

Gaia and the Early Earth

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The Gaia theory was synthesized by the British scientist, James Lovelock, in the 1960s. Lovelock had been contracted by NASA to design instruments to be sent aboard the Mariner spacecraft in order to detect life on Mars. In thinking about the possibility of life on Mars, Lovelock realized that if life forms *did* exist there, the Martian atmosphere probably would be very different from its known composition: mostly carbon dioxide. Much of Earth's carbon is distributed in a dynamic cycle that includes carbon dioxide within the atmosphere and hydrosphere, living organisms, and carbonate remains in limestone and marble. Carbon based life would have depleted the Martian atmosphere of carbon dioxide making the Martian atmosphere more like the terrestrial atmosphere. From this chain of thought, Lovelock formulated the Gaia concept. His idea was given the name Gaia by novelist, William Golding. Gaia is the belief that the whole Earth is a self-regulating network of interdependent physical and biological systems.

The Gaia theory includes three principal ideas. Two are widely accepted and have been known to scientists for some time. Firstly, the Earth contains a great variety of living and non-living parts that depend upon one another. Changing any part of the Earth may have profound effects on a variety of other Earth systems. Secondly, our planet exists in a delicate state of equilibrium. Small stresses, such as localized environmental pollution, particularly if they are of limited time and geographic extent, may result in a temporary and regional imbalance of that equilibrium. In these events, the environment is likely to recover from such small changes, and return to its former equilibrium. However, much larger changes applied over wide areas, and for long periods of time are likely to result in a new planetary equilibrium. Unfortunately, these new conditions may be hostile to established life forms. In the geological past, the evolution of new environmental conditions has caused the extinction of some organisms. We can think of the Earth like a rubber band. Stretch it a little, and it bounces back. But, stretch it too much, and a permanent change (in the case of a rubber band, separation) will occur. Start with a three inch rubber band; end with a six inch flexible cord. Not so bad, provided a six inch cord meets your needs as well as the three inch rubber band.

¹ Thomas McGuire is an Earth science teacher at Briarcliff High School, Briarcliff Manor, NY 10510. This is his second major article in *The Science Teacher*. His first, about deterministic chaos, (*Up in Smoke*) was published in March, 1991. You might know that Gaia and Chaos were the ancient rivals of order and disorder. In the end, Gaia won and created the benign planet that we inhabit. As this article follows McGuire's chaos article, Gaia appears to have the last word. We all hope for a more ordered world.

Lovelock's third idea is more controversial. He has suggested that our planet is, itself, a gigantic living organism. Lovelock envisions planet composed of organs, such as the oceans, forests, and continents. Each part has a pseudo-biological function; such as photosynthesis, protection from harmful forms of radiation, and tectonic plate motion. Many scientists are skeptical about taking the Gaia idea that far. However, in the past few years, the work of scientists in a variety of fields have moved Gaia from a fashionable idea of "new age" set, to a respectable paradigm that may prove useful in analyzing past and future conditions of the Earth.

Lovelock writes, "All that I ask is that you consider the Gaia theory as an alternative to the conventional wisdom of a dead planet made of inanimate rocks, oceans and atmosphere merely inhabited by life. Consider our planet as a complete system, comprising all of life and all of its environment tightly coupled so as to form a self-regulating entity."²

One of the most valuable aspects of the Gaia hypothesis has been a new understanding of the evolution of Earth's atmosphere. From studying other planets and from studies of very old rock formations, we know that the atmosphere of the early Earth was very different from the atmosphere of today. The following graphing exercise should help you and your students to understand the co-evolution of our physical environment and the biosphere for the 4½ billion years of Earth's history: the theory of Gaia.

I use the following exercise with my students in grades 8 and 9. It conforms to a variety of content and skill objectives including ecology, evolution, geologic history, and graphing. Students may be unfamiliar with this type of graph. In introducing the exercise, I show the students an overhead projection of another example of a cumulative graph, such as the ESCP chart that shows the most likely mineral compositions of common igneous rock. (This chart also found in many college level geology and Earth science texts.) I then allow them time to construct the graph in cooperative groups, and enter the events below the graph. Guiding the class as a single large group through the questions on the second page of the lab helps them to understand the Gaia concept and its broad implications, and it also guides the students through important ideas that are not immediately obvious. Actually, it's fun to watch the "light bulbs turn on" as individuals reach a new understanding of Planet Earth.

² What is Gaia? by James Lovelock in the *Sim Earth Manual*, by Michael Bremer, Maxis, 1990

The Gaia theory has helped us to understand why conditions on the Earth have changed so much through geologic history. When James Lovelock first proposed the Gaia hypothesis, the theory was either rejected, or treated as the fanciful musing of an eccentric scientist. However, the Gaia theory is now gaining widespread acceptance because it has given us new insights into the the complex relationship between the living and the non-living parts of terrestrial environments.

In particular, the Gaia theory has helped us to understand how primitive forms of life interacted with Earth's atmosphere in Precambrian time.

Changing Percent Composition of Earth's Atmosphere

Gas	Millions of years before the present									
	4500	4000	3500	3000	2500	2000	1500	1000	500	Present
Carbon Dioxide	80%	20%	10%	8%	5%	3%	1%	0.07%	0.04%	0.025%
Nitrogen	10	35	55	65	72	75	76	77	78	78
Hydrogen	5	3	1	0.5	0	0	0	0	0	0
Oxygen	0	0	0	0	0	1	5	10	15	21
Other Gases	5	42	34	26	23	21	18	13	7	1

On page 3 you will find a diagram for making a special running time graph. Use the data in the box above to show the changing percentage composition of Earth's atmosphere since the formation of the Earth. Please note that these figures are cumulative; each gas must be shown on top of the previous gas, and, at every time interval, they add up to 100% of the atmosphere. Label each gas by its chemical symbol within or next to its own area on the graph. (CO₂, N₂, H₂, O₂, & Other Gases)

When you have constructed and labeled your graph, plot the times of the events listed below. Write each event with an arrow showing the appropriate place below the graph. *(Please note that the first one has been done for you on page 3.)*

IMPORTANT EVENTS IN THE EVOLUTION OF THE EARTH	{	1. Formation of the Earth	4500 million years ago
		2. Oldest known Bedrock	3900
		3. Oldest Rocks of Organic Origin	3700
		3. Precambrian Iron Deposits	3700–1800
		4. Photosynthesis in Plants Begins	3000
		5. Oxygen in Air Dominates Weathering	2100
		6. Limestone Deposition Becomes Common	1800
		7. Fossils Become Abundant	570
		8. Earliest Plants and Animals on Land	420

Discussion:

1. What is the approximate age of the Earth? _____
2. How long do we think that living things have existed on Earth? _____
3. How many millions are there in a billion? _____
4. From your knowledge of biological evolution, what characteristic of life forms older than 570 million years ago makes fossils of these life forms relatively rare?

5. Why wasn't oxidation type chemical weathering common more than 2 billion years ago?
(Hint: See the graph.)

6. From your knowledge of life science, what gas is given off by green plants during photosynthesis? _____
7. What gas was depleted (used up) by the time that oxygen became abundant? _____
8. Why couldn't this gas exist with oxygen in the atmosphere? _____
9. Therefore, what seems to have been the major cause of the dramatic change in the composition of Earth's atmosphere over the past ~~4 1/2~~ billion years?

10. What major atmospheric changes seem likely in the future? (*Please be specific.*)

11. How do these changes in the atmosphere illustrate the Gaia theory?

12. Both Mars and Venus have atmospheres that are dominated by carbon dioxide. Why is the Earth different?

13. Aside from providing oxygen for respiration, how else did the production of elemental oxygen within the atmosphere allow the development of terrestrial life forms?

Answer Key:

1. The data table and graph show the Earth to be about 4.5 billion years old.
2. Living things have existed on the Earth for at least 3.7 billion years.
3. There are 1000 millions in a billion.
4. These earliest forms of life had no hard parts (shells or skeletons), so fossils of these primitive organisms are usually rare and poorly preserved.
5. Oxydation was not very active more than 2 billion years ago because the atmosphere of the time had little or no free oxygen.
6. Green plants give off oxygen in photosynthesis.
7. Oxygen became abundant when there was no free hydrogen left.
8. If oxygen and hydrogen existed together, they would react explosively to produce water (H₂O). (This may be dramatically demonstrated to students by igniting a *small* balloon filled with hydrogen³. The balloon may be lighted from a distance by using a candle attached to a meter stick. Please use appropriate precautions, such as wearing goggles and warning the class of the noise.)
9. Photosynthesis, using carbon dioxide and creating free oxygen, was responsible for this change.
10. Our combustion of fossil fuels is releasing great quantities of carbon dioxide into the atmosphere.
11. These changes result from the activities of living organisms.
12. Photosynthesis has depleted Earth's atmosphere of carbon dioxide.
13. Oxygen provided for the formation of the ozone layer, which protects land dwelling organisms from the high energy radiation found in outer space. (X-rays, gamma rays, etc)

³ The author thanks Nancy Doi of Bainbridge-Guilford High School (NY) for this demonstration idea.

References:

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Broderbund Softwear w/ assistance from James Lovelock (1990) *Sim Earth: The Living Planet* (Softwear for Macintosh or IBM) Maxis, Moraga, CA

Joseph, Lawrence E., (1990) *Gaia: The Growth of an Idea*, St. Martins Press, New York

Lovelock, James; (1988) *The Ages of Gaia*, Norton, New York

Weiner, Jonathan, (1986) *Planet Earth*, (companion volume to the PBS series by the same title) Bantam, New York

Extensions:

Research Questions –

1. Why do we think that life exists on no other planet in our solar system?
2. How can we account for the unique conditions on our planet?

For Discussion –

1. If we used the Gaia metaphor to justify a complete lack of ecological concern, how might we change our environment?
2. How is the Earth likely to change in spite of our best efforts to preserve the environment?
3. What could we do to improve the Earth for human beings?
4. In a group of about three or four students, “invent” a life form that could thrive on Venus or Mars.

(Conclusion)

The Gaia concept has provided a new paradigm to help us understand major changes in Earth systems. These changes often involve a coupling of natural systems. For centuries, we have known that ocean currents are driven, in large measure, by the circulation of the atmosphere. Recent discoveries have shown us that the interaction of the atmosphere and ocean currents are actually more complex. El Niño, periodic warm currents in the Pacific Ocean, have a dramatic effect on atmospheric circulation and weather. Interactions between major parts of our planet, the atmosphere, the hydrosphere, the geosphere⁴ and the biosphere, need to be understood if we are to understand how we as humans take part in terrestrial changes.

The focus of our ecological efforts should not be simply to preserve the present state of our planet. (Although, in the short term and local context, that is a relatively viable and conservative approach to our activities.) In the long run, major changes are inevitable. We need to accept the fact that the Earth will change. But we also need to investigate how these changes will affect humans. We need to understand how we can both prevent traumatic changes and adapt to the dynamic evolution of our planet. Gaia is a valuable metaphor that helps us to understand our interactions with the complex systems of a dynamic planet Earth.

⁴ Some authors have used the term lithosphere to mean the solid earth. But others use lithosphere to mean the rigid portion of Earth's outer layer. The term geosphere is used here to connote the rocky portion of our planet including rock in its solid, plastic and molten forms.

(Sidebar)

Another Point of View...

Dr. James W. Kirchner of the University of California at Berkeley has written that the Gaia hypothesis is not scientifically valid because it cannot be verified or negated in the normal process of peer review. In 1987 Mr. Lovelock suggested that the concentrations of dimethyl sulphide (DMS), a precursor of cloud forming condensation nuclei produced by algae, should increase in periods of global warming. Lovelock envisioned that the production of DMS by the biosphere should cool the overheated planet to maintain planetary homeostasis. However, ice core data published a year later seemed to show exactly the opposite. DMS levels are apparently highest during glacial periods. “Undeterred, Lovelock promptly inverted the theory to match the data. He now argues that Gaia *prefers* **(Editor: italics from the original entry in Nature)** a glacial deep freeze and that interglacial periods represent a “fevered state” of the planet.... The risk is this: a metaphor like Gaia, flexible enough to be wrapped around almost any data set, is also versatile enough to be involved *ad hoc*, to lend a spurious air of scientific legitimacy to almost any reckless conjecture... Even Lovelock argued in the 1970s that we need not control our emissions of chlorofluorocarbons (CFCs) because “our capacity to pollute on the planetary scale seems rather trivial by comparison, and the (terrestrial) system does seem to be robust and capable of withstanding major perturbations.”⁵ Additionally, many of the applications of Gaia in the popular literature, by Lovelock and others, are unscientific at best and tragically misleading at worst.

⁵ Nature, June 6, 1990, “Gaia metaphor unfalsifiable”