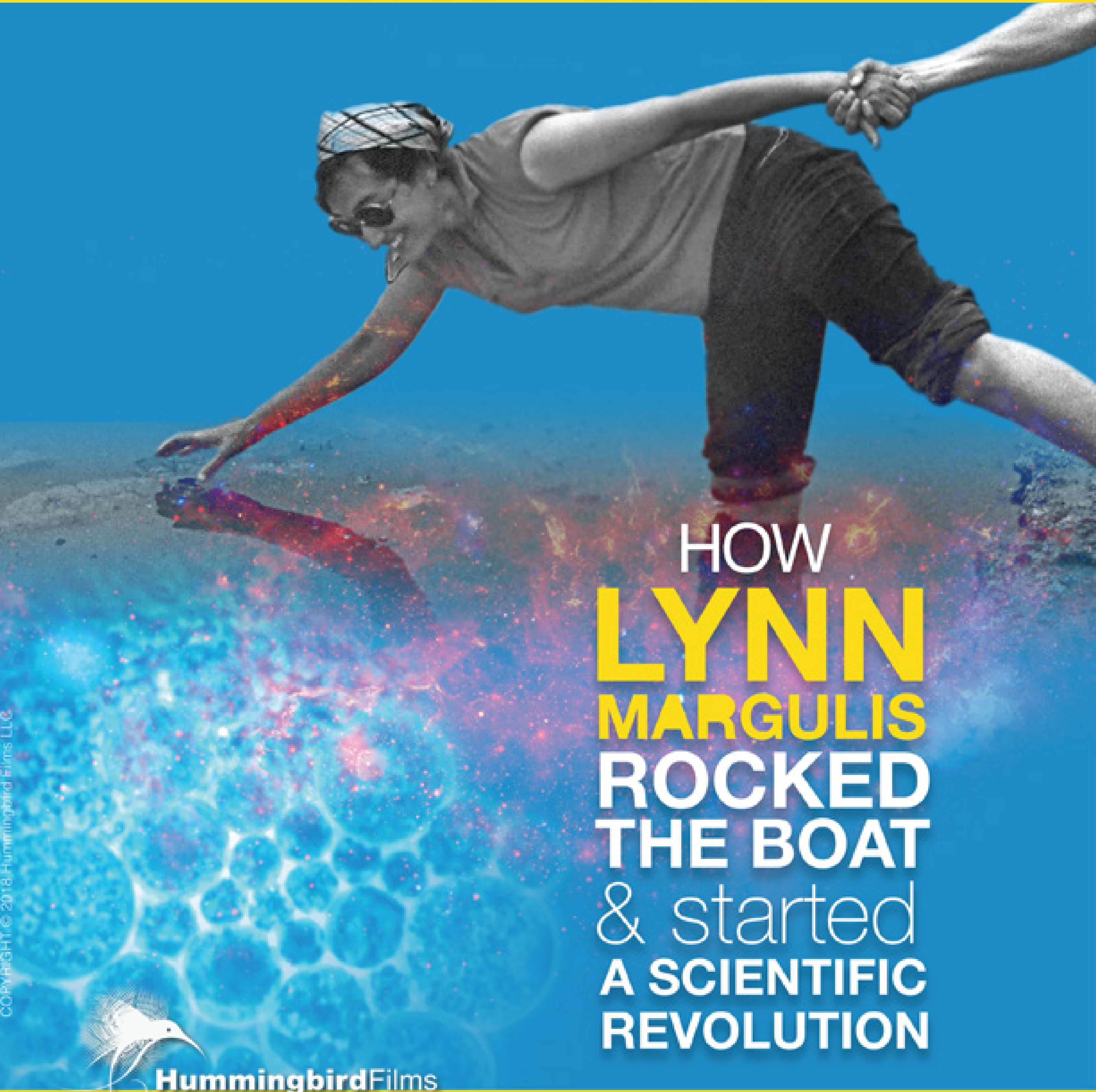
SYMBIOTIC EARTH

STUDY GUIDE



HOW
LYNN MARGULIS
ROCKED THE BOAT
& started
A SCIENTIFIC REVOLUTION

HummingbirdFilms

A FILM BY JOHN FELDMAN

Symbiotic Earth Study Guide

for the documentary by John Feldman
SYMBIOTIC EARTH: How Lynn Margulis Rocked the Boat and Started A Scientific Revolution

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Photos and illustrations in this guide are taken from the film *Symbiotic Earth: How Lynn Margulis rocked the boat and started a scientific revolution*

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INTRODUCTION

This guide is designed as a tool for groups and individuals to maximize the learning potential of the documentary *Symbiotic Earth: How Lynn Margulis Rocked the Boat and Started a Scientific Revolution*. A change in worldview is both a collective change and an individual one, and so group discussion and personal reflection are each essential.

The guide follows the film's structure and is divided into chapters that correspond with the film's eleven essays. Each chapter starts with an abstract and then a summary of the essay. Next, there are a variety of questions ("Questions for Discussion and Reflection") designed to stimulate discussion among the people who have gathered together – whether in an informal setting or a classroom.

After the questions there is a list of words from the Expanded Glossary that first appear in that essay. Then there is a list of recommend books for further reading to follow up on topics in the current essay – all of which can also be found described in "Further Reading – Books and Hotlinks."

The Expanded Glossary can be read on its own as a map of the topics of *Symbiotic Earth* as well as its rich interconnections.

We hope you enjoy this Study Guide, which provides ample leads for further explorations, scientific, philosophical, and practical, of the ideas and work championed by Lynn Margulis.

WATCHING *"SYMBIOTIC EARTH"* IN DIFFERENT CONTEXTS

Although it is highly recommended that *Symbiotic Earth* be watched in its entirety in order to get the full experience, there are many situations in which this is just not possible. The film is divided into an introduction, ten essays and an epilogue. Each of the essays explores a particular theme and can be watched on its own. Thus, the film is particularly curriculum-friendly for both secondary schools and college/university courses.

The introduction, ten essays, and epilogue can be selected and played individually from the menu.

Here is the menu (table of contents) of essays. The duration of each essay is in minutes and seconds. The name of each essay indicates the subject matter contained:

Introduction (3:00)

1. **How Lynn Margulis Coerced Me Into Making This Film** (7:23)
2. **How Science Gave Us Permission To Exploit the Earth**
   aka: From Reductionism to Systems Thinking (10:28)
3. **Confronting the Neo-Darwinian Capitalist Zeitgeist**
   aka: How Science Gave Us Permission To Exploit Each Other (17:59)
4. **Lynn Margulis' Lifelong Quest** (12:02)
5. **Working Together**
   aka: How Did She Do It All? (12:17)
6. **Bacteria Run The Planet** (13:42)
7. **Symbiosis Is The Way Of Life** (16:00)
8. **The Cell (Not DNA) Controls the Organism** (10:48)
9. **Evolution Through Mergers** (20:00)
10. **Gaia: A Physiological System On the Surface of the Earth** (14:31)

Epilogue: Embracing How Little We Know (8:53)

The 3 minute introduction to the entire film ends just after the main title but before the graphics for chapter 1. It works as an introduction to any essay or group of essays.

Here are a few of the possible versions:

Lynn Margulis and bacteria: Introduction, Essay 6 (16 minutes)

Lynn Margulis, bacteria, and symbiosis: Introduction, Essay 6, Essay 7 (33 minutes)

Lynn Margulis' life's work: Introduction, Essay 4, Essay 5, Epilogue (36 minutes)

Science, politics, thought collectives and metaphors:
Introduction, Essay 1, Essay 2, Essay 3 (39 minutes)

The Five Pillars of the Scientific Revolution:
Essay 6, Essay 7, Essay 8, Essay 9, Essay 10 (77 minutes)

Symbiotic Earth can also be divided into three parts of approximately 50 minutes each:

Part 1: **Science, Politics, Thought Collectives and Dangerous Metaphors:**
Essays 1 to 4 (51 minutes)

Part 2: **Holobionts and Symbiotic Networks:** Essays 5 to 8 (53 minutes)

Part 3: **From Symbiogenesis to Gaia and Beyond:** Essays 9 to Epilogue (44 minutes)

– CHAPTER 1 –

HOW LYNN MARGULIS COERCED ME INTO MAKING THIS FILM

This is a film about the natural world

Abstract

Lynn Margulis was a feisty courageous scientist who ushered in a scientific revolution for the 21st century. Upon viewing filmmaker John Feldman's documentary on evolution, EVO, she called it "quaint American empire political propaganda" and encouraged him to make a new documentary about cutting edge ideas in evolution. When she passed away of a stroke in 2011, Feldman went on to make *Symbiotic Earth*. To change his worldview Feldman realizes that he must give up several ideas that he once thought were true forever. The first of these is about truth. In science we can never really know the truth because our knowledge is always biased and incomplete.

Summary

The introduction to the entire film *Symbiotic Earth* starts with a shot looking down onto a dense array of buildings in New York City; no signs of non-human life can be seen. Over this shot the narration says: "This is a film about the natural world." This provocative thought – that human-made structures, like the Empire State Building, are *part of* the natural world – is a theme that resonates throughout the film. The introduction then goes on to say that Lynn Margulis was a revolutionary scientist who turned conventional ideas about evolution, the environment, and life itself upside down. Interviewees point out that Margulis sees evolution as the result of cooperation not competition and that when Margulis looks at the natural world she see symbiosis and interdependence.

Essay 1 itself starts as John Feldman narrates the story of how he met Lynn Margulis while making his film, *EVO: Ten Questions Everyone Should Ask about Evolution* (2011). Upon viewing the finished film, Margulis wrote to John that "unless you make a sequel, this film will be regarded as quaint American empire political propaganda in a few years." John Feldman and Lynn Margulis then began to plan a new film – which was abruptly halted when Lynn Margulis died of a stroke on November 22, 2011, at the age of 73.

A tireless naturalist Lynn Margulis' two main contributions were 1) showing that – and how – the cells of our bodies, and those of all other animals, plants, and fungi, come from symbiotic bacteria and 2) that the gases of Earth's atmosphere, as well as much of the biosphere, are continuously modulated, affected, and produced by microbial life – this is the Gaia Theory, which she developed with James Lovelock.

Lynn Margulis had a different worldview than most of us and this led to her development of a new "grand narrative" about the evolution of life. This builds upon Darwin, but rejects many of the ideas that are currently taught in biology classes. The filmmaker realizes that, if he is to make a film about Lynn Margulis' visionary science, he must change his worldview. But how does one do that? He began his study of Lynn Margulis by reading many of her books and scientific papers – she was incredibly prolific. He then began extensive travels to interview her students and colleagues around the world.

While the old guard scientists continue to dismiss and even ridicule Lynn Margulis' theory about symbiosis driving evolution and the Gaia theory, Feldman learns that many of her colleagues share her vision and are today advancing ideas that will reshape our understanding of life.

Feldman realizes that if he is to change his worldview, he's going to have to give up many of the ideas that he once thought were true forever. The first of these is the notion that in science we can ever really know the "truth" because our knowledge is always biased and incomplete.

The essay ends with Margulis reciting from memory Emily Dickinson's poem "Tell all the truth, but tell it slant –"

Emily Dickinson: Poem # 1263
Tell all the truth but tell it slant —
Success in Circuit lies
Too bright for our infirm Delight
The Truth's superb surprise
As Lightning to the Children eased
With explanation kind
The Truth must dazzle gradually
Or every man be blind —

Questions for Discussion and Reflection

What is a worldview? Is it possible to consciously change one's worldview?

How does the filmmaker, John Feldman, propose to change his worldview?

Does science discover the truth? What is the difference between truth in science, religion, law, mathematics?

In the introduction of the documentary Mary Catherine Bateson talks about how Lynn Margulis turned things "upside down" and that she "shakes people up . . . because it's not the way they're used to thinking." In what way did Lynn Margulis shake people up? In what way did she turn things "upside down"?

What is the origin story for this documentary? Did the director, John Feldman, begin the process of making the documentary by thinking he knew a lot about the subject, or not? Do you think his status as an expert or a novice or something else helped him in making this documentary, or was this a hindrance? What is the difference between how this film is presented and the way a textbook is written? Is one way more scientific? Why or why not?

Dutch scientist Peter Westbroek claims that Margulis' theories herald a new "symbiotic worldview?" What is different about Margulis' perspective? Does it differ from Charles Darwin's view of evolution, or evolution as usually presented? How so?

How might a symbiotic worldview, if widely adopted, change people's attitudes towards the Earth, and our fellow species?

Expanded glossary words

Darwinism, Neo-Darwinism, zeitgeist, symbiosis

Further Reading and Links*

Derrida, Jacques. *Positions*

Kuhn, Thomas S. *The Structure of Scientific Revolutions*

Margulis, Lynn and Dorion Sagan. *What is Life?*

McFall-Ngai, Margaret: "Lynn Margulis (1938 –2011) Truth Straight On: Reflections on the Vision and Spirit of Lynn Margulis": http://www.journals.uchicago.edu/doi/pdfplus/10.1086/BBLv223n1p1

Sagan, Dorion. "Remembering Lynn Margulis: An Evolutionary Eulogy": sevenpillarshouse.org/article/remembering_lynn_margulis

Westbroek, Peter. *Life as a Geological Force*

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 2 –

HOW SCIENCE GAVE US PERMISSION TO EXPLOIT THE EARTH

aka: From Reductionism to Systems Thinking

We are at war with nature

Abstract

We understand and describe nature through the lens of our culture. Mechanistic reductionist science of the 16th and 17th centuries – which sees people as separate from nature and allows us to exploit the environment – is today being replaced with systems thinking which looks at the relationships, patterns, and connections in nature and builds a picture of the whole, including people.

Synopsis

Lynn Margulis was, like Darwin, a naturalist. She studied and observed the natural world in the field and in the laboratory and she encouraged her students to do the same. She was also a prolific reader. Indeed one of her close friends once said to her: "You know what sleeping is, don't you? It's lying in bed, *not* reading."

One of the books that she recommended to everyone was Ludwik Fleck's *Genesis and Development of a Scientific Fact.* In this book Fleck explores the idea that scientific facts are the product of "thought collectives" and can change as the culture changes. The idea of the "thought collective" fascinated Margulis because it reminded her that whenever we look at and study nature, we see through the lens of our culture. The problem with that is that you can get stuck in a thought collective and only see things the way you are taught to see them. Alfred Whitehead called the propensity to *not* see things, because you are taught not to see them, "trained incapacities."

Indeed Lynn Margulis had a magnet on her refrigerator that said, "If everybody is thinking alike, then somebody isn't thinking."

Next, Stephan Harding points out that one of the things that we tend not to see is that our culture is "at war with nature." We are destroying our environment, because we see humans as separate from and superior to nature. This has allowed us to exploit the Earth's natural resources.

This idea of people being separate from nature came about during the scientific revolution in the 16th and 17th centuries and is based on the "natural philosophy" of Rene Descartes. Descartes proposed that the universe and all of nature, including the human body, is nothing more than a machine. This metaphor was the product of Descartes' culture which had just entered the "machine-age." The clock is the great example of the wonders of that industrial revolution.

This is called "mechanistic science," and remains the basis of 21st century science. Several ideas follow from mechanism: Scientists must remain detached from the objects of their studies and are not supposed to get involved emotionally with the world they are studying. Just as one might take a clock apart in order to understand how it works, a mechanistic worldview proposes that if you want to understand, for example, an organism, you need to break it down into its components parts. This is called "reductionism."

The problem with reductionism is that it is limited. It works and has given great insights and knowledge, but it ignores the big picture. In particular, it ignores how parts of organisms and parts of nature interact with one another to bring about new properties that couldn't have been predicted from a knowledge of the parts in isolation. These are called "emergent properties." This brings about a new way of thinking called "systems thinking."

Fritjof Capra points out that we need systems thinking because the problems of our time are interconnected. Indeed everything is interconnected and interdependent and if we are to understand the natural world and to solve any of our social, economic and environmental problems we need to think in terms of patterns, in terms of relationships, and in terms of how things interact. This change from a mechanistic view of life to a systemic view of life is indeed a revolution in the life sciences.

As Lynn Margulis says, "There is no such thing as a fully independent organism, because every organism requires food to be delivered and waste to be removed, so that it's a system on the surface of the Earth."

Questions for Discussion and Reflection

How has the mechanistic worldview given us permission to exploit the environment?

What is a thought collective? Can you give examples of thought collectives that you are a part of?

Discuss the difference between the mechanistic view and the systems view of the human body. What implications does this have for medicine and healthcare?

Teachers Emily Case and Lorraine Olendzenski tell of how as students Margulis used to take them to the Marine Biology Laboratory in Woods Hole on Cape Cod in Massachusetts and would always point out the motto on a plaque in the library that read, "Study Nature, Not Books." What does this say about Margulis' attitude toward learning?

Can you give some examples of how people, viewing themselves as separate from nature, have isolated themselves from natural processes, and caused problems for themselves?

We human beings can modify ourselves and our environment with our technology. For example, even if your eyesight is poor in a way that would have made you an easier target for a predator millions of years ago, today you can wear glasses—and generally don't have to worry about animal predators, because there are few of them in the human-modified environments where we live. Does this mean that evolution has stopped or slowed down with humans?

To what extent are the opinions of others important in determining the truth?

Systems theorist, physicist, and science writer Fritjof Capra, suggests at the end of this chapter that a revolution is going on in the life sciences, from a mechanistic view of life to a systems view of life. What does he mean? What is the difference between these two views? Which view is better characterized as one of interdependence?

What is the relationship between (scientific) objectivity and (dangerous) detachment? How, according to Stephan Harding, did Descartes' followers in the 17th century interpret the cries of animals according to this philosopher's view of nature as mechanical?

Expanded glossary words

anthropocentrism, thought collective, epistemology, mechanism, systems thinking, Scientific Revolution

Further Reading and Links*

Abram, David. *Spell of the Sensuous*
Bateson, Gregory. *Mind and Nature: A Necessary Unity*
Capra, Fritjof and Pier Luigi Luisi. *The Systems View of Life: A Unifying Vision*
Fleck, Ludwik. *Genesis and Development of a Scientific Fact*
Harding, Stephan. *Animate Earth*
Lenton, Tim. *Earth System Science: A Very Short Introduction*
Whitehead, Alfred North. *Science and the Modern World*
Wulf, Andrea. *The Invention of Nature: Alexander von Humboldt's New World*

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 3 –

CONFRONTING THE NEO-DARWINIAN CAPITALISTIC ZEITGEIST

aka: How Science Gave Us Permission to Exploit Each Other

Lynn differed from the neo-Darwinists on almost every point of their theory

Abstract

Two popular metaphors developed by scientists as models of the evolutionary process – *survival of the fittest* and *the selfish gene* – have led to a world-view based, in part, on the notion that humans are genetically selfish and that success comes by winning in competitive struggles. Lynn Margulis fought strenuously against these ideas.

Synopsis

Lynn Margulis proclaimed vehemently that neo-Darwinism is very bad, indeed so reductive that it "took the life out of biology." What is neo-Darwinism?

First we need to ask: What is Darwinism? Lynn Margulis was a Darwinist because, 1) she agreed with Darwin that all organisms have common ancestry and, 2) she agreed that natural selection was a fundamental property of life. For her, natural selection is the fact that there are always more organisms born than can ever survive. That's all it is. It is an elimination process: most individuals die before they reproduce leaving the others to carry on the species. Which individuals die is influenced in large part by the environmental conditions surrounding the organisms at that time.

Darwin took this metaphor of natural selection one step further. He said that since each individual of a species has "variations" that make it different from other individuals of the same species, then if a variation is useful for survival in a particular environment at a particular time it will be preserved, and gradually this results in evolutionary change.

The neo-Darwinists took the metaphor even further. In the 1930s and 1940s a group of scientists, all white male academics, combined Darwin's theory of evolution by natural selection with Gregor Mendel's "laws of inheritance" (which later became the discipline of genetics) and developed a new theory of evolution that said that each of the variations from one individual to another is caused by differences in their genes and that these differences are the result of mistakes that happen when the genes are copied during reproduction. These mistakes are called "random genetic mutations." Gradually, over long periods of time, the accumulation of many favorable random genetic mutations leads to significant changes in a population and this – when populations of the same species are separated from one another – can result in new species.

This theory of evolution became canonized in the textbooks and was promoted as the only theory of evolution. The neo-Darwinists simplified Darwin and cleaned up his ideas – ignoring much of what Darwin had studied and written. For example, Darwin also considered the French evolutionist Jean Baptiste Lamarck's theory, that organisms can inherit characteristics that they *acquired* during their lifetime, to be worthy of consideration and part of a general theory of evolution – but the neo-Darwinists ridiculed this idea.

Lynn Margulis disagreed with the neo-Darwinists on almost every point of their theory. Throughout her life she continually asked for evidence that demonstrated that random genetic mutations create new species, and was never satisfied. She championed an alternative: that new species come about when organisms *join* with one another; this is the symbiotic view, which is explored in Essay 9.

This debate between Margulis and the neo-Darwinists is often framed as one between *competition* and *cooperation*, but Lynn Margulis tried to avoid using these two words when describing nature. She said they were appropriate for the banks and the basketball courts, but not for science. She was also very cautious about the use of metaphors in science, although she well understood their explanatory power.

Filmmaker John Feldman uses this opportunity to ask where the idea that organisms *compete for survival* and the metaphor "survival of the fittest" come from.

It turns out that Darwin got the metaphor "survival of the fittest" from the writings of philosopher and sociologist Herbert Spencer who had used it to describe the social behavior of men during the Victorian industrial age – the beginnings of capitalism. Darwin applied this metaphor to what he was observing in nature.

The neo-Darwinists found a way to use this metaphor within biology by contextually defining the word "fitness" to mean *best able to live long enough to reproduce*. They then turned fitness into a quantifiable attribute based on how many offspring an organism has.

While the metaphor does help one understand natural selection and is neither right nor wrong, Mary Catherine Bateson reminds us that the metaphor is not the thing itself and that it's important to ask "where the metaphor is taking you next."

The metaphor "survival of the fittest" has entered the popular vocabulary in a way which is not what either Darwin or the neo-Darwinists intended. It has been taken to mean that the strongest individuals will win in the competitive struggles of life and that this is how nature works. This idea, equated with Darwin, has been turned into a "law of nature" and used to justify brutal competition in schools and business, global exploitation of people and the environment, as well as racism and genocide. (see Expanded Glossary entry for "survival of the fittest") That doesn't mean that these activities didn't exist long before Darwin, and long before science. It means that the metaphor has given contemporary humans a scientific justification for these behaviors.

Another dangerous metaphor is the "selfish gene" which is the title of a popular book by Richard Dawkins, an outspoken neo-Darwinist. In this book Dawkins writes that "we are survival machines, robot vehicles blindly programmed to preserve the selfish molecules know as genes."

Lynn Margulis points out that "a gene doesn't have a self, a gene is not a self. How can something be selfish if it has no self?"

Filmmaker John Feldman puts the pieces together as he realizes that these two metaphors – *survival of the fittest* and *the selfish gene* are the basis of what Margulis called "the neo-Darwinian capitalistic zeitgeist" which is the pervasive belief that humans are genetically selfish and that success comes by winning in competitive struggles.

Mary Catherine Bateson then introduces the idea that we can choose the metaphors that animate our lives and that with each metaphor we can ask: how does it change the way we *behave.*

Federico Mayor Zaragoza has chosen to believe that *sharing* is the most important human behavior. "We must share."

To conclude this essay, we learn a bit about Lynn Margulis' youth through photos and a few words from her son and co-author, Dorion Sagan. We learn that Lynn entered the University of Chicago when she was 16 and there met Carl Sagan, who she was married to from 1957 - 1964 and who would become an important and popular astronomer and science educator. Margulis attributes her enthusiasm for science to Carl Sagan and the University of Chicago. Dorion says that Carl Sagan wanted his wife, Lynn, to stay home and take care of the family, but she had huge ambitions of her own.

Questions for Discussion and Reflection

What is natural selection?

Darwin used "survival of the fittest" as another way to say natural selection. What does "survival of the fittest" mean to you? In your worldview is it an appropriate metaphor for nature? For human society? What are its dangers?

Can you give an example of competition in nature (excluding, for the moment, human society)?

Can you give an example of collaboration in nature (excluding again human society)?

The full title of Charles Darwin's worldview-changing 1859 book was, *On the Origin of Species by Means of Natural Selection or the Preservation of Favoured Races in the Struggle for Life.* What in this title might be construed as being influenced by the climate of Victorian capitalism?

Who came up with the term "survival of the fittest"?

Did you know there was a difference between Darwinism and Neo-Darwinism before you saw this film? Do you know what it is now? Can you explain it?

What is an individual? Can groups become individuals?

Expanded glossary words

"survival of the fittest," selfish gene, capitalism, zeitgeist, taxonomy, neo-Darwinism, Thomas Hobbes, Victorian Era, Lamarckism, laissez-faire economics, Social Darwinism

Further Reading and Links*

Darwin, Charles. *The Origin of Species*

Dawkins, Richard. *The Selfish Gene*

Hsü, Kenneth J. *The Great Dying*.

Skinner, Michael. 2016. "Unified Theory of Evolution: Darwin's theory that natural selection drives evolution is incomplete without input from evolution's anti-hero: Lamarck": aeon.co/essays/on-epigenetics-we-need-both-darwin-s-and-lamarck-s-theories/ (November 9)

Windchy, Eugene G., 2009. *The End of Darwinism: And How a Flawed and Disastrous Theory Was Stolen and Sold*

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 4 –

LYNN MARGULIS' LIFELONG QUEST

The course of my professional life was set forever

Abstract

As a young scientist Margulis articulated and contextualized a hypothesis – which had been explored by other scientists – that the nucleated cell, which makes up our bodies and the bodies of all the other organisms except bacteria – came about through the symbiotic merger of four pre-existing bacteria. This hypothesis was ridiculed at first, but Margulis was later vindicated.

Synopsis

When Lynn Margulis was a young woman, life was divided into two great kingdoms: plants and animals. But Margulis and others saw that this division didn't accurately reflect the diversity of life: many organisms are neither. So she and Karlene Schwartz wrote a book that included all the groups of organisms. This book, based on the classification system of Robert Whittaker, divides life into five kingdoms. The five kingdoms are: bacteria, protoctists, fungi, animals, and plants.

Bacteria are the smallest organisms, so small that they are hard to see even with a microscope. They are approximately one thousandth of a millimeter in length/diameter.

Protoctists are considerably larger, but most of them are still too small to see with the unaided eye. Some of them are single celled, called protists, and these include amoebae and *Paramecium*. But there are larger ones, notably kelp. Lynn Margulis co-authored a handbook of protoctists.

Viruses are smaller even than bacteria, but they are not considered to be alive because they cannot reproduce by themselves. They are contagious particles that contain RNA or DNA and use the host's system to reproduce.

All organisms have DNA – this is what unifies life and part of what convinces scientists that all organisms have a common ancestor. For Margulis, the most important division of life is between two big groups of organisms: the *prokaryotes* and the *eukaryotes*. Prokaryotes, which means "before the seed" are organisms that have DNA, but do not have a nucleus; these are the bacteria. Eukaryotes, which means "true seed," have their DNA arranged into chromosomes inside the nucleus of the cell. All life other than bacteria are eukaryotes: protoctists, animals, fungi, and plants.

For Lynn Margulis the question that drove her entire career was: how did bacteria evolve into the nucleated cells and then all the rest of life?

Her quest began in 1959 when she was a student of Hans Ris at the University of Wisconsin getting her masters degree in zoology and genetics. Dr. Ris used to read aloud to his students from a book by Edmund Wilson called *The Cell in Development and Heredity*. One day he read to them that, "Wallin has maintained that mitochondria may be regarded as symbiotic bacteria."

Years later, Lynn Margulis wrote that this was the moment that changed her life. From that day onward "the course of my professional life was set forever."

In 1967 she published her landmark paper, *On the Origin of Mitosing Cells*. This paper was the first statement of her endosymbiotic theory that says that the nucleated cells originated through a series of symbiotic mergers between already existing bacteria.

Jan Saap points out that while other scientists had proposed similar ideas, Lynn Margulis' paper was completely novel because it put the idea into a geo-chemical *context*. She told a narrative about what happened about 2 billion years ago that resulted in the "complex" cell having a nucleus, mitochondria, and chloroplasts inside its cell wall. Some of these, notably the mitochondria and chloroplasts, were once bacteria on their own.

This theory was ridiculed by mainstream academic scientists. As Jim Lovelock says: "They didn't like it. It changed the rules of the game and that is not popular ever." But eventually through genetic analyses she was vindicated: it was shown that the mitochondria did indeed come from oxygen-breathing bacteria and that the chloroplasts did come from cyanobacteria.

Questions for Discussion and Reflection

What was Lynn Margulis' lifelong quest?

What is a prokaryote and what is a eukaryote?

Why was Lynn Margulis' 1967 paper ridiculed?

Lynn Margulis is sometimes credited with coming up with the idea that the cell organelles of plants and animals evolved from free-living bacteria. Is this correct?

Lynn Margulis published "On the Origins of Mitosing Cells" in 1967. What was its significance?

Expanded glossary words

mitochondria, chloroplasts, protoctists, methanogenesis, carbon fixation, photosynthesis, cytology, molecular biology, geochemistry

Further Reading and Links*

Lazcano, Antonio, and Juli Peretó, 2017. "On the origin of mitosing cells: A historical appraisal of Lynn Margulis endosymbiotic theory": http://www.sciencedirect.com/science/article/pii/ S0022519317303223. A PDF from the Journal of Theoretical Biology (Volume 434, 7, pp. 80–87, December).

Margulis, Lynn, and Michael Chapman. *Kingdoms and Domains: An Illustrated Guide to the Phyla of Life on Earth*

Margulis, Lynn, John O. Corliss, Michael Melkonian, and David J. Chapman, eds. *Handbook of Protoctista*

Quammen, David. *The Tangled Tree: A Radical New History of Life*

Sagan, Lynn. 1967. "On the origin of mitosing cells," *Journal of Theoretical Biology* Volume 14, Issue 3, March 1967, Pages 225- 274: https://doi.org/10.1016/0022-5193(67)90079-3

Sapp, Jan. *The New Foundations of the Tree of Life*

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 5 –

WORKING TOGETHER

aka: How Did She Do It All?

Cyanobacteria, masters of the world, the cyanobacteria.

Abstract

Lynn Margulis spent her career developing her serial endosymbiosis theory. She gave credit to the scientists who had preceded her in these ideas. The first step in the theory remained controversial and was an uphill battle for Margulis. Through her career she received many awards, raised a large family, taught non-stop, traveled extensively, and persistently pursued her objectives.

Synopsis

This essay starts with Jan Saap pointing out that people often mistakenly say that Margulis "discovered" that chloroplasts and mitochondria were once bacteria that are now symbionts inside nucleated cells. This is incorrect, Saap says, because individual scientists don't make discoveries, their work is part of an ongoing process. What they can do, and what Lynn did throughout her life, *is promote different ways of seeing.*

Throughout her career, Lynn Margulis gave credit to the scientists who preceded her in advancing the idea that symbiosis plays a key role in evolution. In particular she drew attention to three Russian scientists: Andrei Faminitzyn (1835-1884), Boris Mikhaylovich Kozo-Polyanski (1890-1957) and Konstantin Mereschkowski (1855-1921) who proposed an idea called "symbiogenesis" that species originate through symbiotic mergers with other species. Kozo-Polyanski wrote a book entitled *Symbiogenesis: A New Principal of Evolution* in 1924. Lynn Margulis and her colleague Victor Fet edited and translated an English version of this book that was published in 2010.

The fourth scientist was the American biologist Ivan Wallin (1883-1969) who wrote a book about the same idea: *Symbioticism and the Origin of Species*. Wallin was "laughed out of New York" when he presented these ideas.

What Lynn Margulis did was investigate, develop, and contextualize the ideas of other scientists. The film now employs a graphic illustration that Margulis often used that describes how four kinds of bacteria (one of them would be called archaea in Woese's taxonomy) merged, creating the basis (the eukaryotic cell) for all familiar larger organisms (see graphic on page 28).

The first of these mergers is the most contentious and has still not been proven correct. The second (which formed the mitochondria and then all the animals and fungi) and the third (which formed the chloroplasts and then all the plants) have been established by molecular analysis and are in the textbooks.

That first merger between a spirochete and an archaebacterium Lynn Margulis hypothesized formed the undulipodia (what is commonly termed "flagella" and "cilia"), the kinetosomes, and the structures necessary for mitosis. In order to learn more about spirochetes, the filmmaker traveled to Norway to visit Morten Laane, a long time colleague of Lynn Margulis'. They looked at spirochetes under the microscope. Spirochetes are long, thin bacteria that move like corkscrews. One particular spirochete is the cause of Lyme disease and Dr. Laane showed Feldman that when these spirochetes are exposed to antibiotics they enter the red blood cells and form round bodies (also called cysts). They can stay in this form for a long time and only come out and take on the worm-like form when the environment is safe again. This is called "persistent Lyme disease." Many doctors and scientists don't agree that there is such a thing as persistent Lyme disease.

In 1967, Lynn Margulis married Dr. Thomas N. Margulis, a crystallographer, and had two more children: Zachary Margulis (born 1967) and Jennifer Margulis (born 1969).

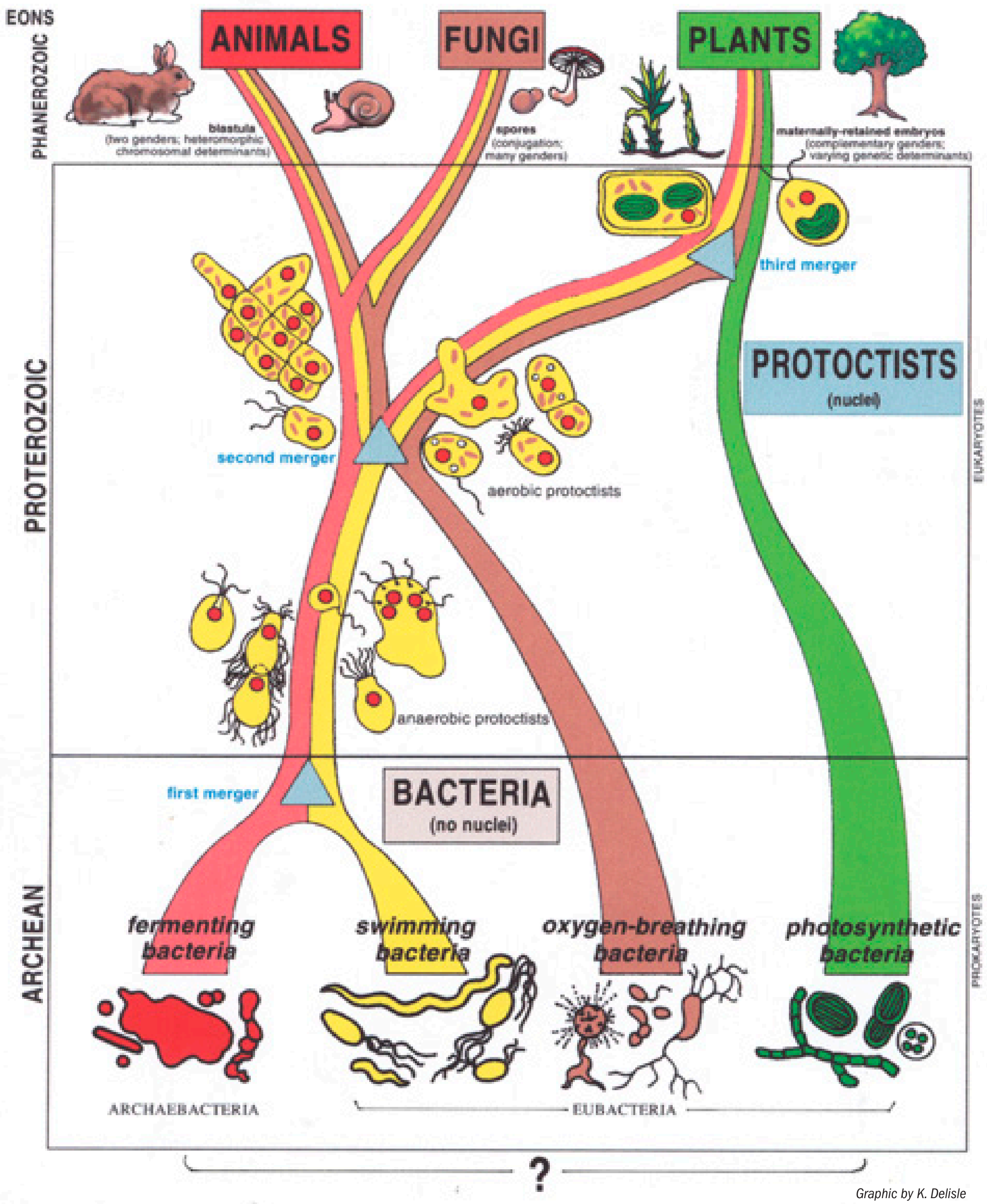
Margulis won numerous awards and honorary degrees, including admission to the National Academy of Sciences and the National Medal of Science. She was also a visiting professor at many universities, including Oxford and the University of Barcelona.

In 1988 she left Boston University and became a distinguished University Professor at the University of Massachusetts Amherst where she spent the rest of her career.

While she did receive funding from NASA, she never received major government funding from the National Science Foundation or NIH (National Institute of Health), although some people at those institutions were supportive of her work.

Lynn Margulis was passionate about her science and had to push her ideas upstream against the prevailing wisdom of the mostly male scientific establishment. She was often openly critical of government agencies and was, as her son Dorion Sagan points out in the beginning of Essay 3, a troublemaker. Today many – probably most – of her ideas are accepted and being taken on board by mainstream scientists.

During times of rejection, she found refuge in her society of students and colleagues and in nature itself.



Graphic by K. Delisle

The History of Life

Questions for Discussion and Reflection

Three of the four scientists that Lynn calls her illustrious predecessors where Russian. Discuss how the politics of scientists' culture affects their discoveries.

If scientists don't discover the absolute truth about the world how would you describe science?

Briefly sketch the history of life according to the diagram, The History of Life.

What was/were Lynn Margulis' major contribution(s) to evolutionary biology? What does historian of science Jan Sapp mean when he exhorts us to "Stop being heroic"?

Who was Ivan Wallin? What happened to his scientific career? Why?

Do you think Lynn's ideas of symbiosis filtered into or influenced her own life? How so? Might they affect ours, or society's as a whole?

Norwegian biologist Morten Laane is seen examining the blood of someone with persistent Lyme disease. What are the "round bodies" he describes?

What does Laane mean when he says that, "One scientist may be right against 30,000 other scientists"?

Sapp says, about being a woman, that Margulis "didn't play that card"? Why or why not? What is the relationship between her ideas and feminism, if any?

Expanded glossary words

spirochetes, round bodies, Lyme disease

Further Reading and Links*

Boston, Penny. "Jokin' in the Girls' Room," In *Lynn Margulis: The Life and Legacy of a Scientific Rebel*, Dorion Sagan, ed.

Kozo-Polyansky, Boris Mikhaylovich. 2010. *Symbiogenesis: A New Principle of Evolution*. Victor Fet, trans., Victor Fet and Lynn Margulis, eds.

Margulis, Lynn, "Speculation on Speculation." In *Dazzle Gradually: Reflections on the Nature of Nature,* pp. 48–56

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 6 –
BACTERIA RUN THE PLANET

Bacteria are very promiscuous

Abstract

Bacteria were the first cells and, it is believed, the first forms of life. Throughout evolution they have formed communities. Bacterial mats are one such kind of community as are all the plants, animals, and fungi. That's why Lynn Margulis says that "bacteria rule the world."

Synopsis

In the first billion years of life on Earth, bacteria (prokaryotes) developed many different forms of metabolism. Metabolism is the flow of energy and matter through a network of chemical reactions within an organism that allows it to maintain and perpetuate itself. Human metabolism (which is more than human, being shared by everything from respiring bacteria to fungi), which is not very complex, was developed by bacteria during this time.

In footage shot in 1993 Lynn Margulis visits the bacterial mats of Delta de Ebro, Spain. She takes a piece of slime out of shallow water and tells us that in the Archaean there was nothing but such anaerobic bacterial ecosystems everywhere on Earth. She calls the slime "the tissue of Gaia."

Intercut with this scene, filmmaker John Feldman and Betsey Dexter Dyer are exploring bacterial mats on Cape Cod Bay in 2012.

For most of the 20th century, bacteria were considered the "enemy" and only associated with disease. Lynn was one of the first scientists to dubunk this popular notion. In this 1993 video, Lynn points out that we are each 10% dry weight bacteria and that we need the bacteria. She cuts a piece of mat and shows the strings that form the mat to the camera. Each of these strings, which hold the mat together so that it's like a carpet, contain hundreds of microscopic filamentous cyanobacteria.

Cyanobacteria, sometimes called blue-greens, are major photosynthesizers: they capture energy from the sun and use that energy to make sugars (i.e. food). Margulis says that these bacteria represent the highest level of evolution because they live off carbon dioxide, sunlight, and water. And that's all. "They run the planet, " Margulis says. Their relatives are inside all plants.

We then see another major photosynthesizer, the purple sulfur bacteria, which are ancestors of the cyanobacteria and require hydrogen sulfide instead of water for their metabolism.

Margulis then points out that the waste of one bacterium is food for others and "that's how the ecosystem goes around." Bacterial communities recycle everything. From them we learn that "we can't just throw things out. You never throw anything out. It goes around." The vast majority of the ecological cycles in the world are microbial cycles, this includes the nitrogen cycle, the carbon cycle, the oxygen cycle and others.

Margulis goes on to say that bacteria do and make everything . . . except they can't talk and they can't make wood. When plants formed wood that made trees (about 400 million years ago) the biosphere grew upwards so that it was no longer a slimy flat environment. This greatly expanded the surface area available for photosynthesis.

Animals come and go, animals go extinct, but in Margulis' opinion bacteria don't go extinct because they don't have species. They don't have species because they transfer their genes back and forth. Bacteria often exchange DNA, permanently acquiring genetic material from other very different types of bacteria with no regard for would-be "species" barriers. So in this regard one can consider all bacteria as one planetary organism.

Lynn concludes with the thought that the unit of life is bacteria and that bacteria are community-forming organisms. Bacteria form communities such as the bacterial mats, and they form new kinds of communities – which we recognize as plants, animals, fungi, and protoctists. So bacteria formed all of life. They were here long before we got here and they will be here long after we are gone.

Questions for Discussion and Reflection

How do bacteria run the biosphere?

"The waste of one is the food for the other." Can you think of examples of how what we observe in bacteria can help us live more in harmony with our environment?

What is a species? If we define species on the animal model as populations whose members can breed with one another to form new fertile individuals, do bacteria have species? Do bacteria need to have sex to reproduce?

How old is planet Earth? When is life thought to have evolved? When did humans appear during Earth's history?

What was the biggest "air pollution" crisis in Earth's history? When did it happen? What happened afterwards? How do these and other evolutionary events still affect us today?

What does Lynn Margulis mean when she says "garbage doesn't go *out*; it goes *around*"?

For Lynn, why is wood so important?

What is bacterial sex?

What does Betsey Dyer mean when she says that we animals are a kind of "scaffolding"?

Expanded glossary words

microbial mats, stromatolites, carbon dioxide, extinctions, nucleic acids

Further Reading and Links*

Dexter-Dyer, Betsey. *A Field Guide to Bacteria*

Margulis, Lynn and Dorion Sagan, *Microcosmos: Four Billion Years of Microbial Evolution*.

McFall-Ngai, Margaret et al. 2013. "Animals in a Bacterial World, a New Imperative for the Life Sciences": http://web.stanford.edu/~fukamit/mcfall-ngai-et-al-2013.pdf

Sagan, D, and Lynn Margulis, 1988. *Garden of Microbial Delights: A Practical Guide to the Subvisible World*

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 7 –

SYMBIOSIS IS THE WAY OF LIFE

Every animal or plant or even fungus that we look at and label and consider an individual is in fact many different individuals of different species

Abstract

Symbiosis is when organisms of different species live together for a prolonged period of time. Lichens, mycorrhizal fungi, and the bacteria living in our bodies are all examples of symbiosis. Indeed all of the individual organisms that we see around us – the plants, animals, and fungi – are actually consortia of many different organisms living symbiotically. These consortia are called "holobionts."

Summary

The essay starts with Lynn Margulis saying: "We are symbionts on a symbiotic planet. Symbiosis is everywhere."

Margulis then describes one of the most common examples of symbiosis: the lichen. The lichen, which looks like a plant, is a symbiosis between an algal and a fungus.

Margulis' definition of symbiosis is simple: It's the *living together of organisms from different species for a prolonged period of time*. So, for example, ants in an ant colony do not have a symbiotic relationship with each other, because they are of the same species. Similarly people don't have a symbiotic relationship with each other.

Margulis' definition is not the way most people define the word *symbiosis*. Usually we describe *symbiosis* as a relationship that is *mutually beneficial*. But Lynn Margulis didn't like to use terminology like *mutually beneficial* when describing nature because, for her, such terms are anthropocentric. In Margulis' view, a parasite is a symbiont. Most importantly, she points out that symbiotic relationships can change – a symbiotic relationship can start out mutually beneficial and then change to become detrimental.

Next Feldman visits Andre Fortin in Quebec where he learns about mycorrhiza. Mycorrhiza is a symbiosis between a plant and fungi. Mycorrhizal fungi use thin microscope tubules (called mycelia) that attach to the plant's roots and extend far into the soil. In this way, they extend the reach of the plant's roots. The fungi can dissolve rock through the production of organic acid and are able to get from the rocks nutrients that are essential for the growth of the plant. They are able to make a tree more drought tolerant because the mycorrhizal fungi can penetrate into the soil and rocks and get small bits of moisture that the tree itself couldn't get.

Unfortunately, modern agriculture techniques, particularly deep plowing, destroy mycorrhizae. In India, where the soils are depleted, scientists are developing ways to grow mycorrhizae in greenhouses and then culture the fungi in the laboratory where spores are produced, harvested, dried, and then delivered to farmers in various forms. In the film we see one of the lead scientists in this project hold a jar of tablets that contain mycorrhizal propagules (spores and root).

In the mycorrhizal symbiosis the plant gives the fungus food, while the fungus helps the plants find water and nutrients and grow on rocks. In addition, and what's most amazing, mycorrhizae allow the plants to communicate with one another. For example, trees are connected to one another by a filamentous network of mycorrhizea in the soil. If one of these trees is attacked by insects or a pathogenic fungus, it will mount a chemical defense to save itself and at the same time it will send a message to neighboring trees, through the mycorrhizae, so that those trees can prepare a chemical defense before they are attacked.

This plant-fungal symbiosis is just one example of how organisms from different kingdoms form consortia. Coral, for example, is an animal which depends on a symbiotic algae called zooxanthellae. The algae provides food through photosynthesis to the coral and is essential for the life of the coral. As ocean waters warm up (due, for example, to global warming) the corals expel their symbiotic partners and they die. This is called "coral bleaching."

So the coral is not one organism, it is several. Similarly, a cow requires a host of microscopic organisms in its gut to digest the cellulose that it eats. All mammals require many symbiotic microorganisms to develop properly and to live. We are all consortia.

Margaret McFall-Ngai then explains that we humans have different populations of microbes in and on different parts of our body. Different things live in our bronchial tubes than live in our trachea or our nasal cavities. And each of these is a stable community that is required for our healthy lives.

On the skin for example, the microbiota in the palm of the hand is different than the microbiota in the center of the forearm, which is different than the microbiota in the underarm. Each of these is a stable population of microorganisms. McFall-Ngai then points out that the microbiotia in her forearm, for example, is more closely related to the microbiota in my forearm than it is to the microbiotia in the axil of her arm. To her this suggests a strong co-evolution in site specificity.

Feldman then asks when the bacteria arrive in the human body. They arrive immediately as the baby descends the birth canal.

"What about those wipes that they give you at the supermarket," he then asks, "are they killing the bacteria?" Margaret McFall-Ngai replies that if they are like Purell and contain high levels of alcohol, then it will destroy some of the normal microbiota on your hands and that will cause you to get skin infections, because your normal microbiota is part of your health.

We then learn from scientist George Feehrey that when a person has a particular disease the diversity of their microbiomes collapses.

Lynn Margulis says that in her opinion when the bacteria that make up our bodies are growing and eating properly, we feel healthy and happy. And when they are cramped for space and drowning in their own waste, then we feel unhealthy.

We have approximately 10 times more bacterial cells in our body than animal cells. So "we are 90%

non-human by cell." By gene, there's one human gene for every 200 microbial genes. (These are approximate estimates at the time that Margaret McFall-Ngai was interviewed. The estimates are changing as scientists continue research into the human microbiome.)

"We are more *them* than *us*," scientist Douglas Zook says. We are not individuals, we are each an ecological system. We co-evolve, co-develop and co-metabolize with the diverse array of microbes in our bodies. "This is a new way of thinking about biology," Scott Gilbert says.

The new word that scientists are beginning to use for all organisms is "holobiont" – meaning that the individual organism is not made up of one genome, but of many organisms each with their own genome. The holobiont is the name for a team, a consortium.

"Every animal or plant or even fungus that we look at and label and consider an individual, is in fact many different individuals of different species," says Lynn Margulis.

This essay then points out that Lynn Margulis "lived symbiotically": she got people to think synthetically, she brought people together, she helped people, she connected people. The door to her home was open and she would have lots of different people over for dinner where there were lively discussions and good food.

The essay concludes with a scene of Lynn Margulis showing her students an amazing video of the slime mold *Minakatella*. We see a spore germinating in the soil and then out comes an amoeba. Then we see a swarm of these amoebae as they eat bacteria. Then they join together in a pack that appears to be a multicellular mass that forms an upright fruiting body that looks like a balloon on a string. In the background we hear enthusiastic students – astonished at what Lynn is showing and describing.

Questions for Discussion and Reflection

How did you understand the word 'symbiosis' before watching this film? Was it different from how Margulis defined symbiosis?

Describe the mycorrhizal symbiosis.

If bacteria are symbionts in our bodies, does that mean they are always beneficial?

How does knowing that bacteria are an important part of your body affect you? Are there any changes you will make in your life?

Lynn says, "We feel terrible when they are cramped for space" Who is "we" and who are "they" in this sentence?

When we look at a "cow," "human," or "coral" we generally think we are looking at a single organism. What is the new paradigm way of seeing them? Why? Is this helpful?

How does the discovery that bacterial genes in our bodies outnumber human genes in our bodies by a ratio of 200 to 1 change how we think of ourselves?

If our bodies' microbial diversity is a gauge of our overall health, does that imply that species diversity may be beneficial to healthy functioning of ecosystems and planetary processes?

How is the concept of an "individual" changing?

Expanded glossary words

mycorrhizae, coral bleaching, rumens, holobiont, ecosystem, consortia

Further Reading and Links*

Fortin, J. Andre, Christian Plenchette, and Yves Piche. 2009. *Mycorrhizas: The New Green Revolution*

Gilbert, Scott, Jan Sapp, and Fred Tauber "A Symbiotic View of Life: We Have Never Been Individuals": http://www.journals.uchicago.edu/doi/10.1086/668166

Margulis, Lynn, Celeste A. Asikainen, and Wolfgang E. Krumbein, eds., *Chimeras and Consciousness: Evolution of the Sensory Self*

Margulis, Lynn and Dorion Sagan, *Microcosmos: Four Billion Years of Microbial Evolution*

Margulis, Lynn*, Symbiotic Planet: A New Look at Evolution*

Sapp, Jan. *Evolution by Association: a History of Symbiosis*

Stamets,Paul. "TEDMED 2011": https://www.youtube.com/watch?v=Mjv8Zj1ABAc and "Future is Fungi": https://www.youtube.com/watch?v=cwLviP7KaAc

Stamets, Paul. *Mycelium Running: How Mushrooms Can Help Save the World*

Wild, Aisla, Aviva Reed, Briony Barr, and Dr. Gregory Crocetti, *Zobi and the Zoox*

Zook, Douglas*,* "Symbioisis - Evolution's Co-Author." In N. Gontheir (ed.), *Reticulate Evolution*.

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 8 –

THE CELL (NOT DNA) CONTROLS THE ORGANISM

But DNA doesn't actively control anything

Abstract

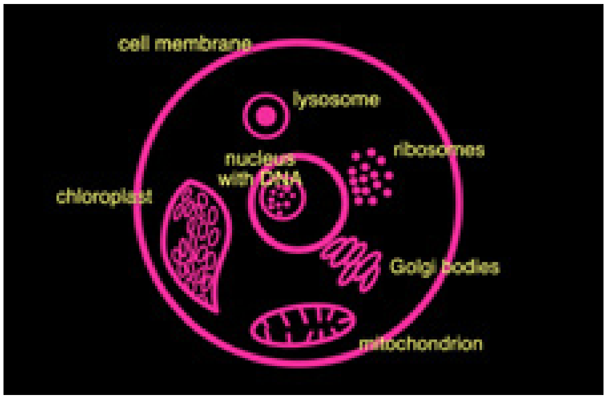
While the prevailing wisdom is that the DNA (the "genome," commonly known as the "genes") in each of our cells determines who we are and who we will become, scientists are now reversing this idea: the cell and the tissues, organs, and environments surrounding the cell tell the genome what to do. The genome is a database that is used by the cell.

Summary

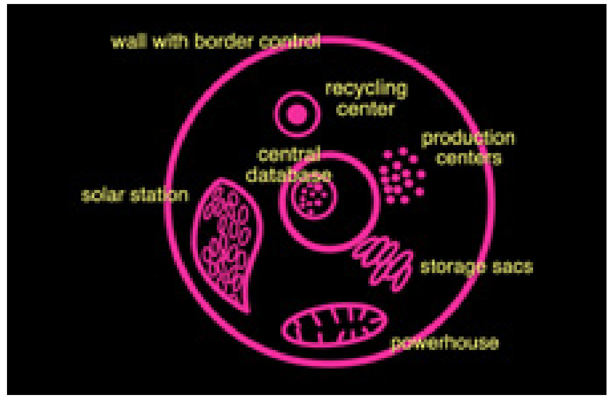
As a lone figure walks toward the camera on a misty beach, filmmaker John Feldman narrates that while he is trying to see her as a "holobiont," it's hard to do. Isn't she really an *individual* with one set of genes that she inherited from her parents and which are a blue print for who she is and who she will become? This idea, called *genetic determinism*, or as people say "it's in our genes," is so ingrained in our culture that millions of dollars were spent to decode the human genome with the expectation that we would isolate genes for human diseases and abnormalities and be able to cure them, but the results of the Human Genome project were disappointing . . . very few genes were found that related one-to-one with human characteristics, normal or abnormal. Indeed the very concept of the gene was brought into question. James Shapiro goes on to say that the "gene is a complex philosophical concept." (See Glossary for further explanation)

Having sequenced or "decoded" what was once called the "book of life" and having not found what they were looking for, scientists were left with many questions, and according to Denis Noble, were forced to completely rethink the basic assumptions about life.

This leads filmmaker Feldman to ask: What is life? For Margulis – and many others – life is defined as a process that makes itself. This is called "autopoiesis." Autopoiesis is the process through which components from the environment are taken in and



Technical names for cell components



Functions of cell components

moved around in each cell and in each organism to maintain the organism and to make more of the organism – through growth and reproduction.

The cell is the smallest simplest unit that can do this. Fritjof Capra shows us that the cell can be thought of as a community. This becomes clear if the technical names for the major parts of the cell are replaced with each part's function, as in the diagrams above.

The prevailing neo-Darwinist wisdom is that the DNA molecule controls the organism, but James Shapiro points out that "DNA by itself doesn't do anything. It can only be replicated, it can only be expressed." DNA is a storage molecule. It is part of the cell system and the cell uses it to reproduce, but "it's the cell that reproduces, not the DNA that reproduces."

Adding to this idea, Denis Noble points out that the scientist Barbara McClintock described the genome as *an organ of the cell*. It's a database and it's the rest of the cell and indeed the tissues and the organs beyond the cell that tell it what to do. This means that we must reverse our thinking. Instead of thinking that once we decoded the genome we would understand life and be able to mechanically reproduce the whole of biology, we have to ask the question: how does the cell system tell the genome what to do?

This question is the basis of *epigenetics*. Scott Gilbert defines epigenetics as the science that studies the ways by which different genes are used at different times and places so that the same genome that is inherited in the fertilized egg can give rise to all the different cells types of the body. So what you look like and act like is not a "readout" of your genome, but the outcome of a process through which the cell – and indeed the entire organism – responds to its environment and "makes itself," using the genome as a database for the production of proteins as needed.

For example, the metabolic network of the body constantly makes changes to the organism in response to what's in its food as well as what's in the air and water it takes in.

So the answer to the popular question "nature or nurture?" is always: both.

Mary Catherine Bateson points out that the more we assume that the characteristics of humans are genetically determined the less effort we will put into creating and sustaining environments in which people can grow and develop in a humane way.

In other words, as Federico Mayor Zaragoza says, when we go against the idea of "genetic determinism" and realize that our genes do not determine who we are and who we will become, "we are free to invent our future."

Returning to the person walking on the beach, narration concludes by describing the person as a complex metabolizing system. This system – including her genome, her microbiome, her culture, and her environment – determines who she is and who she will become.

Questions for Discussion and Reflection

What is genetic determinism? Has this idea influenced your life?

Discuss how the conception of the role of DNA in the body has been reversed.

What are the implications to society – and your life – that we are not "determined" by our genes, but rather our intelligent cells tell the DNA what to do?

Are genes "selfish"? Why or why not?

What are the arguments for saying that cells, rather than genes, are the basic units of life?

What is meant by the term "autopoiesis"? Can you describe what it means in terms of your own body?

The "central dogma" in molecular biology was the idea that genes produce organisms, but information never flows from the organism back to the genes. Why is this no longer considered true?

Expanded glossary words

autopoiesis, gene, selfish genes

Further Reading and Links*

Dawkins, Richard. *The Selfish Gene* and *The Extended Phenotype*
Keller, Evelyn Fox. *A Feeling for the Organism: The Life and Work of Barbara McClintock*
Margulis, Lynn and Dorion Sagan. *What is Life?*
Maturana, Humberto, and Francisco J. Varela. *Autopoiesis and Cognition: The Realization of the Living*
Noble, Denis. *The Music of Life*

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 9 –

EVOLUTION THROUGH MERGERS

Random mutation and natural selection is a gross oversimplification and it's wrong

Abstract

The neo-Darwinian theory of evolution is that evolutionary change comes about gradually through the natural selection of variations that result from random genetic mutations that occur when an organism reproduces. This idea is an oversimplification and wrong. Evolutionary change happens in many ways. Lynn Margulis was most interested in the ways that evolution results from organisms exchanging and acquiring genomes. She calls these "merger-integration-fusion processes." The essay reviews several of these ways and concludes that much of evolution remains an awe-inspiring mystery.

Summary

As we look at an egret standing on a tree branch and preening itself, filmmaker John Feldman expresses that he has always been troubled by the idea that the magnificent diversity of life came about through the natural selection of a string of accidents – random genetic mutations that happen when the genes are copied.

Immediately, molecular biologist James Shapiro says that this neo-Darwinian idea is an oversimplification and is wrong.

First of all, cells can detect and repair copying errors. The cell "quality control system" is so efficient that copying errors are reduced to less than one in a billion. He says that "the cell is not the helpless victim of mistakes that its replication apparatus makes." His research has shown him that "genetic change is an active process that cells carry out on their genomes."

Mutations are not random. They are mediated by the cell system. "The DNA is changed by a whole series of different kinds of biochemical process," says James Shapiro, "In many cases these involve cutting and splicing DNA – just as we do in the laboratory – and that's why I like to call it *natural genetic engineering*."

So instead of the genome being a read-only memory system, it's a read-write memory system.

Next we are introduced to the Nobel Prize-winning scientist Barbara McClintock (1902 –1992) who studied the ability of the genome to change in response to the environment. We listen to excerpts of her Nobel Prize address as she explains that cells deal with and manipulate their genomes in a sentient, cognitive manner. She says that cells are very smart. Lynn Margulis agreed that all beings are sentient because they make decisions. "Life is matter that chooses," Margulis says.

James Shapiro tells us that he doesn't use the words "think" or "consciousness" when describing cells because these words are "filled with philosophical implications and a lot of desire on our part to limit it to ourselves." He likes the word "cognition" because you can define it: Cognition is action based on sensory information.

It's not too much of a stretch to realize that all animals have cognition, but plants? Barbara McClintock used an oak gall as an example of how a plant makes decisions – cognition – to reprogram its genes. An oak gall forms when a particular wasp lays its eggs on a particular species of oak. The oak reprograms its genome to make a ball-shaped structure to house the wasp's eggs. This is a symbiosis between an insect and a plant.

Next Emily Case points out that while Lynn Margulis didn't totally dismiss genetic mutations as a source of evolutionary novelty, she argued that their impact was small and can't alone account for the big changes in evolution. "When we look at big evolutionary change, when we look at speciation, we have lots and lots of examples that involve symbiosis," Case says.

Filmmaker John Feldman then returns to the e-mail that Lynn Margulis sent him. "Saltatory evolution prevails," Margulis writes, and then she lists a handful of ways in which evolution results from organisms exchanging and acquiring genomes.

First on the list is symbiogenesis. Symbiogenesis is when very different sorts of organisms come together to make a new kind of being. For example: green animals. We see green worms in shallow water while Margulis tells us that the ancestor of these worms swallowed, ate, but did not digest the green entity that does photosynthesis and the result is a green worm that is fully photosynthetic and which has lost its mouth. Margulis goes on to say that "these kinds of symbiogenetic events, that is the living together of organisms with very different abilities that leads to new tissues, new organs, new forms, to me is a much more – it's not a much more important – it is the major mechanism of change in the fossil record and in evolution."

Next the film investigates how evolutionary change comes from sex. Sex is defined by Margulis and others as the processes through which individual cells and organisms acquire and recombine DNA from more than a single source. Most people's understanding of sex and reproduction is limited to animals. But there are organisms that reproduce without sex and there is sex without reproduction.

There is also what Lynn called forbidden fertilization: sex between two very different types of organisms producing a third type of organism. The organism *Geosiphon* is only made when a fungus is "fertilized" by a cyanobacteria. The resulting organism looks like neither – it looks like a little moss. "You have a new organism formed routinely by a fertilization like fusion between members of different kingdoms," Margulis says.

James Shapiro then tells us that "mixing between organisms that normally don't mate together or hybridization is a very powerful source of genetic novelty."

This leads to the story of Don Williamson. A friend and colleague of Lynn Margulis, Don Williamson was a biologist who spent his career on the Isle of Man studying planktonic larva. After he retired, he turned his attention to a puzzle that had haunted him throughout his life: how did the larval stage of many animals evolve.

In many cases, larvae are very different from the adults, for example we all know that the caterpillar, which is a larva, is very different from the butterfly. In particular he was intrigued by the case of the starfish *Luidia sarsii*. In these organisms the young adult starfish forms within the larva and then the young adult starfish drops off the larva and starts its life, while the larva goes on living in the ocean.

After many years of puzzling over this double life of the larva and adult, Don arrived at a hypothesis: hybridization. The idea is that once in a million years (literally) the sperm of one animal fertilized the egg of another animal and a viable hybrid was born. This is possible in the sea because in most cases the female sheds her eggs and the male sheds his sperm in the open water, so it's quite possible for two unrelated groups of animals to be spawning at the same time and for the sperm of one group to contact the egg of another. Of course in most cases nothing happens, but once in a million years or so a viable offspring may result.

Don Williamson and Lynn Margulis called this process "hybridogenesis." Don Williamson conducted several hybridization experiments to see if he could create such hybrids in the lab and he did get some viable creatures (larvae). "They were fascinating little creatures, but like nothing I had seen before." They died before developing much further.

The hypothesis proposes that from one set of chromosomes two distinct animals are born, one after the other. Don calls these "sequential hybrids" to distinguish them from hybrids that contain a mixture of the characteristics of each parent.

This hypothesis has not been accepted by the scientific community. Many think it's laughable. It goes so far against the grain of the traditional understanding of animal evolution that one critic wrote: "if Williamson is correct, then our current understanding of animal evolution is fundamentally wrong, and many scientific careers have essentially been wasted."

The current thinking about evolution is based on the model of the "evolutionary tree" that Darwin first developed and which has been elaborately developed over the years. The tree model shows evolution as a continually branching structure. Lynn Margulis, in a debate at Oxford University called "Homage to Darwin" sponsored by Voices from Oxford that included Richard Dawkins, argued that the tree model was wrong because "a tree assumes that the lineages continue to branch and branch and branch from a common ancestor [but] there is movement of genetic material from one branch to another, that makes the topology a net . . . a web . . . and no longer a tree." Both symbiogenesis, now accepted, and hybridogenesis, still heretical, are examples of genetic material from one "branch" combining with the genetic material of another "branch."

In that same debate there is a very revealing moment in which Richard Dawkins says that "if you take the standard story for ordinary animals . . . and what's wrong with that? It's high plausible, it's economical, it's parsimonious, why on Earth would you want to drag in symbiogenesis?" Lynn Margulis replies, laughing, "Because it's there."

This exchange points out that often scientists try to fit nature into their theories. But to Margulis and others such efforts indicate that it's time for a theory to change.

Evolutionary theory is today undergoing a major change and much of evolution remains an awe-inspiring mystery. Evolution is the growth and development of life from one cell to a living system with many interconnected and co-evolving parts that covers the Earth.

The chapter ends with a dissolve from a shot of New York's Times Square in 1922 to a similar view in 2016 in which the narration points out that while the cars, clothing and buildings in the shot aren't alive, they are part of humanity's *living system* and they evolve from generation to generation.

Questions for Discussion and Reflection

What does it mean that the genome is a read-write memory system?

If life is matter that chooses, how do plants choose?

Do you believe that all organisms have cognition?

What does it mean to say that a car evolves because it is part of our living system?

Neo-Darwinian biology defines evolution as natural selection working on the gradual accumulation of random genetic mutations. What is right or wrong about this view? Is it complete?

James Shapiro says that there is on average only about one copying error in a billion during self-replication of DNA. This is in part because DNA uses enzymes to correct such errors, both before and after replication. Should the discovery that DNA corrects its copying mistakes affect our ideas of how evolution works?

What are some quick or "saltational" ways in which evolution can happen?

What does Jim Shapiro mean by bacterial "cognition" and "natural genetic engineering"?

Who was Donald Williamson? Can you describe his theory?

How is Williamson's work similar to and/or different from that of Lynn Margulis?

Expanded glossary words

natural genetic engineering, *Geosiphon*, sequential hybrid, planktonic larvae, PNAS

Further Reading and Links*

Jablonka, Eva, and Marion J. Lamb. *Evolution in Four Dimensions*
Keller, Evelyn Fox. *A Feeling for the Organism: The Life and Work of Barbara McClintock*
Margulis, Lynn, Richard Dawkins, Denis Noble, Martin Brasier, Stephen Bell, et al. "Margulis-Dawkins-Debate." voicesfromoxford.org/news/margulisdawkins-debate/158
Margulis, Lynn, and Dorion Sagan. *Acquiring Genomes: A Theory of the Origins of Species*
Margulis, Lynn, and Dorion Sagan. *Origins of Sex: Three Billion Years of Genetic Recombination*
Maturana, Humberto, and Francisco J. Varela. *The Tree of Knowledge: The Biological roots of Human Understanding*
Noble, Denis. *The Music of Life*
Ryan, Frank. *The Mystery of Metamorphosis: A Scientific Detective Story*
Shapiro, James A. *Evolution: A View from the 21st Century*
Slijepcevic, Predrag. "Riders on the Storm": biocivilizations.com/introduction/
Williamson, Donald I. *The Origins of Larvae*

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

– CHAPTER 10 –

GAIA: A PHYSIOLOGICAL SYSTEM ON THE SURFACE OF THE EARTH

You have the depth of insight into biology from Lynn on the one hand and the physical, chemical and almost philosophical reasoning of Jim Lovelock on the other

Abstract

In 1961 James Lovelock was hired by NASA to develop an apparatus to detect life on Mars. His research indicated to him that one can detect life on a planet by analyzing its atmosphere. This led to his formulation of the Gaia hypothesis. With the help of Lynn Margulis they developed the Gaia hypothesis which says that life on Earth regulates its own environment. They worked out some of the ways in which this happens. For Margulis, bacteria are the key life form that regulates the Earth's atmosphere.

Summary

In 1961 James Lovelock was hired by NASA to develop an apparatus to detect life on Mars. This challenge led to his development of the Gaia hypothesis.

One day as James Lovelock and Carl Sagan were in their shared office at NASA's Jet Propulsion Laboratory (JPL) a fellow scientist showed them the complete analysis of the Martian and Venus atmospheres. These analyses showed that the atmospheres of both planets are almost entirely carbon dioxide with only traces of other gases present. "I immediately knew this means that they were both dead planets," Lovelock says. By this he means that the atmospheres of both planets were at chemical equilibrium – the concentrations of the gases are stable and nearly all chemical reactions have ceased.

The Earth's atmosphere, on the other hand, is out of equilibrium. There are gases present that are highly reactive – methane and oxygen for example. "If it was a different composition it would blow up. Something must be regulating or it wouldn't stay constant." Lovelock says. "That was my eureka moment. Here was this great system that was looking after itself and keeping the planet habitable."

Lynn Margulis then tells us that the composition of these gases in the Earth's lower atmosphere is actively modulated by the living organisms of Earth in such a way that the atmosphere, a product of biospheric life, remains suitable for life.

The conventional wisdom was that life was a kind of passenger on the Earth and that it didn't have much influence on the chemical composition of the planet. The Gaia hypothesis sees the evolution of life and the evolution of the planet as tightly coupled. The rocks, the atmosphere and the organisms interact as a system and change each other.

James Lovelock developed his hypothesis starting in 1965, but he didn't fully understand how Gaia "worked." Around 1971, Carl Sagan suggested to Margulis that she should talk to Lovelock. Lynn Margulis then contributed her incredible knowledge of the microbial world. "We think it's the major groups of bacteria that actually are running the Gaian system," she said at the time.

Throughout the 70s they worked together to develop the hypothesis and uncover the mechanisms through which life regulated its environment. Timothy Lenton points out that their's was a very productive relationship: "You have the depth of insight into biology from Lynn on the one hand. You have this physical, chemical and almost philosophical reasoning of Jim Lovelock on the other."

But the idea encountered resistance. The neo-Darwinists in particular argued against it because it implied that organisms were doing something for the benefit of the system as a whole. "They saw anything that looked like an argument for cooperation or so forth – Gaia was the grandest argument in their eyes of biological cooperation – as being somehow heretical to the theory," Lenton says.

Lovelock points out that some of the scientists who were against the idea of Gaia hadn't read any of the papers on Gaia and were just listening to scuttlebutt from their students. Some of these scientists later admitted as much and apologized.

Lovelock also admits that the name "Gaia," suggested by his neighbor the author William Golding, was part of the problem because of its mythological connotations.

The film highlights one important difference that Lynn Margulis and James Lovelock had about the Gaia hypothesis. Lovelock looks at the Earth as a living organism, but Margulis does not agree. For her, the Gaia hypothesis cannot be reduced to the statement: The Earth is an organism. Gaia says that "the Earth is a physiological system made up of ecosystems, themselves made up of communities, and that the minimal unit is a cell."

Filmmaker John Feldman then narrates the conclusion of his part in the film as he stares at his reflection in the window. "Perhaps Descartes famous expression 'I think, therefor I am,' should be changed to 'We think, therefore I am,' for indeed, I am the product of communities of cognitive cells and symbionts that make up my body, and a product of the social and ecological communities of which I am a part. And together we are Gaia, a symbiotic Earth."

Lovelock gets the last word as he points out that Gaia is a sentient entity because we humans are a part of Gaia and we have sentience. For him it's a live thinking planet.

"Perhaps its greatest value lies in its metaphor of a living Earth which reminds us that we are a part of it and most of all that there are no human rights, only human obligations."

Questions for Discussion and Reflection

Do you think naming the hypothesis "Gaia" was a mistake?

How is the Gaia theory an argument for cooperation?

According to Lovelock, Gaia is a sentient entity and the Earth is a thinking planet. Discuss these ideas.

What is the Gaia hypothesis?

Is Gaia an organism? Is it alive?

What is the difference between the scientific description and its public reception? Can they be completely separated?

Lou Kaplan came to Carl Sagan's office at the Jet Propulsion Laboratory when James Lovelock was sharing it with Sagan, and showed Lovelock and Sagan that the atmospheres of Mars and Venus were almost entirely carbon dioxide (CO_2). Mars and Venus, our "sister planets" as Lynn Margulis says, have over 90 percent CO_2 in their atmospheres. Why is there so little CO_2 in our atmosphere relative to our planetary neighbors Mars and Venus?

Are human beings the only ones who have ever affected Earth's surface in a major way? Which other organisms have changed Earth's atmosphere? Was this good or bad? For whom?

Expanded glossary words

Gaia, Gaia hypothesis, carbon dioxide

Further Reading and Links*

Clarke, Bruce. "Gaia is Not an Organism." In Bruce Clarke (ed.), *Earth, Life, and System: Evolution and Ecology on a Gaian Planet*

Grinspoon, David. *Earth in Human Hands: Shaping Our Planet's Future*

Lovelock, James. *Gaia: A New Look at Life on Earth*, *The Revenge of Gaia: Earth's Climate Crisis and the Fate of Humanity*, *The Vanishing Face of Gaia: A Final Warning*

Margulis, Lynn. Speaking to NASA on *Gaia* in 1984: https://archive.org/details/gaia_hypothesis

Schneider, Stephen H., et al., eds. *Scientists Debate Gaia: The Next Century*

Slijepcevic, Predrag. "Cosmic 'Looney Tunes': and we thought we were the supreme species": biocivilizations.com/cosmic-looney-tunes/

Westbroek, Peter. *Life as a Geological Force: Dynamics of the Earth*

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

EPILOGUE:
EMBRACING HOW LITTLE WE KNOW

Communities of bacteria, within communities of protists, within termites, within communities of termites, within ecosystems, within Gaia

Abstract

Lynn Margulis spent her career investigating the bacterial origins of eukaryotic cells – that is, all cells that are not bacteria. In the process she helped develop the idea that evolution happens through "symbiosis," and the Gaia theory. Her quest for knowledge drove her onward, but she also humbly understood that it was an endless quest – the more one knows, the more questions and unknowns there are.

Summary

"When Lynn Margulis was a girl she said she wanted to be an explorer," Betsey Dexter Dyer tells us, "and she wanted to be an explorer in the most adventurous sense of that word, completely, freely, genuinely curious about the world around her and being smart enough to be able to interpret the world as a scientist."

This essay opens as Lynn and a colleague are cutting apart a piece of amber that contains a 20 million year old termite.

Margulis studied termites her entire career. In order to digest wood, termites rely on a community of symbiotic protists that live in their gut. But the protists don't do it by themselves, they in turn rely on a community of symbiotic bacteria. Margulis opens the gut of a termite and we see the protists through the microscope.

One of these protists, *Mixotricha paradoxa* Lynn called "the beast with five genomes." In addition to its own genome, it has spherical bacteria in its gut and three different kinds of bacteria on its surface. Two of these surface bacteria are spirochetes.

So there are communities of bacteria living within communities of protists that live within termites that live within communities of termites that live within ecosystems that all make up Gaia.

Lynn Margulis' quest to understand the origin of the first nucleated cell propelled her ever onward. When asked about her future plans she answered that she wanted to finish her endosymbiotic theory and convincingly demonstrate that it was spirochetes that merged with an archaea-bacteria in the first step of her endosymbiotic theory.

This theory is clearly explained in Margulis' finished but unpublished book, *Symbiogenetics*, which is the fourth edition of her book *Symbiosis in Cell Evolution*.

Fritjof Capra then paraphrases a statement by Blaise Pascal: Knowledge is like a sphere. As it becomes larger, the surface connecting us to the unknown also enlarges. The unknown is always there. As knowledge grows so the unknown grows.

Through a life of rigorous and passionate scientific inquiry, Lynn Margulis gave us a new way of thinking about life and about ourselves.

Lynn Margulis gives Emily Dickinson the last word as she recites the last part of Dickinson's poem, What Mystery Pervades a Well (#96)

But nature is a stranger yet:
The ones that cite her most
Have never passed her haunted house,
Nor simplified her ghost.
To pity those that know her not
Is helped by the regret
That those who know her, know her less
The nearer her they get.

END OF FILM

Questions for Discussion and Reflection

What are some new ways of thinking about our "selves" that Lynn Margulis – and others in this film – helped you understand?

Was Lynn spiritual?

What was the role of poetry in Margulis' intellectual and scientific life?

Fritjof Capra quotes Blaise Pascal's image of a growing sphere to describe the advance of human knowledge. Do you agree this is an accurate metaphor of the increase in scientific knowledge?

What are the social and ecological implications of Lynn Margulis' "Symbiotic Worldview" for our species going forward?

Expanded glossary words

Mastotermes darwiniensis, Mixotricha paradoxa, amber, protists, SET (serial endosymbiosis theory), Archean Eons.

Further Reading and Links*

Dickinson, Emily. *The Complete Poems of Emily Dickinso.,*

Margulis, Lynn and Dorion Sagan, "The Beast with Five Genomes": http://www.naturalhistorymag.com/htmlsite/0601/0601_feature.html

"Dorion Sagan: My Mother's Love Letters—Finding the Orange Bag: Ghosts, Reality, and the Escape into Life," truthbarrier.com/2016/09/13/finding-the-orange-bag-ghosts-reality-and-the-escape-into-life/

Wier, Andrew et al. 2002. "Spirochete and protist symbionts of a termite (Mastotermes electro-dominicus) in Miocene amber": PNAS 2002 February, 99 (3) 1410-1413: http://europepmc.org/articles/PMC122204

* See "Further Reading: Books and Hotlinks" for descriptions of and further information on recommended reading materials.

SYMBIOTIC EARTH EXPANDED GLOSSARY
(with glossary words in bold)

Amber
A semi-precious gemstone, tawny or butterscotch in color, which begins as soft, sticky tree resin and thus can trap and fossilize live material such as insects. Lynn Margulis orchestrated the cutting with a diamond knife a thin section of a piece of amber from the Dominican Republic that contained a specimen of *Mastotermes electrodominicus,* a termite that today is found only in northern Australia. Inside the termite were found fossilized symbiotic microbes. (Footage of this is in the Epilogue) An avid student of the termite hindgut, Margulis wrote of her predecessor Joseph Leidy (1823 - 1891), a founder of the Academy of Natural Sciences in Philadelphia who was the first in North America to take a close-up look at the contents of a termite's intestine. "In watching the Termites from time to time wandering along their passages beneath stones," Leidy wrote, "I have often wondered as to what might be the exact nature of their food." What he saw under his microscope amazed him, according to Margulis. "If the termite's intestine is ruptured by the experimenter," she wrote, and then quoted Leidy, 'myriads of the living occupants escape, reminding one of the turning out of a multitude of persons from the door of a crowded meeting-house.' Leidy immediately realized that what he knew as 'white ants' [termites] were actually composed of dozens of different kinds of tiny life-forms, including bacteria and what we now know are **protists**." Among the many microbes that comprise the termite hindgut community are the symbiotic methanogenic bacteria (classified as **archaea** in the Woesian three-domain system) that actually *di*gest the wood that termites *in*gest, as well as, sometimes, ***Mixotricha paradoxa,*** which is itself a symbiotic collective. (For more, see Wier, et al, 2002, and Sagan, 2016, in "Further Reading – Books and Hotlinks.")

Anthropocentrism
Human exceptionalism; the notion that people, or humankind (Greek: *Anthropos*) is the center, the highest, or the most important life form. Below are Margulis' comments from *Symbiotic Planet: A New Look at Evolution*, posted online here: http://truthbarrier.com/2016/11/18/what-they-said-lynn-margulis/

> "The Gaia [theory] is not, as many claim, that 'the Earth is a single organism.' Yet the Earth, in the biological sense, has a body sustained by complex physiological processes. Life is a planetary-level phenomenon and Earth's surface has been alive for at least 3,000 million years. To me, the human move to take responsibility for the living Earth is laughable – the rhetoric of the powerless. The planet takes care of us, not we of it. Our self-inflated moral imperative to guide a wayward Earth or heal our sick planet is evidence of our immense capacity for self-delusion. Rather, we need to protect us from ourselves …. We need honesty. We need to be freed from our species-specific arrogance. No evidence exists that we are "chosen", the unique species for which all the others were made. Nor are we the most important one because we are so numerous, powerful, and dangerous. Our tenacious illusion of special dispensation belies our true status as upright mammalian weeds…. Less a single live entity than a huge set of interacting ecosystems, the Earth as Gaian regulatory physiology transcends all individual organisms. Humans are not the center of life, nor is any other single species. Humans are not even central to life. We are a recent, rapidly growing part of a single huge ecosystem at Earth's surface."
>
> — Lynn Margulis, Symbiotic Planet: A New Look at Evolution (1998)

Anthropocene Epoch

A proposed name for a new geological age marked by humanity's impact on Earth. If accepted the Anthropocene epoch would follow the Holocene epoch beginning about 10,000 years ago. Larger geological time spans include periods, for example the Quaternary Period of which the Pleistocene, Holocene, and Anthropocene would be parts. Still more inclusive geological time spans include Eras and Eons. (See Geologic Time Scale, page 59.) The Cambrian Period in which animals first proliferate in the fossil record begins approximately 550 million years ago, inaugurating the Phanerozoic Eon. Two other Eons, dominated by microbial life, precede the Phanerozoic – the Archean Eon from 3.8 to 2.5 billion years ago, and the Proterozoic Eon, from 2.5 billion years ago to the beginning of the Phanerozoic Eon, about half a billion years ago. The Anthropocene Epoch (variously beginning anywhere from 14000 years ago to 1945) has not been officially recognized by the International Commission on Stratigraphy or the International Union of Geological Sciences. Humanity is not the only life form to dramatically alter Earth's environment. **Cyanobacteria**, in the **Archean Eon**, raised the level of oxygen (then toxic to most life forms, including cyanobacteria themselves) in Earth's atmosphere from less than one to approximately twenty percent.

Anthropogenic

Human-caused. The adjective denotes something produced by humans, or human-derived. *Anthropogenic* change would mean a change that is wholly or mostly the result of human beings and their activities.

Anthropomorphism

The tendency to relate, describe, or attempt to understand things in terms best reserved for people. Imposing human ("anthropos") form (from Greek *morphē*, "shape"). Disney cartoon animals are anthropomorphic. Even the idea of a mechanical universe may be considered anthropomorphic, insofar as people think of mechanisms as something that are made by humans. The pathetic fallacy, to attribute human emotions to natural things, for example, "The sky is crying," is also anthropomorphic. Anthropomorphism cannot be helped in that we see things in terms of our selves; but part of the progress of science is, arguably, to increasingly see the universe less in terms of ourselves (e.g., "God" as a bearded human such as Zeus) and more to see ourselves as a result of natural processes of a more-than-human universe.

Archaea

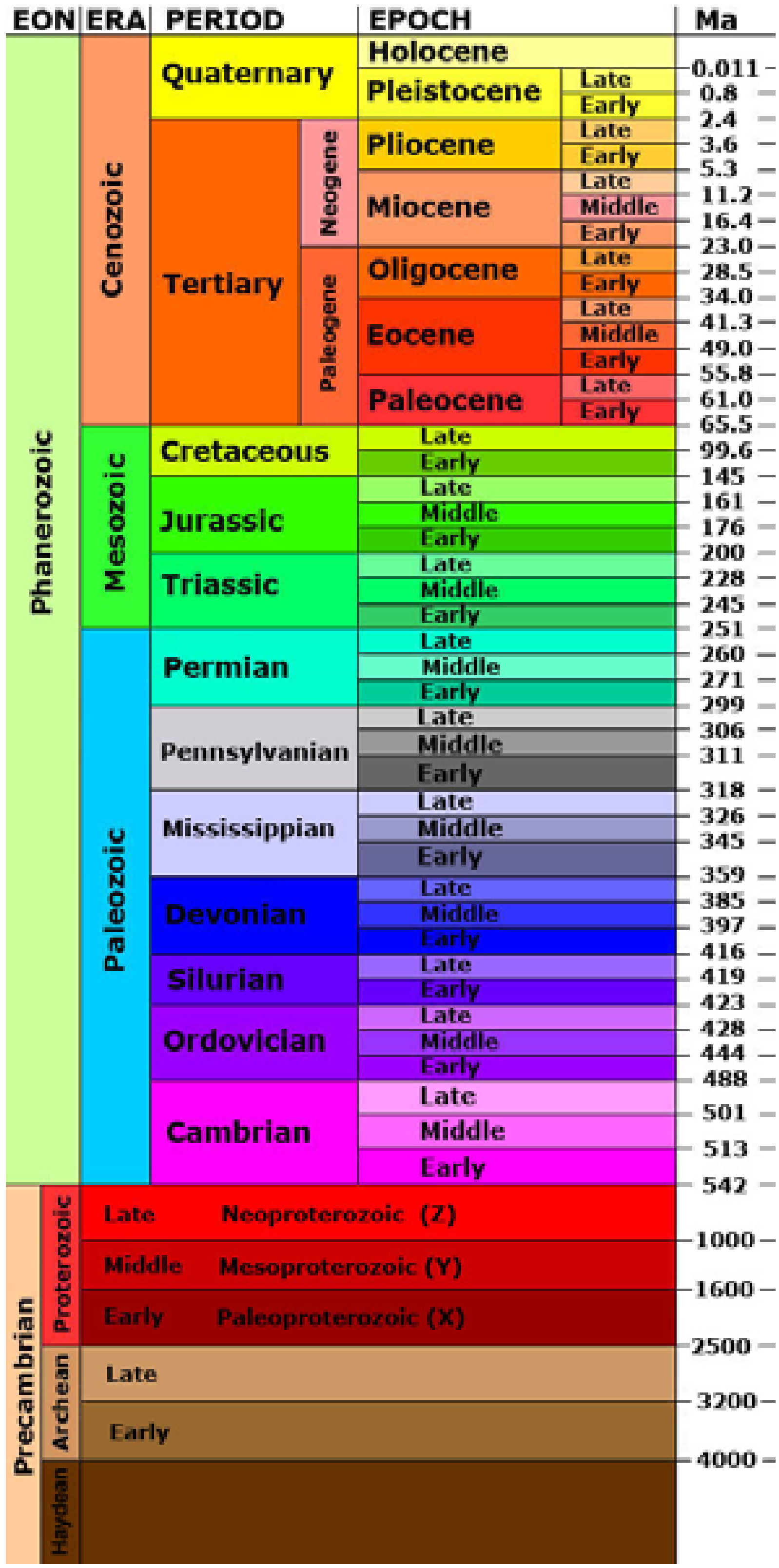
see **Five-Kingdom classification system**

Archean Eon

The second earliest of Earth's Eons, after the Hadean Eon from 4.6 to 4 billion years ago when Earth developed a solid crust, and before the Proterozoic Eon 2.5 billion years ago to 541 million years ago, when the first widespread evidence of animals appears in the fossil record. (See Geologic Time Scale, page 59.) The Archean, the time period in which life on Earth is thought to have evolved, thus stretches from about 4 billion years ago to 2.5 billion years ago. Not to be confused with the **Archaea**, one of three domains in Woese's tree of life.

Autopoiesis

From Greek words for *self* ("auto") and *making* ("poeisis," the same root that gives us the word "poetry.") Coined and explored by biologists Humberto Maturana and Francisco Varela in the book *Autopoiesis and Cognition*, autopoiesis is the property seen in cells and organisms (but not viruses) that allows them to maintain



Geologic Time Scale

and renew themselves by regulating their composition and boundaries. That autopoiesis is a more basic feature of life than reproduction is suggested by the fact that a nun, no less than a mule, is clearly alive but will not reproduce. According to Margulis, **Gaia**, the sum of Earth's biota taken as a self-regulating system, is *not* an organism but *is* autopoietic. Autopoietic systems are complex thermodynamic systems that expend energy to perceive, move, and otherwise ensure their continued access to needed energy and material reserves. Life makes itself continuously through chemical operations, and this is arguably the key feature of life. It is not enough, therefore, to define life by reproduction. For more, see Maturana and Varela in "Further Reading – Books and Hotlinks." See also, **Systems Thinking.**

Biomineralization

The technology-like manipulation of minerals by cells. Calcium carbonate and silica in the oceans, nickel collected by plants, apatite made of mostly calcium phosphate in human bones, and iron minerals and even gold precipitated out of solution by bacteria are all examples of biomineralization.

Capitalism

An economic system emphasizing profit, private property, and private sharing of corporate ownership of the means of production with an eye on ever-increasing profit from consumption and distribution of goods at prices arrived at by competition. Capitalism relies on an endless supply of raw materials and ever increasing growth.

Carbon dioxide (CO_2)

A gas in the atmosphere made of one carbon and two oxygen atoms, carbon dioxide composes over ninety percent of the atmospheres of Mars and Venus, but exists in Earth's atmosphere in a much lower concentration (about .04%). Humans (and all aerobic organisms) breathe-out carbon dioxide as a waste product as they metabolize/burn food. Using the energy from the sun, plants and other photosynthetic organisms combine carbon dioxide with water to make sugars/food. The waste product of this process is oxygen, which aerobic organisms use to metabolize the food. Over the long term, carbon dioxide has been fixed by photosynthetic life forms and buried in Earth's surface, perhaps countering the increase in solar luminosity which otherwise would have been responsible for heating Earth's surface to levels unfit for life. This last may be considered a **Gaian** phenomenon.

CO_2 is produced through the process of combustion. Due to the excessive burning of fossil fuels the concentration of CO_2 in the atmosphere has increased. A greenhouse gas, CO_2, along with methane and some other gases, is generally agreed to be partially responsible for anthropogenic global warming due to this rise in concentration. However from a systemic (Gaian) point of view, anthropogenic global warming (also called climate change) is the result of many interconnected factors, of which the greenhouse (warming) effect is one. Notably, humans have abused the land by cutting down trees, and destroyed the soil through extractive agricultural practices – decreasing the drawdown of carbon into the soil through photosynthesis and disrupting the water cycles and causing floods, droughts, and serious storms. Carbon dioxide dissolves in water to form carbonic acid, and excess carbon dioxide emissions have led to ocean acidification.

Carbon fixation

The biochemical process by which photosynthetic organisms – primarily cyanobacteria and algae, including seaweed and kelp, and plants – take carbon from carbon dioxide in the atmosphere and integrate it into their cells. A most important form of carbon fixation – taking carbon dioxide out of the air and putting it into minerals in the ground – is by life's process of photosynthesis. Since the origin of the solar system the sun is thought to have increased in luminosity, thus heating up the Earth. But as it did photosynthetic organisms on Earth also grew, removing carbon dioxide from the air as part of their photosynthesis. The result of this is generally agreed to have cooled the planet by removing the greenhouse gas, CO_2 just as the sun would have been warming it up to dangerous levels. **Stromatolites,** an ancient form of living rock produced in layers and likely a dominant form of life during the **Archean Eon**, may have fixed enough carbon into carbonate to cool the early Earth. This ancient communal form of **cyanobacteria** dominated life and also added substantial amounts of free oxygen to the air, helping to turn the planet blue due to the blue wavelength light-scattering property of oxygen atoms. Without photosynthetic bacteria, Earth may have become like Venus, a super-hot, unlivable place surrounded by clouds of CO_2. Carbon fixation or assimilation of carbon dioxide into organic compounds can also be done by chemosynthesis, in which some organisms use carbon from the atmosphere in the absence of light. Chemoautotrophs include bacteria that can fix carbon using energy from the oxidation of hydrogen gas or hydrogen sulfide rather than the energy of light. An artist's depiction of the blue Archaean Eon can be found here: alexdoppelganger.com/wp-content/uploads/2016/02/archeaneon.jpg.

Chloroplasts

The green organelles in the eukaryotic cells of plants and algae. Responsible for photosynthesis, these green inclusions have been genetically traced back to cyanobacteria, free-living photosynthetic bacteria. Cyanobacteria are often multicellular, forming chains and layers of microbial mats. Chloroplasts are the green form of plastids, which may be brown or purple-red in kelp or algae, in which case they are sometimes referred to more specifically as phaeoplasts (brown) or rhodoplasts (purple or red).

Cognition

As defined in the film by James Shapiro, cognition is "action based on sensory information." The sensitive, real-time operations of cells, for example checking their DNA for errors before and after replication, is an example of cognition in Shapiro's sense.

Consortium

Plural, consortia; in biology, a group of distinct individuals of different kinds forming a unit at a different level.

Coral bleaching

The lightening in color of corals, due to their expulsion of the algae that live inside their tissues. Healthy corals, which are marine animals dependent upon **endosymbiotic** algae, become more prone to death when they lose their zooxanthellae (undulipodiated dinomastigotes, a kind of algae), which can be caused by increased sea surface temperatures. (For more, see Ailsa Wild et al, 2014, *Zobi and the Zoox* in "Further Reading – Books and Hotlinks.")

Creationism

An atavistic explanation of biological origins by invoking the powers of an unseen entity, often pictured as a giant man, referred to as God. Creationism is often opposed, especially in the United States, to **Darwinism**, which restricts its explanation of life's development and expansion over Earth's surface to natural causes. Evidence of change in organisms via human breeding of animals such as pigeons and plants ("artificial selection"), was part of the evidence put forth by Charles Darwin to argue that, over long periods of time species not only slowly changed but evolved (by "natural selection") into new species no longer able to breed with their ancestors. The invocation of slow change as part of Darwin's argument is clung to by creationists, who argue that the Bible is a sacred, divinely dictated text, rather than a human-originated document, to suggest that gaps in the fossil record are evidence of God's creation of new species. Gaps in the fossil record are better explained by other factors, however, such as deterioration of soft-bodied fossils, and **symbiogenesis**, which can produce new forms of life far more quickly than the process of gradual accumulation of random mutations trumpeted by **Neo-Darwinism**.

Cyanobacteria
Historically also called "blue-green algae," although this term is best avoided as true algae, including green algae, are **eukaryotic** cells with nuclei. Cyanobacteria, by contrast, while also appearing to the naked eye as algae-like scum, are true bacteria; prokaryotes, they lack nuclei and DNA packaged into protein-coated chromosomes, as well as mitochondria. Cyanobacteria, by using hydrogen as an electron donor in photosynthesis, are thought to have begun to release oxygen from water, H_2O, beginning about two billion years ago. This process oxidized the entire surface of Earth, beginning with the oceans and then the atmosphere. (For more, see Sagan, "Beautiful Monsters: Terra in the Cyanocene" in "Further Reading – Books and Hotlinks.")

Cytology
The study of processes in eukaryotic cells outside the nucleus, in the cytoplasm. The detection of nucleic acids, that is, of DNA and RNA, in the mitochondria and chloroplasts, was a major event leading to the insight that **eukaryotic** cells evolved not directly but from **consortia** of **archaea** and different kinds of **bacteria.**

Darwinism
The complex suite of ideas associated with the work of Charles Darwin, the two most important of which are 1) that all life evolved from a common ancestor and 2) the origin of new species by natural selection. Natural selection may be defined simply as differential reproduction, that is, as the combination of organisms generating variety, and reproducing, but with only some variants surviving. Although in popular vernacular the word "Darwinism" has become synonymous with evolution, evolution in the broad sense of biological change over time is now recognized by scientists to involve processes that were not emphasized by Darwin. For example, because Darwin drew on the ideas of geologist James Hutton, who emphasized the great lengths of time necessary for the gradual accumulation of geological processes such as mountain building, Darwin's presentation of evolution by natural selection depended strongly on his emphasis of gradual biological change. Gradualism was a key concept allowing natural selection to be received as a plausible alternative to compete with the 2000 year old narrative of divine creation in which separate species were imagined to be created instantly and separately by an all-powerful creator; that is, **creationism.** In addition to such gradualism, Darwin emphasized the mechanical nature of natural selection; rather than requiring a conscious God, evolution could work itself by the differential reproduction of slightly altering forms, some more and some less adapted to the environment. This idea of the "law" of *natural* selection allowed his presentation of evolution to borrow prestige from Newton's laws in physics, which showed the universe to work itself with mathematical laws and no need for divine intervention. But by doing so, Darwin "took the life out of biology," in the words of Samuel Butler, who both admired Darwin's contribution but regretted that he had portrayed evolution too much on the mechanistic model of physics. In fact, Darwin did allow for a role in evolution to be played by choices and activities of organisms themselves, especially in selection of mates. This latter, which he called

sexual selection, argued that males could be bred by female choice of which males to mate with; for example, in the evolution of peacocks, females preferred to mate with males with more impressive and colorful tail feathers. Although Darwin was convinced that there was no need for God to explain the evolution of increasing biodiversity, he was not as sure whether we could similarly conceive of the epic transition from non-life to life. Which, he wrote, occured in "some warm little pond with all sorts of ammonia and phosphoric salts, light, heat, electricity etcetera present [in which] a protein compound [could be] chemically formed, ready to undergo still more complex changes." Despite Darwin's emphasis on natural, rather than supernatural explanations for life's changes, some scholars, such as science historian Jan Sapp, who appears in *Symbiotic Earth*, prefer to drop the term Darwinism in referring to evolution because Darwin's views are unnecessarily restrictive. Since **symbiogenesis** (and other quick processes unknown to Darwin, such as **genome** replication) *are* involved in evolution, Sapp suggests that the term is best reserved not for evolution generally but for Charles Darwin's 19th century portrayal of natural selection as mostly a gradual and mechanical process.

Ecosystem/Ecological System

Although sometimes used as synonyms, these terms may be differentiated. An ecosystem is a collection of members of different species living in a given locale that successfully recycle the elements and compounds necessary for their continued survival. An ecological system, by contrast, contains multiple species living together but is not necessarily able to continue the process of using available energy to recycle its constituents indefinitely. Thus a human body, according to this distinction, is an ecological system but not an ecosystem, because it does not have the capacity to recycle its wastes. **Gaia**, however, does have this capacity.

Endosymbiosis

Symbiosis in which one organism lives inside (Greek, "endo") another.

Epigenetics

Coined in 1939 by Conrad Waddington from *epi* meaning "close to" or "above" and *genetics*, epigenetics refers to changes in genetic function irrespective of changes in genetic sequence. In *Symbiotic Earth,* Scott Gilbert defines epigenetics as "the ways by which different genes are used at different times and places so that the same genome that you inherit in your fertilized egg can give rise to this set of proteins in muscle cells, this set of proteins in neurons, this set of proteins in lymphocytes, this set of proteins in pancreas cells so that the one genome can give rise to all these different cell types." Epigeneticists study how cell systems in response to environmental stimuli use the DNA template to make specifically required proteins. Molecular factors such as methyl groups (composed of methane) can regulate how DNA functions, and which genes turn on or off, irrespective of the genes themselves. A common form of epigenetic regulation occurs in methylation when a methyl group attaches to the nucleotide molecule, cytosine. (For more see e.g., Michael Skinner, in "Further Reading – Books and Hotlinks").

Epistemology

A branch of philosophy concerned with how we know and the limits of knowledge.

Eukaryote

An organism, whether single-celled or multicellular, consisting of cells with nuclei. Eukaryotic cells are generally agreed now to have evolved from prokaryotes (cells without nuclei, such as archaea and bacteria) that came together in **endosymbiosis**, and evolved into new life forms through **symbiogenesis**. Human beings are just one example; all familiar plants, animals, and fungi consist of variants on colonies of eukaryotic cells.

Extinctions

The dying out of all members of a given species. Examples are the trilobites from the Cambrian period, some of which resemble horseshoe crabs but none of which presently exist, although their fossils are left in the rock record. Dinosaurs are still the most famous examples of extinct species. Several times in Earth's history, large numbers of species went extinct at the same time; these are referred to as mass extinctions. In each case, so far, Gaia has recovered from mass extinctions to reach greater levels of biodiversity. Scientific guesses for causes of mass extinctions include asteroid collisions or volcanic eruptions. Earth currently is considered to be undergoing a sixth mass extinction, the result largely of industrial humanity destroying other organisms' habitats. Although the Cretaceous extinctions that destroyed the last of the big dinosaurs some 65 million years ago is the most famous mass extinction, the earlier Permo-Triassic mass extinction event, some 250 million years ago, was more devastating with, for example, some ninety-five percent of all marine animal species becoming extinct.

Five Kingdom classification system

More complex than the outdated plant-animal dichotomy, the five-kingdom classification system divides life into bacteria, protoctists, plants, animals, and fungi. The five-kingdom classification system was initially developed by biologist Robert H. Whittaker and further developed by Lynn Margulis in collaboration with Karlene Schwartz and Michael Chapman.

All prokaryotes (organisms without a nucleus) belong to the Kingdom Monera (bacteria); while the four other kingdoms – Protoctista (e.g., amoebae, slime molds, and seaweed), Animalia, Fungi, and Plantae – are composed of cells with nuclei, that is, they are eukaryotic organisms.

In 1977 Carl Woese (1928 -2012), a microbiologist and biophysicist, presented a "three domain system" that broke all of life into three big domains: archaea, bacteria, and eukaryotes. In this classification system the prokaryotes are broken into two domains: archaea (formerly archaebacteria or archaeobacteria) and bacteria. All other organisms, the eukaryotes, are in the domain eucarya. This scheme was based on molecular analysis of 16s ribosomal RNA of prokaryotes. Because it is believed that this RNA evolves very slowly, it is considered useful in constructing phylogenies.

Both the five-kingdom and the three-domain systems represent an improvement on the Linnaean system which largely ignored microbes, lumped fungi with plants, and separated all visible life forms into animals or plants.

Although the three-domain taxonomy of Carl Woese has become popular recently as the would-be most "scientific" taxonomy for life on Earth, it is open to the criticism that it is too narrowly based on molecular evidence to be an inclusive guidepost for life's diversity and complex ancestry. Critics point out that it suffers from being based only on sections of RNA of the organisms in question; in the Woesian taxonomy bacteria and archaea are more different from one another than archaea are from humans. Woese also suggested, based on the genetic differences between bacteria and archaea, that life evolved twice on Earth. The five-kingdom system by contrast, combines morphological, evolutionary, biochemical and genetical criteria and according to its proponents, more accurately represents life's diversity and evolution than the three-domain system, (For more on classification, see e.g., Whittaker and Margulis, 1978; Margulis and Chapman, 2009; and Carr, 2011 in "Further Reading – Books and Hotlinks.")

The documentary *Symbiotic Earth* sticks to the Five Kingdom Classification system with only a brief mention of Carl Woese's system because Lynn Margulis consistently used the Five Kingdom System in her career and while she accepted the validity of Woese's scheme (with some reservations) she never adopted it into her work. Margulis, who collaborated with Whittaker in 1979 shortly before the latter's death, points out that, "'Systematic' classification schemes that attempt to reflect evolutionary history and graph it on 'phylogenetic diagrams' require 'webs'; no 'trees' topology is ever adequate."

Gaia

The biosphere or global ecosystem taken as the sum of Earth's biota as a self-regulating system. Gaia is not an organism but may be likened to a superorganism that flexibly controls global mean temperature, marine acidity, and atmospheric chemical composition. Despite its name, there is nothing mystical or female about Gaia, which riffs off the same root, Ge-, used to form the words geology and geography. In the film Lynn Margulis disavows the notion that the Gaia is an organism, defining it instead as "a physiological system made up of ecosystems, themselves made up of communities." (For more see Bruce Clarke, "Gaia is not an Organism" in "Further Reading – Books and Hotlinks.")

Gene

A unit of nucleic acid, whether of RNA or DNA, that codes for the proteins that together compose the bodies of organisms. The term gene was defined as the unit of heredity before the discovery of the role of DNA. Although the "father of modern genetics," Gregor Mendel never used the term, his close study of inheritance patterns in pea plants suggested the existence of discrete units controlling inheritance, which could be dominant or recessive, skipping generations. The term gene was first used in 1905 by Wilhelm Johanssen, who also distinguished between the genetic material of an organism (which he called "genotype") and its visible body (the "phenotype"). The term genetics was introduced that same year, 1905, by William Bateson. James Shapiro in *Symbiotic Earth* argues that the gene is a philosophical concept in the sense that Darwin and Mendel were looking for the physical basis of heredity, and the later discovery of DNA's role seemed to suggest that there was an unchanging biochemical basis for all the traits of an organism. But as Shapiro chronicles in his 2011 book *Evolution: A View from the 21st Century* (praised by both Carl Woese and Lynn Margulis), the genome is more a read-write than a "read-only" system. As he says in the film, "The gene is one of those complex philosophical concepts which was useful at one time but is now hindering progress." Shapiro states that modern researchers are not searching for the genes per se but looking at coding DNA sequences (CDSs) to understand how those work together to produce proteins and organisms.

Genetic Determinism/Reductionism

Genetic (or biological) determinism refers to a tendency to overreach in ascribing biological traits and behaviors to the genes or, more generally, to biological inheritance. Complex bodies and behaviors are reduced to a single sort of molecule. Genetic determinism is questionable in that the **gene** has been recognized to be part of a molecular matrix of proteins and **nucleic acids** that together make up the working autopoietic organism. Genetic reductionism or determinism is also questionable politically because explaining traits and behaviors by genes and inheritance suggests that we may not be able to change if our genes do not. **Evolution** is traditionally described as the result of the accumulation of random genetic mutations over many generations. **Epigenetics** and **symbiogenetics** refer to changes that can occur at levels above or beyond that of individual genes, including whole organisms merging their entire genomes. Nonetheless, the continuing investigation of the relationship between our molecular inheritance and our traits and behaviors, insofar as it reveals our tendencies, can reveal obstacles we must overcome to make desired changes as individuals and a species. The problems with genetic determinism are thus twofold: 1) they tend to demote influence of the environment, experience, epigenetics, self-directed behaviors and other factors and, 2) in doing so, they may prematurely lead us to conclude that certain behaviors we would like to get rid of are impossible to change. In drawing attention to mindsets that assume that human traits are exclusively due to unchangeable genetic factors, these questions and explorations may be helpful in combatting biological modes of explanation historically linked to eugenics, racism, sexism, and genocide.

Genome

The genome refers to the total genetic complement of a given organism; all of an organisms genes, taken together, in other words, comprise its genome. **Genetic Determinism** led to the false hope that complete characterization of an organism's genes would allow for a complete biological picture of an organisms structures and function. This hope was dashed, however, in the **Human Genome Project** when it was found that many genes are not expressed, being redundant or regulated through **Epigenetics.**

Geochemistry

The study of Earth's chemistry. Geochemistry uses the tools and principles of chemistry in an attempt to understand geological processes. Examples of geochemistry include studies of the composition of meteorites, abundance of elements in Earth's crust, and the production of Earth's magnetic field. Geochemistry may be contrasted with biogeochemistry or Gaia science, more commonly known as Earth System Science. Biogeochemistry, Gaia science, and Earth System Science integrate an understanding of biological systems into a study of Earth's surface and its chemistry. Atmospheric chemist James Lovelock referred to the century-plus tendency for separation among the various scientific disciplines as "academic apartheid"; collaborating with Lynn Margulis, he developed the interdisciplinary **Gaia** hypothesis, which clarified the impossibility of understanding Earth's atmospheric chemistry without understanding the microbes growing on its surface. Since life has long since penetrated into the lithosphere and become part of the hydrosphere, and continuously produces the atmosphere, it is no longer sufficient to consider planetary processes, on Earth's surface at least, apart from life; geochemistry has become biogeochemisry.

Geosiphon

The genus containing only one species, *Geosiphon pyriformis*, a fungus that hosts members of colony-forming **cyanobacteria** genus *Nostoc* within its cells.

Hadean Eon

The earliest period of Earth's history, from 4.6 – 4 billion years, giving way to the **Archean** from which the first evidence of life on Earth are found. (See Geologic Time Scale, page 59.)

Holobiont

Holobiont, coined by Lynn Margulis, from the Greek word *holos*, for whole, and *bionts,* a discrete unit of living matter. Holobiont refers to **consortia** of different species that form coherent ecological systems and eventually bodies from individuals of different species or lineages that remain in contact for significant portions of their life history. The term was introduced by Margulis and Fester, eds, in the 1991 book *Symbiosis as a Source of Evolutionary Innovation*.

Human Genome Project

Formally begun in 1990 and declared complete in 2000, the Human Genome Project (HGP) was a government project that attempted to discover the complete sequence of nucleotide base pairs (the chemical "steps" on the helical ladder of DNA) that make up all of a human being's **genes.** Because each human is individual, the sequenced genetic information, which was taken from a number of different people, and then mapped to form a composite individual, does not represent any single person. Despite its declared success, the HGP in its survey identified neither the DNA in centromeres, at the centers of duplicated chromosomes, nor telomeres, the ends of chromosomes, implicated in human aging. The HGP also did not inventory the genes in the microbiota of humans. These genes, which make all of us **holobionts**, and which together comprise the human **microbiome**, are currently under investigation by the **Human Microbiome Project.**

Human Microbiome Project

Enabled by new technology that rapidly samples and sequences DNA, the Human Microbiome Project is a National Institutes of Health project meant to discover and characterize the microbiota belonging to the human gut, mouth, skin, airways, urogenital tract, blood and eyes. Incorporating the work of teams of scientists, this project recognizes that most microbes are not disease-causing "germs" but neutral, helpful, or even necessary. Many of these microbes are crucial to our health, digestion of food, synthesis of vitamins, and even feelings of well being. Taken as a whole the changing populations of microbes that live in, on, and as our bodies—our **microbiome** —has garnered increasing interest, and has important implications for the future of medicine and ecology.

Laissez-faire economics

Refers to economic systems in which transactions among people are considered to be relatively free of government regulation or interference in terms of taxes, tariffs, and subsidies. From French words literally meaning "to let-to do," and signifying an ideology of efficiency by being left alone

Lamarckianism

Lamarckianism (or Lamarckism) named after French biologist Jean-Baptiste Lamarck (1744-1829), is an evolutionary theory arguing that changes occurring in organisms through use and disuse of their body parts in a single generation can be inherited by their offspring. The classic example is that giraffes, by stretching to reach higher leaves, somehow transmitted their incrementally longer necks to their offspring. Despite the ridicule Lamarck was exposed to in suggesting that efforts in one generation may lead to traits inherited in the next, Darwin himself entertained "Lamarckian" ideas, such as his notion of "gemmules," theoretical particles shed by the organs into the bloodstream and reaching the reproductive organs. Lamarckianism is still considered a misunderstanding of how evolution works, with the orthodox belief being that only random mutations in genes can lead to different traits, whereas anything an organism does with its body or behavior will not affect its genetic material or offspring. Indeed, the belief that only **genes** (the "genotype") influence organisms but organisms never influence genes, was christened the "central dogma" of evolutionary biology by Francis Crick in 1958: It is possible to transfer information "from nucleic acid to nucleic acid, or from nucleic acid to protein . . . but transfer from protein to protein, or from protein to nucleic acid is impossible." Watson's claim, however, was found to be premature. As explored in **epigenetics, symbiogenetics,** and **natural genetic engineering**, the real-time behavior of organisms can directly impact their own DNA. Symbiotic inheritance may be considered a form of Lamarckian inheritance insofar as an organism, by taking in another (using its body, made of proteins) then acquires the genetic traits of the organism it takes in. For example, when ancestral members of the species of green worms known as *Convoluta roscoffensis* fed on algae that they then failed to digest, they acquired the DNA of the algae they engulfed. In this case Lamarckism, defined as the "inheritance of acquired characters," can be considered accomplished because the behavior (eating, engulfing) has led, in a single generation, to new traits which (admittedly by taking in the algae's genome) "breed true." Now adult *C. roscoffensis*, whose mouths remain closed, never need to eat in the traditional manner, because they are fed from the inside by the photosynthate of their living green gardens. In a single generation the algae acquired not only new characters (such as burrowing out of harm's way into the sand when the surf pounds), but new genes and indeed, a whole new genome, that of the animal which swallowed them. Thus, despite the dismissal of the Lamarckian idea of the inheritance of acquired characteristics, **symbiogenesis** provides a real example of organisms acquiring traits from efforts and events occurring within their own lifetimes.

Lysenko

Trofim Lysenko (1898-1976), a Soviet agricultural biologist who rejected Mendelian genetics in favor of a version of Lamarckianism, which emphasized the heritability of acquired characteristics. Lysenkoism became a state-approved scientific ideology in the Soviet Union. A story suggests that the final blow to Lysenkoism occurred when a meek man with glasses, at the back of a lecture by Lysenko, asked why, if characteristics acquired in one generation are indeed passed to the next, were Soviet girls born virgins.

Life

The *process* evident at Earth's surface in the growth, **autopoietic** self-maintenance, and reproduction of evolving organisms. Since life is characterized, among other things, by an evolutionary process of growth and change on our planet, a precise definition remains elusive. "To *define*," from Latin roots meaning to give a limit to, may prematurely characterize the planetary process in which we are involved: already over three billion years old and likely to continue for billions more, expanding and involving new chemical elements, perhaps until the death of the Sun some five billion years in the future.

Lyme disease

A neurodegenerative disorder caused by *Borrelia* spirochetes carried by ticks.

Mastotermes darwiniensis

The species name of a termite, known from Darwin, Australia. Like other termites, insects of the species *M. darwiniensis* are **holobionts**, with microbes in their hindguts, both bacteria and protists, without which they would not be able to digest the wood that is their food.

Mechanism

As distinguished from specific mechanisms, the general machine metaphor of early modern and continuing science. Isaac Newton's Laws of Motion, connecting celestial movement to Earthly movements, helped portray the entire cosmos as mathematically explicable. However, Newton (1642-1727) still believed in a Creator God, and his ideas were compatible with deism, the notion that while God wasn't involved directly in the universe's day-to-day operations by exerting His will, the entire cosmos could be seen as his great device, contraption, or mechanism. For René Descartes (1596-1650) living organisms themselves could be considered clockwork mechanisms, with only human beings, endowed with divine free will, being a partial exception. Mechanism and allied deism opened the way for investigating nature as products of the mind of God, but they also, as Darwin's contemporary Samuel Butler (1835-1902) exclaimed in his critique of natural selection presented as a physics-like law, "took the life out of biology." Ironically and paradoxically, the "**Selfish Gene**" perspective of evolution, used to combat **Creationism**, presents life as largely a self-working mechanism; thus, while it adamantly rejects a creator God, it reinforces the notion of human-like productions of biology's crucial parts. A similar argument can be leveled against the theorizers of artificial intelligence, who generally believe that "mind" can be created if the right biological or computer parts are put together in a suitable mechanism. In general Mechanism runs the risk of prematurely attempting to explain nature in a too-narrow context, derived less from observation than humankind's experience in putting together models and machines that function differently than natural complex systems.

Metabolism

Metabolism, as defined in *Symbiotic Earth*, is the flow of energy and matter through a network of chemical reactions within an organism that allows it to maintain and perpetuate itsef. It refers to any of the various ways in which evolved organisms are able to remain alive and reproduce through access to energy and material substrate. Methanogenesis (in **archaea**), photosynthesis (in **cyanobacteria**, algae, and plants), anaerobic respiration, aerobic respiration, sulfate reduction (by sulfate-reducing bacteria), sulfur oxidation (for example by the white bacterium, *Beggiatoa*), fermentation (for example, by yeast growing on sugars and producing alcohol and carbon dioxide as wastes) are all examples of metabolism. Remarkably, considering our **anthropocentrism**, all of the main forms of metabolism used to get energy and nutrients from different sources already evolved in prokaryotes; but only one of them, aerobic respiration, is exploited by all familiar animals, including humans.

Methanogenesis

The production of methane, a greenhouse gas, by methanogens, a type of prokaryotic microorganism.

Microbial mats

Textile-like masses, often found by the ocean where there is no human development and few larger animals, consisting of distinct layers of metabolizing bacteria. The main players are usually cyanobacteria on the surface, with oxygen-avoiding anaerobic bacteria living in lower levels. **Stromatolites**, domed-rocks both living and fossil, also appear in marine settings as group structures built by different kinds of bacteria.

Microbiome

The microbes and communities that normally coexist inside, with, and on larger organisms such as animals. In the middle ages it was often thought that demons, or witchcraft or ill humors were the cause of infectious sickness. The great medico-scientific triumph of Louis Pasteur's "germ theory of disease" led to medical breakthroughs, and includes the synthesis of penicillin (originally discovered from the anti-bacterial effects of *Penicillium* mold) and other antibiotics in treating bacterial infections. However, the emphasis on microbes as germs neglected the opposite, less obvious but equally medically important truth, that the health of humans and other organisms often depends upon interactive stability of microbial communities that help maintain the organism, which is a **holobiont**. This has led to a reversal of the earlier judgment of microbes as "bad." Healthy organisms consist not only of their eukaryotic cells but of their environmentally acquired bacteria, fungi, viruses, and protists. Antibiotics, although they can destroy "bad" bacteria, may also destroy "good" microbes in the process. Consider the case of *Clostridium difficile,* a bacterium that can colonize the gut, causing sometimes devastating recurrent infections, after treatment with antibiotics knocks out a person's normal microbiota, his or her microbiome. In such cases it has been found that fecal transplants from a healthy person can restore health and get rid of the *C. difficile* infection. In terms of the life-work of Lynn Margulis the coinage of the term microbiome is significant because it underscores her oft-repeated claims that microbes, formerly understood almost exclusively as germs or curiosities, are far more: crucial to life on Earth, these prokaryotes are both our comrades and our evolutionary ancestors; and, as our microbiome, they are also necessary adjuncts in keeping our bodies healthy and happy.

Microtubules

Living tubes of polymers of the protein tubulin found in the cytoplasm and involved in many intracellular processes, such as mitosis and meiosis wherein the chromosomes are apportioned to offspring cells in cell division. Microtubules also exist in **undulipodia**, the waving cilia that propel cells or particles within larger organisms. They are also found in the human brain. Margulis suggested that some of their characteristic patterns, such as being organized in circles of nine doublets surrounding a central pair, as found in the tails of microorganisms as well as human sperm tails and oviduct cilia, may have originated from an ancient wriggling symbiotic microorganism, perhaps a spirochete. While the symbiotic origins of **mitochondria** and **chloroplasts** are well accepted, this aspect of her **SET** narrative has found less support, in part because to date no DNA sequences have been unambiguously detected in such microtubular structures.

Mitochondria

Singular, mitochondrion. Bean-shaped DNA-containing "power stations" found outside the nucleus in almost all eukaryotic cells. They use oxygen to burn food (sugars) and produce energy for the cell, releasing carbon dioxide. The mitochondria have their own DNA. The DNA of mitochondria has been traced to free-living respiring bacteria, specifically alpha-proteobacteria. This is called respiration; the complementary process, photosynthesis, performed by cyanobacteria and the chloroplasts of plants and algae, uses sunlight (energy), water, and carbon dioxide to make food (sugars), releasing oxygen. The mitochondria use a metabolic mode known as respiration, and produce the body's ATP (adenosine triphosphate), which is used in cells to store energy. The fact that mitochondria contain their own DNA, outside the nucleus, and that they are the same size as bacteria, and that they can reproduce on their own timetable, were all clues leading to the current consensus that mitochondria originally existed as respiring bacteria. The free-living bacterial ancestors of mitochondria would have proliferated after oxygen began to build up in the atmosphere due to the **metabolic** waste product of **cyanobacteria**, namely oxygen. By teaming up symbiotically with **archaean** hosts, the oxygen-respiring bacteria helped inaugurate the first **eukaryotic** cells, from which all protoctists, fungi, plants, and animals, including humans, evolved.

Mitosis

The process, sometimes called the "dance of the chromosomes," by which eukaryotic cells, whose number of nuclear chromosomes vary, divide. Mitosis is organized by the mitotic spindle, which depends on **microtubules.**

Mixotricha paradoxa

Found inside the intestines of termites, *M. paradoxa*, a sort of poster organism or mascot for **symbiosis**, is notable for integrating in its single body at least five sorts of organisms. Included are two kinds of spirochetes that are permanently attached to its surface, and help it swim. A **holobiont**, *M. paradoxa*'s mixed constitution is perhaps not so surprising, since it typically inhabits a packed community with other microbes found inside the wood-digesting termite.

Molecular biology

Biology based on examination of the molecular constituents, particularly the genetic sequences of bases making up RNA and DNA, in microbes and larger organisms.

Mycorrhizae

Singular, mycorrhiza. Mycorrhizae are symbiotic structures integrating fungi with the roots of plants. The fungi may exist externally or within the vascular plants' root tissues. As with lichens, which are cross-kingdom associations between fungi and algae or between fungi and cyanobacteria, mycorrhizae show how interactions between very different organisms can form new structures. Life on land, involving colonization of the soil, is thought by many to have been a kind of cooperative venture between fungi and algae, the ancestors to plants. Mycorrhizae give the fungus access to the plants' carbohydrates, its sucrose and glucose, while the mycelium of the fungus partner, are adept at moving through soil and finding water and nutrients, such as phosphate and iron, which might otherwise be inaccessible to the plants. By making acids that break down rocks mycorrhizae help create soil while giving plants access to essential minerals.

Natural Genetic Engineering

James Shapiro's term for the manifold abilities of bacteria and other cells to modify their own DNA, generally in response to stress. See his *Evolution* in "Further Reading – Books and Hotlinks."

Neo-Darwinism

Also known as the "Modern Synthesis," Neo-Darwinism represents the orthodox but relatively narrow version of Darwinism that brings together Mendelian genetics with Darwinian natural selection. Standard Neo-Darwinism models propose that almost all evolution is the result of the gradual accumulation of random genetic mutations via natural selection. However, Darwinism, evolution by natural selection, is intrinsically broader, allowing multiple other modes of evolutionary change, including sudden ("saltational") ones, such as those described in SET.

Nucleic acids

RNA and DNA, found in prokaryotes (bacteria) and eukaryotes in chromosomes coated by protein inside the cell nucleus, as well as in mitochondria and chloroplasts in the cytoplasm of cells. Nucleic acids are also found in viruses outside **autopoietic** cells.

Photosynthesis

Arguably the most important innovation in the history of life on Earth, photosynthesis is the metabolic conversion of light energy into chemical energy, specifically carbohydrates such as sugars which are synthesized from carbon dioxide and water. The earliest photosynthesizers were probably anaerobic, using hydrogen or hydrogen sulfide, but cyanobacteria evolved to use water, thus producing oxygen as a waste gas, and oxygenating Earth's atmosphere. Photosynthesis is the basic process that produces and regulates Earth's oxygen atmosphere, providing the energy and organic compounds for the rest of planetary life.

Planktonic larvae

The floating (planktonic) stage of most marine organisms. Larvae hatch from eggs and then change through the process of "metamorphosis" into adults. Such larvae generally do not look like "little adults" but may appear very different from the adult forms into which they metamorphose.

PNAS

Proceedings of the National Academy of the Sciences, the official scientific journal of the National Academy of Sciences of the United States.

Pre-Phanerozoic

Refers to the long, rich history of Earth and life before the Phanerozoic Eon beginning about half a billion (550 million) years ago, with the Cambrian Period. The Cambrian, characterized by an "explosion" of visible fossils of ancient animals, was once thought to contain the oldest fossils (all animals) of life.

Proterozoic Eon

The long Eon in Earth's geological history from 2.5 billion years ago to the beginning of the Phanerozoic (from ancient Greek *phaneros*, visible and *zoe*, life, beginning some 550 million years ago. (See Geologic Time Scale, page 59.)

Protists

Protists are single-celled **protoctists,** which comprise one of the **Five Kingdoms of Life.** Single-celled protoctists include amoebae, *Paramecium*, and other unicellular ciliates. Sexual reproduction involving meiosis, which reduces the number of chromosomes after fertilization, is thought to have evolved in protists.

Protoctists

The second kingdom to evolve in the **Five Kingdom classification system,** after the prokaryotes (bacteria and **Archaea**), protoctists (technically the **Protoctista in the Five Kingdom classification system)** include all organisms made of eukaryotic cells that are not plants, animals, or fungi. With 100,000 plus species, these organisms, while fascinating, are understudied as they are of little relative commercial importance. However, it is in members of this group that animals evolved; that our own kind of sexual reproduction (involving production of sperm and eggs from two parents) evolved; that bodies growing in a "diploid" state (that is with two sets of chromosomes) evolved; and that the first embryos (itself a trait shared by all animals) evolved. Finally, death as we know it in animals and its relationship to the sexual production of aging, dying bodies also probably first arose in this understudied group. Single-celled protoctists are called **protists**. The protoctists, ancestral to fungi, animals, and plants, continue to thrive in many environments on planet Earth.

Round bodies

Refers to the immuno-cryptic, dormant, and circle-shaped form of spirochetes infecting animal bodies. Round bodies are formed by spirochetes in both syphilis and **Lyme disease.** Continued study of the ability to form round bodies in ancient and extremely prevalent spirochete bacteria may shed light on ancient symbioses and incorporation of spirochete motility systems into the cells they invade but don't kill. Round bodies are thought to be the cause of the persistence and reoccurrence of diseases caused by spirochetes. For more see MacAllister, 2018 in "Further Reading – Books and Hotlinks."

Rumen

The larger section of the first part of the alimentary canal in ruminant animals which is the site of microbial fermentation. Within the rumen, part of the "stomach" of the grass-eating cow, are bacteria, archaea, protists, fungi, and viruses. Included in the rumen are archaean methanogens that use hydrogen produced by bacteria, protists, and fungi to reduce carbon dioxide into methane, which is then belched into Earth's atmosphere. This methane, although it reacts with oxygen in the atmosphere to produce water and carbon dioxide, is continuously produced by cows and other organisms to such an extent that the combination of reactive methane and oxygen could signal to intelligent extraterrestrials the existence of planetary Earth life, i.e., **Gaia**. It is also worth noting that the combination of life forms that makes the cow "do its thing," in terms of digesting the cellulose of grass in its **metabolism**, involves all five kingdoms of life in the **Five Kingdom classification system**, thus showing that the cow (among others) is a **consortium** or **holobiont**.

Scientific Revolution

A radical shift in thinking, perspective, and explanation that interprets key data in a different, evidence-supported way or ways from the former now outmoded, or incomplete understanding; a "paradigm shift," in Thomas Kuhn's terminology as developed in *The Structure of Scientific Revolutions*. Examples include the switch from a view of the solar system with Earth at the center to one of planets, including Earth, orbiting around the sun; of life being composed of a vital or divine substance distinct from nonliving material to the understanding of living matter as chemically continuous with nonliving elements and inorganic compounds; and the shift from a religious view of species as specially created to **Darwinism** in which species evolve. **SET** and **Gaia** theory also may be counted as scientific revolutions, or parts of a scientific revolution/paradigm shift. **SET** shows that life forms do not just form a branching "tree," but that the branches sometimes anastomose, that is come back together when **symbiogenesis** creates new types and species of organisms. **Gaia** theory, in turn, replaces the outmoded notion of Earth as a planetary rock with some life on it with a picture of a biosphere continuously created and modified by life working as a system.

"Selfish Gene"

A metaphor, developed by Richard Dawkins, that popularizes the perspective and mathematics of **Neo-Darwinism** by portraying genes as the main actors in evolution. Metabolizing bodies, like an oak tree or a human, in this portrayal, are secondary vehicles for the propagation of self-regarding genetic material, whose goal is to maximize its representation and quantity among competing forms. A main objection to this view is that genes are inactive outside of the cell and that, moreover, they do not act alone; that, not having selves, they cannot be selfish. In the **Symbiotic Worldview** the minimal unit or agent of life is not the **gene** but the cell, the simplest known entity which displays **autopoiesis**.

SET (Serial Endosymbiosis Theory)

Lynn Margulis' work in the 20th century and early 21st century was crucial for developing a new narrative of the history of life on Earth. Although she had predecessors (for example, Ivan Wallin in the United States and Boris Mikhaylovich Kozo-Polyansky in the Soviet Union, whom she acknowledged and in some cases helped become published in the English-speaking world) her tireless advocacy, presentation of evidence, and interdisciplinary and international collaborations transformed the idea of cell evolution by symbiosis from being an ignored and dismissed idea to being taught in high school textbooks. SET is the acronym for the different steps in her theory, which itself changed over time. SET identifies endosymbiosis, the living of cells *within* one another, as a fundamental process without which life as we know it would never have evolved. While traditional paleontologists and paleobiologists had assumed that most of evolution prior to the "Cambrian explosion" some 550 million years ago, was bereft of interesting events, Margulis combined paleobiology, microbial ecology, and genetic analyses to present a new, coherent, and detailed theory that highlighted the crucial early period – more than two-thirds of evolutionary history – when life on Earth consisted entirely of microbes. In the **Archean** and **Proterozoic Eons** we find the evolution of bacteria and archaea, and their symbiotic mergers into new cells which eventually evolved nuclei with chromosomes; these were the first eukaryotes**,** the first **Protoctists.** The "serial" in SET refers to Margulis' attempt to tease out the precise order of the major symbiotic events that led to the protoctist ancestors to animals, fungi, and plants. In her initial account of SET she presented evidence for the symbiotic merger first of oxygen-using bacteria and larger, anaerobic prokaryotes (now called **archaea**) that were poisoned by oxygen. These would have formed the first protists, similar to modern-day amoebae. Margulis argued that eating and infections were crucial in inaugurating the sort of **endosymbiosis** that led to larger life forms. Thus it is not quite right to consider these harsh beginning simply as "cooperation." Although many of the infected, or eaten but not digested, would initially have died, survivors were sometimes at a great advantage: they gained new genes, new traits and new metabolic skills. For example, the anaerobic archaea that picked up the ancestors to mitochondria used these undigested respiring bacteria to scavenge oxygen. Their still-living infectors or undigested food thus came to genetically protect them from a deadly toxin – the same O_2, or free oxygen, which we consider "fresh air."

A second major symbiotic event in Margulis' SET was the addition of green inclusions—initially cyanobacteria—to some free-living protist cells. The addition of cyanobacteria to the archaean-bacterial symbiotic cell paved the way for plant life. Trapped photosynthesizers produced food for the new combines. These cells would have been like modern-day *Euglen*, a single cell able to swim and scrounge for (bacterial) food like an animal but also able to feed itself in the sun like a plant.

Once heretical, in part because it violated the long-held notion that the road from microbe to human was one of gradual evolution by the accumulation of random mutations over immense periods of time, Margulis' view of eukaryotic cells as the result of a series of symbioses, is now accepted by the scientific community. Part of the reason it triumphed is that DNA sequencing studies showed persuasive likenesses between mitochondria and free-living aerobic bacteria; and also likenesses between chloroplasts inside eukaryotic cells, and free-living cyanobacteria outside them. See Dance, 2018 in "Further Reading – Books and Hotlinks."

Sex

As defined in *Symbiotic Earth* sex is the acquisition of DNA by a cell or organism from more than a single source. Sex involves the production of a new individual via the integration of new genes into the same or a separate body. Thus horizontal gene transfer, genetic exchanges even without production of new offspring, qualifies as sex. Bacterial sex, for example, entails two individuals both before and after genetic exchange. Two-parent sex in eukaryotes is, however, "vertical": new individuals are produced through fertilization, which entails combining a complement of roughly the same number of genes from each of two parents in a new individual. At its root sex can be considered genetic recombination, whether or not an additional cell or body is produced as a result of the process. (For more, see Margulis and Sagan, 1990.)

Social Darwinism

The conflation of Darwinism with the social "dog-eat-dog" milieu of 19th century capitalism, imperialism, and racism in which Charles Darwin lived, and which influenced his language and certain emphases in the presentation of his theory of evolution by natural selection.

Alfred Tennyson famously described nature as "red in tooth and claw." Nature, however, is also green with cyanobacteria creating food without blood from air, light, and water; and cyanobacterial waste, oxygen atoms, colors the Earth blue because oxygen atoms scatter blue wavelength light in seawater and atmosphere. Darwinism proper allows for many modes of natural selection, including that of groups, which Darwin explicitly explored in his speculations on human evolution. Popular expositions by some, however, such as Herbert Spencer and his term **"survival of the fittest,"** quickly became associated with a kind of shorthand for evolutionary theory that presented nature as everywhere competitive and individualistic, and which rewarded and excused ruthless behaviors, such as poor treatment of workers in factories, slavery, child labor, and exploitation of animals. Others, such as Prince Peter Kropotkin writing *Mutual Aid* after the Russian Revolution, gave different accounts of nature, emphasizing a deep tendency for cooperation and collaboration. In fact, all **protoctists,** plants, fungi, and animals are walking collectives, the cells of whose bodies evolved from ancestral endosymbiotic **archaea** and bacteria working together. Thus, although evolutionary history is full of uneasy truces and mass die-offs, the hierarchical notion that some organisms (such as people), some humans (such as the rich), are "higher" or "more evolved" ignores the insight that all organisms on Earth share a common ancestry from equally ancient primordial microbes, and are thus in this sense equally evolved. Our bodies themselves are evolving networks of ancient social and symbiogenetic relationships. It no longer seems credible, if it ever did, to describe evolutionary success in terms of the triumph of the individual.

Spirochetes

Corkscrew-shaped wriggling bacteria, both anaerobic and aerobic, that are prevalent throughout the microbial world. Spirochetes' motility mode allows them to penetrate muds and other viscous media, including animal bodies. Agents of pathology, for example **Lyme disease** and syphilis in human beings, spirochete symbioses may also have beneficial effects, for example helping to confer motility, that is, the power to swim, on **eukaryotes** such as ***Mixotricha paradoxa***. The tendency of these helical bacteria, which contain an internal bacterial flagellum, to range from deadly to helpful or even necessary, is typical of **symbiosis** and **symbiogenesis** in that permanent alliances and internal relationships can begin as infections or attempts at phagocytosis, that is, microbial ingestion that is never completed.

Stromatolites

Rounded stones, for example as found in Shark's Bay, Australia, that turn out to be precipitated by communities of bacteria, mostly cyanobacteria, slipping out of their polysaccharide sheaths as they move toward the sun. The biofilms, such as found in **microbial mats**, trap and bind sediment to produce the biogenic structures, which may have been a far more common feature on the **Archean** Earth. Both fossil and live versions of stromatolites are known.

"Survival of the Fittest"

Often attributed to Charles Darwin, this is philosopher Herbert Spencer's metaphor that Darwin used to explain "natural selection." The phrase "survival of the fittest" was used to popularize Charles Darwin's ideas and suggests a battle of sorts, perhaps a boxing match or other sporting competition, where only the strongest survives. However, since for Darwin "fitness" is a measure of an individual's ability to survive and reproduce, the term is misleading because the "fit" (not the "fittest" nor the strongest) by definition survive. In **Neo-Darwinism** fitness was given a mathematical value based on the number of offspring an individual produces. So, as Margulis says in *Symbiotic Earth*, "Your maiden Aunt is not fit no matter what, no matter how much money she gives to the New York public library. Yet the slob down the street who has ten kids is more fit by definition." The term "survival of the fittest" tends to twist, within the capitalist **zeitgeist**, the original Darwinian meaning of the word from a gauge of survival and number of offspring, towards a meaning of social standing and power, more appropriate to **Social Darwinism** than evolutionary theory proper. (see **Social Darwinism**)

In his book *The Great Dying*, Kenneth Hsü writes: *Survival of the fittest* was immediately embraced as a natural law that justified for capitalists ruthless competition. Andrew Carnegie wrote that "*the law of competition, be it benign or not, is here; we cannot evade it; no substitutes for it have been found; and while the law may be sometimes hard for the individual, it is best for the race, because it ensures the survival of the fittest in every department."* John D. Rockefeller grandiosely maintained that *"the growth of a large business is merely a survival of the fittest. It is merely the working out of a law of nature and a law of God."* (from Hsü, Kenneth J. 1986. *The Great Dying*, pp. 10-11.)

Symbiosis

As defined by Lynn Margulis, the prolonged physical contact of two different life forms or species, for most of their respective life cycles. Symbiosis does not refer to members of the same species; thus you are not, technically, symbiotic with your friend, lover, or family member, however much time you may spend with them. For Margulis it is confusing, if not incorrect, to describe symbiosis as a mutually beneficial relationship, as is often done — even by biologists — since parasites and some pathogens are symbiotic with their host, and secondly, symbiotic relationships can change: a symbiont that was beneficial can become detrimental.

Symbiogenesis

The generation of a new kind of life, new species or new organ system after close **symbiosis**. The most famous is the origin of the first protists**,** or eukaryotic cells, from mergers of bacteria and **Archaea**. In the history of cells, the encapsulation of the bacteria ancestor to mitochondria, lead to symbiosis and ultimately, symbiogenesis, as the two kinds of cells merged to form a new kind of cell. This new kind of cell, the **eukaryote**, then reproduced in colonies with many variations, some of which went on to become animals, fungi, and plants.

Symbiogenetics

Symbiogenetics is the proposed name of the broad discipline that studies the living together, both now and in the past, of microbes and other life forms in ecosystems; applying the principles of such observations to constructing new living systems on Earth's biosphere could be called "applied symbiogenetics." In retrospect Lynn Margulis, although she was an expert in several disciplines, may be called a symbiogeneticist. *Symbiogenetics* (the term was suggested by Dorion Sagan) is the working title of Margulis' last work, in press with University of Chicago Press.

Symbiotic Worldview

A phrase that stands for Lynn Margulis' new paradigm worldview and which is explored in the film *Symbiotic Earth*. It was suggested by Peter Westbroek in his presentation at the 2012 Lynn Margulis memorial symposium, which is excerpted in the first essay of the documentary. The symbiotic worldview encapsulates the perspective that all of life is interdependent and interconnected; that bacteria run the planet; that all organisms live in symbiosis with other organisms; that the cell is a sentient entity that controls the organism; that evolution is about organisms joining with one another; and that all of the organisms work together to form a self regulating system that covers the Earth: Gaia.

While completely Darwinian, this viewpoint emphasizes cellular interactions, mutual behaviors, and **symbiogenesis** among different forms. A symbiotic worldview ranges from the role of viruses in creating bacterial and other genomes, to the association of similar cells in the origin of plants, animals, and fungi from **protoctists**, to the cumulative effect of global Earth life, **Gaia**, on its planetary environment.

Systems Thinking

A way of thinking about living and non-living things that takes inspiration from the systems of nature, in which each individual part is intimately connected, often in many different ways, to the working whole. Systems thinking is contrasted with mechanism and reductionism in which understanding comes from reducing the objects of study (whether ideas or material) to smaller and smaller parts.

An excellent example, from Gregory Bateson, contrasts evolved nature with human-built machines: instead of spreading seed or laying sod, adding fertilizer, and mowing grass as is common on suburban lawns, in nature, as Bateson pointed out, the connections are more integral: the grass feeds the grazing cows, their grazing cuts the grass, and their feces fertilizes the grass. This is a good example of a natural system. Systems thinking is influenced by complexity theory and cybernetics, the study of control loops in organisms and machines.

Systems thinking does not exclude reductionism as a method of investigation, but posits that reductionism (focusing on the parts) is limited because it doesn't generally take into account interactions among the parts. Often these interactions generate new properties, called emergent properties. Water is an emergent property of hydrogen and oxygen, which couldn't have been predicted by a knowledge of hydrogen and oxygen in isolation.

The study of systems concentrates on studying patterns and relationships because, as Fritjof Capra says in the documentary, "from a systems point of view there can only be interdependence, every part is dependent on other parts. For examples of systems thinking see Bateson, Capra and Luisi, and Noble in "Further Reading – Books and Hotlinks."

Taxonomy

Classification; the study of general principles of classification and the criteria for inclusion of certain kinds of organisms in some groups and not others. Evolutionary taxonomy attempts to organize life forms phylogenetically, reflecting their origins from common ancestors. The **Five kingdom classification system**, for example, emphasizes the origin of all non-prokaryotic forms from bacteria and **Archaea.** Such classification systems recognize fundamental commonalities, for example the presence of mitochondria in the cells of both plants and animals, thus moving beyond defunct taxonomies which would group all living organisms that are not animals as plants. The term "protozoa," while still in use, comes from Greek roots meaning "prior to animals" – and is thus best avoided in deference to the terms "protists" and "**protoctists**," because these eukaryotic cells did not evolve just into animals, but also into fungi and plants. Modern classification systems, such as the five kingdom system and Woese's three domain system, increasingly recognize that the traditional evolutionary "tree of life" branching into new forms must be conceived of more as a web or net to accommodate the realization that separately evolving lineages can come together again in **symbiogenesis**, and that genes can cruise across would-be inviolable species borders via **sex**.

Thought Collective

Ludwik Fleck's term for the existence of groups of people who individually and collectively reinforce one another's ideas and scientific narrative, making it difficult for new ideas, even if strongly supported by evidence, to be accepted.

Undulipodia

Lynn Margulis' preferred term that encompasses the waving appendages, cilia, of ciliates, sperm tails, and similar eukaryotic structures which share a common structure of pairs of **microtubules**. Although these structures are sometimes referred to as flagella, this word, and its singular form, flagellum, are best reserved for bacteria. The bacterial flagellum is much smaller, and consists of a single protein, flagellin, whereas the undulipodia of eukaryotes are larger, and consist of multiple proteins, in addition to other differences. Although, as with the difference in terminology between **protoctists** and protozoa, the distinction between undulipodia (singular, undulipodium) and flagella has not yet been fully adopted, such terminology is more precise, reflecting differences in nature rather than repeating historical imprecisions.

Victorian Era

The period of history of the United Kingdom under the reign of Queen Victoria, from 1837–1901.

Zeitgeist

The main intellectual and ideological climate of a given culture during a given time; a given culture's zeitgeist helps determine the beliefs and actions of members of a society under its sway. From German, Z*eit* (time) and *Geist* (spirit, or mind).

FURTHER READING – BOOKS AND HOTLINKS

Books and Chapters:

Abram, David. 1996. *Spell of the Sensuous: Perception and Language in a More-Than-Human World*. Vintage Books. Drawing from philosophy and Gaian notions of a living Earth, sleight-of-hand artist, traveler, and student of perception shows how human awareness derives from and is still immersed in planetary ecology.

Bateson, Gregory. 2000. *Steps to an Ecology of Mind*. University of Chicago Press. First published in 1972, and integrating conversations with Gregory Bateson's daughter, Mary Catherine Bateson (who appears in the film *Symbiotic Earth*), this collection of essays shows systems thinking in action by perhaps its most influential practitioner.

Bateson, Gregory. 2002. *Mind and Nature: A Necessary Unity*. Advances in Systems Theory, Complexity, and the Human Sciences Series, Hampton Press. Biology, anthropology, epistemology, ecology, earth science, cybernetics, politics, medicine, and philosophy come together in Bateson's system thinking.

Bateson, Mary Catherine. 1994. *Peripheral Visions*. Harper Collins. A great introduction to the work of Mary Catherine Bateson. In this series of narratives, Mary Catherine Bateson explores both the familiar and the unfamiliar about society and culture and shows how an open mind learns from experience.

Capra, Fritjof, and Pier Luigi Luisi. 2014. *The Systems View of Life: A Unifying Vision*. Cambridge University Press. Capra and Luisi's masterful text gives a comprehensive vision of life through the lens of *system thinking*. Capra acknowledges that he learned much from Margulis — and he expands on her ideas in many areas.

Capra, Fritjof. 1996. *The Web of Life*. Anchor Books. After his ground breaking work, *The Tao of Physics*, Capra turned to biology. This book explores the interconnections that tie life together.

Carr, Nancy, et al. 2001. *The Nature of Life: Readings in Biology*. Foreword by Lynn Margulis and Dorion Sagan. The Great Books Foundation. Selected reading from such scientists as Charles Darwin, Rachel Carson, Richard Dawkins, Stephen Jay Gould, and Lynn Margulis. This book is the antithesis of a biology textbook — offering a rich array of personal visions of biology which are embedded in the author's culture.

Clarke, Bruce (ed.) 2016. *Earth, Life, and System: Evolution and Ecology on a Gaian Planet*. Fordham University Press. A collection of essays inspired by the memory of Lynn Margulis. Essays by scientists, historians, and writers explore the Margulis legacy as it applies to the Gaia hypothesis, symbiosis, origins of life, taxonomy, epigenetics, evolutionary change, and our human presence on Earth. Includes "Gaia is not an Organism" by Bruce Clarke and "Life on a Margulisian Planet" by Dorion Sagan.

Crocetti, Gregory and Ailsa Wild. 2015. *The Squid, the Vibrio & the Moon: Small Friends.* Scale Free Network. A short, beautifully illustrated children's book but suitable for adults about the symbiotically luminous bobtail squid.

Darwin, Charles. 1976. *The Origin of Species*. Gramercy Books. First published in 1859 by J. Murray, London, under title: *On the origin of species by means of natural selection*.

Dawkins, Richard. 1976. *The Selfish Gene.* Oxford University Press. The go-to book that popularizes the notion of the gene as the unit of evolution, and metaphorically endows it with self regard.

Dawkins , Richard. 1982. *The Extended Phenotype: The Long Reach of the Gene*. Oxford University Press. In this rather dense book Dawkins seems to reverse himself somewhat, arguing that "selfish" genes can advantage themselves by ensuring their survival even in faraway bodies.

Derrida, Jacques. 1981. *Positions. (*Alan Bass, trans.), University of Chicago Press. Accessible interviews with the philosopher discussing among other things the practice of deconstruction as "reversal" and "displacement." Of relevance to the symbiotic worldview because it reverses both the role of microbes (as germs, and the lowest organisms to key players in the biosphere) and the place of humans (from the "highest" to one of many species).

Dexter Dyer, Betsey. 2003. *A Field Guide to Bacteria*. Comstock Publishing Associates. *Symbiotic Earth* interviewee explains how to find, catalog, and understand bacteria with the naked eye.

Dickinson, Emily. 1976. *The Complete Poems of Emily Dickinson.* Ed. T. H. Johnson. Back Bay Books.

Fleck, Ludwik. 1979. *Genesis and Development of a Scientific Fact*. University of Chicago Press. Original edition, 1935, Benno Schwabe Co., Switzerland. A book mentioned in the documentary and belatedly acknowledged by Thomas Kuhn, whose *The Structure of Scientific Revolutions* popularizing the notion of "paradigm shift."

Fortin, J. Andre, Christian Plenchette, and Yves Piche. 2009. *Mycorrhizas: The New Green Revolution*. Andrew P. Coughlan, trans. Editions MultiMondes. A handbook about mycorrhizae: the life-sustaining symbiosis between plants and fungi.

Grinspoon, David. 2016. *Earth in Human Hands: Shaping Our Planet's Future.* Grand Central Publishing. Grinspoon, an astrobiologist, uses Gaia theory to speculate about the possibility of life on other planets, and draws upon evolutionary history in an attempt to draw lessons about the future.

Hsü, Kenneth J. 1986. *The Great Dying*. Harcourt Brace Jovanovich. This thoroughly researched and important book looks at the nature of survival and extinction and examines the role of mass extinctions in the history and evolution of life.

Jablonka, Eva, and Marion J. Lamb. 2006. *Evolution in Four Dimensions*. The MIT Press. A revolutionary look at evolution. The four dimensions are: genetic, epigenetic, behavioral and symbolic.

Keller, Evelyn Fox. 1983. *A Feeling for the Organism: The Life and Work of Barbara McClintock*. W.H. Freeman & Co.

Kuhn, Thomas. S. 1996. *The Structure of Scientific Revolutions*, third edition. The University of Chicago Press. Kuhn's groundbreaking work about the nature of paradigm shifts.

Harding, Stephan. 2006. *Animate Earth: Science, Intuition, and Gaia*. Chelsea Green Publishing. A professional scientist devoted to his craft explores the implications of the Gaian view that Earth's surface is a living system.

Kendrick, Bryce. 2017. *The Fifth Kingdom: An Introduction to Mycology*. Focus. *Fourth Edition*. By a Professor Emeritus of Mycology at the University of Waterloo, this reputable book is notable for its "infectiously enthusiastic writing style" according to the *New Zealand Journal of Botany.*

Kozo-Polyansky, Boris Mikhaylovich. 2010. *Symbiogenesis: A New Principle of Evolution*. Victor Fet, trans., Victor Fet and Lynn Margulis, ed. First published in Russian in 1924. Harvard University Press.

Lenton, Tim. 2016. *Earth System Science: A Very Short Introduction*. Oxford University Press.

Lovelock, James. 2000. *Gaia: A New Look at Life on Earth*. First published 1979. Oxford University Press. Lovelock's classic and breathtakingly clear book.

Lovelock, James. 2006. *The Revenge of Gaia: Earth's Climate Crisis and the Fate of Humanity*. Basic Books.

Lovelock, James. 2009. *The Vanishing Face of Gaia: A Final Warning*. Basic Books.

Margulis, Lynn. 2007. *Luminous Fish: Tales of Science and Love*. Chelsea Green Publishing Company. *Largely fictional*, these tales give an insiders look at the life of a scientist.

Margulis, Lynn. 1998. *Symbiotic Planet: A New Look at Evolution*. Basic Books. Margulis' classic book is a clear exposition of her scientific ideas for the layperson.

Margulis, Lynn, and Celeste A. Asikainen and Wolfgang E. Krumbein, eds. 2011. *Chimeras and Consciousness: Evolution of the Sensory Self*. Cambridge, MIT Press. A wide-ranging anthology with essays that explore the evolution of sensory systems and the role of microbial ancestors in co-constituting our health and perception.

Margulis, Lynn, and Michael Chapman. 2009. *Kingdoms and Domains: An Illustrated Guide to the Phyla of Life on Earth.,* New York: Elsevier/Academic Press. A book that updates the Five-Kingdoms taxonomy of Lynn Margulis and Karlene Schwartz to include the genetic domains taxonomy of Carl Woese.

Margulis, Lynn, John O. Corliss, Michael Melkonian, and David J. Chapman, eds. 1990. *Handbook of Protoctista*. Jones and Bartlett.

Margulis, Lynn, and René Fester, eds. 1991. *Symbiosis as a Source of Evolutionary Innovation*. MIT Press.

Margulis, Lynn, and Dorion Sagan. 2002. *Acquiring Genomes: A Theory of the Origins of Species*. Basic Books.

Margulis, Lynn, and Dorion Sagan. 2007. *Dazzle Gradually: Reflections on the Nature of Nature.* Chelsea Green Publishing.

Margulis, Lynn, and Dorion Sagan. 1986. *Microcosmos: Four Billion Years of Microbial Evolution*. University of California Press. A readable history of life on Earth that does not leave out the two billion years of amazing evolution that occurred before the appearance of animals.

Margulis, Lynn, and Dorion Sagan. 1991. *Mystery Dance: On the Evolution of Human Sexuality*. Summit Books.

Margulis, Lynn, and Dorion Sagan. 1988. *The Microcosmos Coloring Book.* Illustrated by Christie Lyons et al. Harcourt Brace Jovanovich, Publishers.

Margulis, Lynn, and Dorion Sagan. 1986. *Origins of Sex: Three Billion Years of Genetic Recombination*. Yale University Press.

Margulis, Lynn, and Dorion Sagan. 2000. *What is Life?* University of California Press.

Maturana, Humberto, and Francisco J. Varela. 1980. *Autopoiesis and Cognition: The Realization of the Living*. Boston Studies in the Philosophy of Science, D. Reidel Publishing: Boston. The original book that attempts to define and explain the recursive concept of autopoiesis, in which organisms continuously produce themselves.

Maturana, Humberto, and Francisco J. Varela. 1987. *The Tree of Knowledge: The Biological roots of Human Understanding*. Revised Edition. Shambhala. This book about thought and perception takes us from the authors' definition of life as the process of autopoiesis to the idea that cognition is the "bringing forth of the world through the process of living itself."

Mayor, Federico, in collaboration with Jérôme Bindé. 2001. *The World Ahead: Our Future in the Making*. Zed Books in association with UNESCO Publishing.

Mitteldorf, Josh, and Dorion Sagan. 2016. *Cracking the Aging Code: The New Science of Growing Old—and What It Means for Staying Young.* Flatiron Books. A popular book that both exposes the mathematical gaps in neo-Darwinism and deploys Lynn Margulis' "symbiotic worldview." The book argues that aging, which does not exist in all species, is a genetic legacy that keeps organisms from overgrowing their environments and endangering their local ecosystems.

Noble, Denis. 2017. *Dance to the Tune of Life: Biological Relativity*. Cambridge University Press. Nobel's daring follow-up to the *Music of Life*.

Noble, Denis. 2006. *The Music of Life.* Oxford University Press. In this remarkable essay Noble looks at the processes of life and evolution and turns upside down conventional thinking.

Quammen, David. 2018. *The Tangled Tree: A Radical New History of Life.* Simon and Schuster.

Ryan, Frank. 2016. *The Mysterious World of the Human Genome.* New York: Prometheus Books.

Ryan, Frank. 2011. *The Mystery of Metamorphosis: A Scientific Detective Story.* Chelsea Green Publishing. A medical doctor chronicles the history of scientific investigation into the process of metamorphosis, including Donald Williamson's "heretical" notions of larval transfer.

Sagan, Dorion. 2017. "Beautiful Monsters: Terra in the Cyanocene." In *Arts of Living on a Damaged Planet: Ghosts and Monsters of the Anthropocene.* Anna Lowenhaupt Tsing, Nils Bubandt, Elaine Gan, and Heather Anne Swanson, eds, University of Minnesota Press, pp. 169-74.

Sagan, Dorion, ed. 2012. *Lynn Margulis: The Life and Legacy of a Scientific Rebel*. Chelsea Green Publishing.

Sagan, Dorion, and Lynn Margulis, 1988. *Garden of Microbial Delights: A Practical Guide to the Subvisible World,* Harcourt Brace Jovanovich (Kendall Hunt 1993).

Sapp, Jan. 1994. *Evolution by Association: A History of Symbiosis*. Oxford University Press.

Sapp, Jan. 2003. *Genesis: The Evolution of Biology*. Oxford University Press.

Sapp, Jan. 2009. *The New Foundations of Evolution: On the Tree of Life*, Oxford University Press.

Schneider, Stephen H. et al. eds. 2004. *Scientists Debate Gaia: The Next Century.* MIT Press.

Shapiro, James A. 2011. *Evolution: A View from the 21st Century*, FT Press. In this groundbreaking book, Shapiro reshapes the theory of evolution and explains that cells can actively engineer their own chromosomes.

Stamets, Paul. 2005. *Mycelium Running: How Mushrooms Can Help Save the World,* Ten Speed Press. A bestseller by a world expert on fungi, who by his own account became interested in them as a shy youth looking down at the ground in Washington State.

Thomas, Lewis. 1974. *The Lives of a Cell: Notes of a Biology Watcher*. Bantam. A remarkable book of inspiring and insightful essays about biology.

Tsing, Anna Lowenhaupt, and Nils Bubandt, Elaine Gan, and Heather Anne Swanson, eds. 2017. *Arts of Living on a Damaged Planet,* University of Minnesota Press. An anthology that addresses humanity's global environmental problems with essays from a variety of perspectives in science, science studies, literature, and the humanities.

Vernadsky, Vladimir I. 1998. *The Biosphere*, Copernicus Books. A carefully translated edition by the great Russian-speaking geochemist who popularized the term biosphere, and whose ideas help unify life as a material phenomenon with planetary and Earth science.

Westbroek, Peter. 1991. *Life as a Geological Force: Dynamics of the Earth*, W.W. Norton, & Co. An exploration of the surprising connections between biology and geology.

Whitehead, Alfred North. 1997. *Science and the Modern World,* Free Press. Although Whitehead can be difficult this book of essays is relatively accessible and illuminates the relationships between and creative practices of science and philosophy.

Whittaker, Robert H. and Lynn Margulis. 1978. "Protist classification and the kingdoms of organisms." *BioSystems* 10: 3–18.

Wild, Ailsa and Aviva Reed, Briony Barr, and Dr. Gregory Crocetti. 2015. *Zobi and the Zoox*. Small Friend Books: *http://www.smallfriendsbooks.com/*. A beautifully illustrated symbiotically themed 44 page children's book, set on the Great Barrier Reef, whose characters include microbes, molecules and mucus – the microscopic members of the symbiotic society that make up corals.

Williamson, Donald I. 2003. *The Origins of Larvae*. Kluwer Academic Publishers. The revised and enlarged edition of Williamson's first book, *Larvae and Evolution: Toward a New Zoology*. (1992. Chapman and Hall.) Both books have forwards by Lynn Margulis and Alfred I. Tauber. and are about larval transfer (also called hybridogenesis) the hypothesis that, at infrequent intervals during the course of evolution larval forms (or genes that specifiy them) have been transferred between different groups of animals.

Windchy, Eugene G. 2009. *The End of Darwinism: And How a Flawed and Disastrous Theory Was Stolen and Sold*. A fascinating look at the history of Darwinism.

Woese, Carl and O. Kandler and M. Wheelis. 1990. "Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya," *Proceedings National Academy of the Sciences* USA, 87 (12): 4576–9.

Wulf, Andrea. 2015. *The Invention of Nature: Alexander von Humboldt's New World. Vantage Books* A biography of an influential scientist prior to Lynn who, like her, unified many different scientific fields. Humboldt, whose own account of his voyages inspired Charles Darwin, by combining romantic poetry and hard science, was arguably the first science writer and nature writer. His ardent naturalism and lifelong devotion to understanding Earth as a single, far-more-than-human network anticipate the work of Lynn Margulis. The religious, and later mechanistic view of, as Lynn said, "Man separate from nature" as the source of environmental crisis, was recognized by Humboldt.

Yong, Ed. 2016. *I Contain Multitudes: The Microbes Within Us and a Grander View of Life,* Ecco. An engaging wide-ranging and best-selling view of the role of microbes in animals, especially humans, told from the view of a science writer. Yong takes his title, I contain multitudes, from poet Walt Whitman, who was thinking more about spiritual presences and history than tiny biological beings when he wrote it. Although highly accessible, Yong's book contains some mistakes, such as his claim that symbiosis only happened importantly once (a "one-off event") in the history of life. By this he means the merger of the ancestors of mitochondria, which evolved from invasive or eaten bacteria into the "power factories" (still containing their own DNA) in your cells. As important as this is to animals, it pales in comparison to the functioning of Earth as a global system to the incorporation of green bacteria (cyanobacteria) into the forerunners of algae and plants. Those symbiotic events gave our biosphere the ability to remove carbon from the atmosphere and bury it in the ground, keeping the Earth cool and, moreover, making animal life possible. Yong's book is thus interesting from a history-of-science perspective, showing how mainstream accounts, in their quickness to appropriate and make familiar scientific revolutions—in this case a symbiotic view of life as a whole, not just humans and animals—can both make major errors and erase the role of major developers.

Zook, Douglas. 2015. "Symbioisis — Evolution's Co-Author." In *Reticulate Evolution*. N. Gontheir (ed.). Springer.

Hotlinks:

Alexander, Victoria N., 2018. "Lynn Margulis, Evolutionary 'Naturalism,' Chance and Conspiracy https://victorianalexander.com/2018/05/02/lynn-margulis-evolutionary-naturalism-chance-and-conspiracy/ In this article novelist and philosopher of science Victoria N. Alexander concludes that Margulis' "legacy, far from being limited to her scientific achievements, will involve her contributions to culture and politics as well."

Carr, Steven M. 2011. "Alternative Classifications of Life Five Kingdoms *versus* Three Domains": https://www.mun.ca/biology/scarr/Five_Kingdoms_Three_Domains.html

Clarke, Bruce. 2012. "Autopoiesis and the Planet." In *Impasses of the Post-Global: Theory in the Era of Climate Change*, vol. 2, ed. Henry Sussman. Ann Arbor: Open Humanities Press: https://www.academia.edu/8370134/Autopoiesis_and_the_Planet

Dance, Amber. 2018. "Archaea Family Tree Blossoms, Thanks to Genomics: Identification of new archaea species elucidates the domain's unique biology and sheds light on its relationship to eukaryotes," *The Scientist*, (June): the-scientist.com/?articles.view/articleNo/54649/title/Archaea-Family-Tree-Blossoms—Thanks-to-Genomics/

Johnson, Thomas. 2013. "Book review: James A. Shapiro's *Evolution: A View from the 21st Century," Journal of Evolution and Technology, v*ol. 23, Issue 1 (December), 61-64: https://jetpress.org/v23/johnson.htm

Lazcano, Antonio, and Juli Peretó, 2017. "On the origin of mitosing cells: A historical appraisal of Lynn Margulis endosymbiotic theory": http://www.sciencedirect.com/science/article/pii/S0022519317303223. A PDF from the *Journal of Theoretical Biology (*Volume 434, 7, pp. 80-87, December). Margulis colleague Antonio Lazcano and Juli Peretó of the Department of Biochemistry and Molecular Biology of the University of Valencia consider Margulis' legacy.

Lazcano, Antonio. 2017. "Symbiosis and cell evolution: Lynn Margulis and the origin of eukaryotes," *The Conversation*, Phys Org (November 23): https://phys.org/news/2017-11-symbiosis-cell-evolution-lynn-margulis.html (a shorter version of the above)

MacAllister, James, 2018. "Round Bodies: The Boat's Still A Rockin'," *Environmental Evolution: Effects of the Origin and Evolution of Life on Earth* (June Newsletter): envevo.org/environmentalevolution.org/Home_files/June%202018%20Environmental%20Evolution%20newsletter.pdf

Margulis, Lynn 1984. Speaking to NASA on *Gaia Hypothesis* while a professor at Boston University: https://archive.org/details/gaia_hypothesis.

Margulis, Lynn, Richard Dawkins, Denis Noble, Martin Brasier, Stephen Bell, et al, 2012. "Margulis-Dawkins Debate." This three-part, four-hour "Homage to Darwin" debate, featuring exchanges between Lynn Margulis and Richard Dawkins, among others, parts of which were included in *Symbiotic Earth*, was filmed at Balliol College, Oxford University in May 2009 on the occasion of the 150th anniversary of the publication of *On the Origin of Species* by Charles Darwin. With commentary by James D. MacAllister. http://www.voicesfromoxford.org/news/margulisdawkins-debate/158

Margulis, Lynn, and Dorion Sagan, 2001. "The Beast with Five Genomes." *Natural History.* June, Volume 110, no. 5. 38-41. Hotlink: naturalhistorymag.com/htmlsite/0601/0601_feature.html

Gilbert, Scott F., Jan Sapp, and Alfred I. Tauber. 2012. "A Symbiotic View of Life: We Have Never Been Individuals": www.journals.uchicago.edu/doi/10.1086/668166 A major review article of symbiotic work directly or indirectly influence by Lynn Margulis, which appeared the year after her death in *The Quarterly Review of Biology* 87 (4) (December): pp. 325–41. A biologist (Gilbert), a historian of science (Sapp), and a philosopher (Tauber) team up to review the revolution in biology that Lynn Margulis helped inspire.

McFall-Ngai, Margaret et al. 2013. "Animals in a Bacterial World, a New Imperative for the Life Sciences": web.stanford.edu/~fukamit/mcfall-ngai-et-al-2013.pdf M. G. Hadfield, T. C. Bosch, H.V. Carey, T. Domazet-Lošo, A. E. Douglas, N. Dubilier, G. Eberl, T. Fukami, S. F. Gilbert, U. Hentschel, N. King, S. Kjelleberg, A. H. Knoll, N. Kremer, S. K. Mazmanian, J. L. Metcalf, K. Nealson, N. E. Pierce, J. F. Rawls, A. Reid, E. G. Ruby, M. Rumpho, J. G. Sanders, D. Tautz, and J. J. Wernegreen. *PNAS* 110 (9) (February 26): 3229–36. A multi-authored manifesto-like scientific review paper, co-written by some of the biggest names in the field, with many references and suggested readings of its own, that argues that Margulis was right in her prediction "that we would come to recognize the impact of the microbial world on the form and function of the entire biosphere, from its molecular structure to its ecosystems," adding that, "The weight of evidence supporting this view has finally reached a tipping point. The examples come from animal bacterial interactions . . . and also from relationships between and among viruses, Archaea, protists, plants, and fungi. These new data are demanding a reexamination of the very concepts of what constitutes a genome, a population, an environment, and an organism." The authors focus on bacteria and the origins of animals, interconnecting genomes, the role of symbiotic bacteria in animal development, and communication among very different kinds of organisms. Published in the influential *Proceedings of the National Academy of the Sciences.*

McFall-Ngai, Margaret: "Lynn Margulis (1938 –2011) Truth Straight On: Reflections on the Vision and Spirit of Lynn Margulis" www.journals.uchicago.edu/doi/pdfplus/10.1086/BBLv223n1p1

Sagan, Dorion. "Remembering Lynn Margulis: An Evolutionary Eulogy": www.sevenpillarshouse.org /article/remembering_lynn_margulis/

Sagan, Dorion. 2016. "My Mother's Love Letters—Finding the Orange Bag: Ghosts, Reality, and the Escape into Life": truthbarrier.com/2016/09/13/finding-the-orange-bag-ghosts-reality-and-the -escape-into-life/ (September 13).

Sagan, Lynn. 1967. "On the origin of mitosing cells," *Journal of Theoretical Biology* Volume 14, Issue 3, March 1967, Pages 225- 274: https://doi.org/10.1016/0022-5193(67)90079-3 Lynn Margulis' breakthrough 1967 paper, written as Lynn Sagan.

Skinner, Michael. 2016. "Unified Theory of Evolution: Darwin's theory that natural selection drives evolution is incomplete without input from evolution's anti-hero: Lamarck": aeon.co/essays/on-epigenetics -we-need-both-darwin-s-and-lamarck-s-theories/ (November 9).

Slijepcevic, Predrag. 2017. "Riders on the Storm," Epistemology of Nature blog: biocivilizations.com /introduction/ Introduction to wide-ranging thinker (and fan of Lynn Margulis) Predrag Slijepcevic's blog, which attempts to understand the more-than-human intelligence of ecosystems and the species within them.

Slijepcevic, Predrag. 2017. "Flora and Mona Lisa – who's more authentic?": biocivilizations.com/flora/ In this blog the Brunel University in London chromosome biologist uses great Renaissance paintings to drive home the startling nature of symbiotic life on Earth.

Stamets, Paul. 2011. "Paul Stamets at TEDMED 2011: Paul Stamets, mycologist talks about the antimicrobial properties of fungi, how they can be used as potent insecticides, and how they may help boost the human immune system": youtube.com/watch?v=Mjv8Zj1ABAc ; and Paul Stamets, 2013. "Paul Stamets – The Future is Fungi [how to save the planet]": youtube.com/watch?v=cwLviP7KaAc

Small Friends Network: www.smallfriendsbooks.com/ Award-winning symbiosis-themed picture books suitable for children, young adults and adults.

Wier, Andrew et al. 2002. "Spirochete and protist symbionts of a termite (Mastotermes electrodominicus) in Miocene amber": PNAS 2002 February, 99 (3) 1410-1413: europepmc.org/articles/PMC122204

ABOUT THE AUTHORS

Dorion Sagan

Author or coauthor of twenty-five books translated into fifteen languages, Dorion Sagan is an award-winning writer, philosopher, and ecological theorist. For over forty years he helped popularize the work of Lynn Margulis on symbiotic evolution and planetary biology. He has written for both specialized venues and popular magazines such as *Natural History*, *Smithsonian*, *Wired*, *Cabinet*, *The Times Higher Education's Supplement,* and *The New York Times Book Review*. He is coauthor, with his parents Carl Sagan and Lynn Margulis, of the entries for both "Life" and "Extraterrestrial Life" in the *Encyclopedia Britannica*.

John Feldman

John Feldman has been making powerful and original films in a range of genres for over fifty years. His films have won numerous international awards. Through his production company, Hummingbird Films, he is currently focusing on documentaries in the arts and sciences. Feldman believes strongly in the power of films to motivate, educate, and inspire change. He has a BA in Biology from the University of Chicago and is an avid naturalist. His documentaries include *EVO: Ten Questions Everyone Should Ask about Evolution* (2011, CINE Golden Eagle Award), and portraits of Jessye Norman, Ming Cho Lee, and Merce Cunningham. His independent dramatic feature films include the pioneering digital video production *Who the Hell is Bobby Roos?* (2002, New American Cinema Award, Seattle International Film Festival), *Dead Funny* (1995, starring Elizabeth Pena and Andrew McCarthy), and *Alligator Eyes* (1990, First Prize Audience Jury San Sebastian Int. Film Festival).

The biographies of the scientists and scholars interviewed in *Symbiotic Earth* can be found on the film's website at http://hummingbirdfilms.com/symbioticearth/symbiotic-earth-scientists-and-scholars/