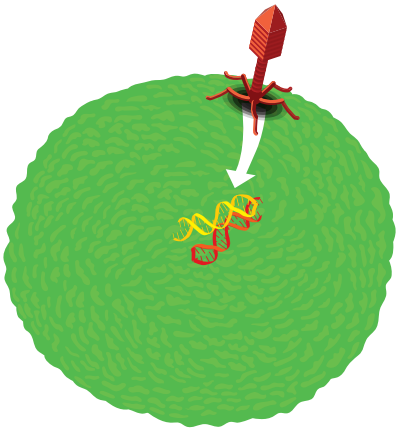
Viruses contribute to evolution

1 Viruses that infect *Prochlorococcus* appear to play an important role in the evolution of cyanobacteria by transporting genes between different populations. The picture shows how a virus particle infects a cell by injecting it with DNA that takes over the cell's activity, making the cyanobacterium a virus factory.



2 When the virus has reproduced itself, the cyanobacterium dies and breaks open, spreading the virus copies. In addition to its own genes, the virus can take DNA from *Prochlorococcus* with it – genes that can be transferred to the next individual infected by the virus.





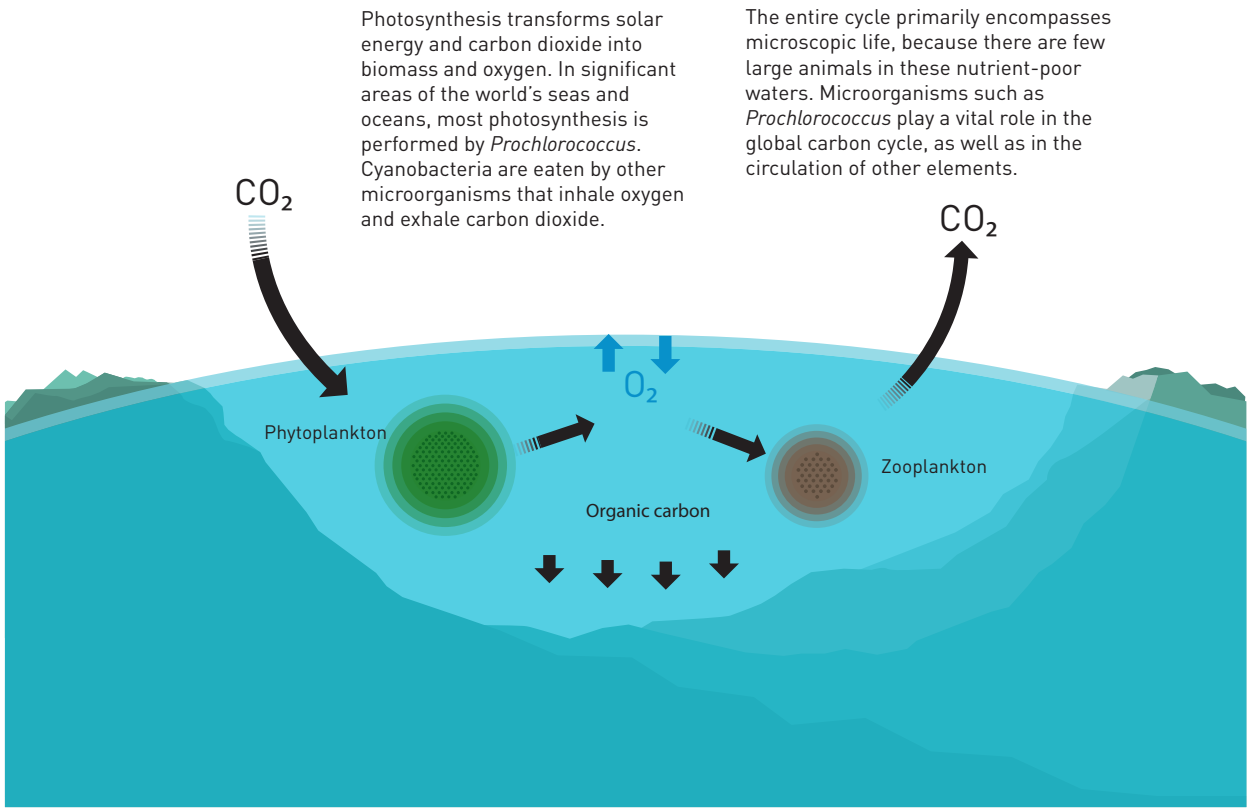
3 Sometimes, an infected *Prochlorococcus* survives a virus attack. If the virus brought a *Prochlorococcus* gene, this can be inserted in the cyanobacterium's own DNA. Because billions of *Prochlorococcus* are infected every day, these rare gene transfers occur all the time. Occasionally, a valuable gene that provides an evolutionary advantage will be transferred, so viruses contribute to spreading the cyanobacteria's genes and thus its evolution.

Interaction with other species

Over time, *Prochlorococcus*' interaction with its surroundings and its importance for the ecosystem, biosphere and evolution have become a central theme of Chisholm's research. The above mentioned studies of the interaction between bacteria and viruses are a major part of this. She has also demonstrated that this type of bacteria exchange important "services" with other microorganisms in seawater, especially with decomposer bacteria. They produce various types of nutrition for each other, and *Prochlorococcus* also benefits from other bacteria's protection against oxygen free radicals.

Chisholm is also interested in the vital contribution that cyanobacteria have made to the development of life on Earth. Photosynthesis is a requirement for almost all life – partly because it produces oxygen for the atmosphere, but also because it creates the energy-rich, carbon-based molecules that all organisms are made from. A couple of billion years ago, cyanobacteria began to produce oxygen as a by-product during photosynthesis, which created the right conditions for new forms of life to evolve. Chisholm believes that studies of current populations of *Prochlorococcus* cyanobacteria and how they co-evolve with the environment can help us to understand this early and crucial period in the development of life on Earth.

Research into *Prochlorococcus* is also extremely relevant for the future, for our understanding of how the oceans and their ecosystems are changing due to human influence and global warming.



LINKS AND FURTHER READING

More information about the prize can be found on *www.kva.se* and *www.crafoordprize.se.*

Popular science lecture

Chisholm: *"The tiny creature that secretly powers the planet"*, TED Talks 2018
www.ted.com/talks/penny_chisholm_the_tiny_creature_that_secretly_powers_the_planet#t-985683

Children's books:

Penny Chisholm (text) & Molly Bang (illustrations): *The Sunlight Series* – a series of popular science books, with the most recent published in 2017.

Scientific article

Chisholm et al: *"Prochlorococcus: the structure and function of collective diversity"*, Nature Reviews Microbiology, January 2015.
www.nature.com/articles/nrmicro3378

The Royal Swedish Academy of Sciences has decided to award the Crafoord Prize in Biosciences 2019

to

SALLIE W. CHISHOLM
Massachusetts Institute of Technology, MIT, Cambridge, USA

"for the discovery and pioneering studies of the most abundant photosynthesising organism on Earth, Prochlorococcus*".*

Born in 1947 in Marquette, MI, USA. PhD 1974 from the State University of New York at Albany, NY, USA. Institute Professor at MIT, Massachusetts Institute of Technology, MA, USA.

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