Gaia Theory: Science of the Living Earth

By David Orrell (http://www.gaianet.fsbusiness.co.uk/gaiatheory.html)

Here is a brief introduction to Gaia theory, as developed by Lovelock, Margulis and others.

In the early 1960's, James Lovelock was invited by NASA to participate in the scientific research for evidence of life on Mars. His job was to design instruments, capable of detecting the presence of life, which could be sent on a spacecraft to Mars. This wasn't straightforward, since it was hard to know what to test for: any life forms on Mars may be radically different from those on Earth. This led him to think about what constitutes life, and how it can be detected. He decided that the most general characteristic of life was that it takes in energy and matter and discards waste products. He also reasoned that organisms would use the planet's atmosphere as a medium for this cyclic exchange, just as we breathe in oxygen and expel carbon dioxide. He speculated that life would therefore leave a detectable chemical signature on the Martian atmosphere. Maybe it could be detected from Earth, so it wouldn't even be necessary to send a spaceship.

To test his idea, he and a colleague, Dian Hitchcock, began to analyse the chemical makeup of Mars, and compare it with that of the Earth. The results showed a strong contrast. The atmosphere of Mars, like Venus, was about 95% carbon dioxide, with some oxygen and no methane. The Earth was 77% nitrogen, 21% oxygen, and a relatively large amount of methane. Mars was chemically dead; all the reactions that were going to take place had already done so. The Earth, however, was far from chemical equilibrium. For example, methane and oxygen will react with each other very easily, and yet they are both present in the atmosphere. Lovelock concluded that for this to be the case the gases must be in constant circulation, and that the pump driving this circulation was life.

Lovelock began to look back at the history of life's interaction with the atmosphere. He noted that about three billion years ago, bacteria and photosynthetic algae started to remove carbon dioxide from the atmosphere, producing oxygen as a waste product. Over enormous time periods, this process changed the chemical content of the atmosphere - to the point where organisms began to suffer from oxygen poisoning! The situation was only relieved with the advent of organisms powered by aerobic consumption. It was life processes, the cumulative actions of countless organisms, that were controlling the atmosphere. And viewed from outer space, the mass effect of these processes was that the Earth itself appeared as a living entity - especially in comparison with its dead neighbours. Lovelock had a sudden realisation that the Earth could best be described as a kind of super-organism:

"For me, the personal revelation of Gaia came quite suddenly - like a flash of enlightenment. I was in a small room on the top floor of a building at the Jet Propulsion Laboratory in Pasadena, California. It was the autumn of 1965 ... and I was talking with a colleague, Dian Hitchcock, about a paper we were preparing ... It was at that moment that I glimpsed Gaia. An awesome thought came to me. The Earth's atmosphere was an extraordinary and unstable mixture of gases, yet I knew that it was constant in composition over quite long periods of time. Could it be that life on Earth not only made the atmosphere, but also regulated it - keeping it at a constant composition, and at a level favourable for organisms?" (1991)

On a stroll with his novelist neighbour William Golding, Lovelock described his idea, and asked advice for a name. Golding suggested Gaia, after the Greek Earth Goddess. The Gaia Hypothesis was born. In 1979, Lovelock wrote the book "Gaia: A New Look at Life on Earth", which developed his ideas. He stated that:

"... the physical and chemical condition of the surface of the Earth, of the atmosphere, and of the oceans has been and is actively made fit and comfortable by the presence of life itself. This is in contrast to the conventional wisdom which held that life adapted to the planetary conditions as it and they evolved their separate ways."

Key to Lovelock's idea was his observation that the planet is self-regulating. He knew, for example, that the heat of the sun has increased by 25% since life began on Earth, yet the temperature has remained more or less constant. However he didn't know precisely what mechanisms were behind the regulation. It was when he began to collaborate with the American microbiologist Lynn Margulis that the full theory began to take shape. Margulis was studying the processes by which living organisms produce and remove gases from the atmosphere. In particular she was examining the role of microbes which live in the Earth's soil. Working together, they managed to uncover a number of feedback loops which could act as regulatory influences.

An example is the carbon dioxide cycle. Volcanoes constantly produce massive quantities of carbon dioxide. Since carbon dioxide is a greenhouse gas, it tends to warm the planet. If left unchecked, it would make the Earth too warm to support life. While plants and animals take in and expel carbon dioxide through life processes such as photosynthesis, respiration and decay, these processes remain in balance and don't affect the net amount of the gas. Therefore there must be another mechanism.

One process by which carbon dioxide is removed from the atmosphere is rock weathering, where rainwater and carbon dioxide combine with rocks to form carbonates. Lovelock, Margulis and others discovered that the process is greatly accelerated by the presence of soil bacteria. The carbonates are washed away into the ocean, where microscopic algae use them to make tiny shells. When the algae die, their shells sink to the bottom of the ocean, forming limestone sediments. Limestone is so heavy that it gradually sinks underneath the Earth's mantle, where it melts. Eventually some of the carbon dioxide contained in the limestone will be fed back into the atmosphere through another volcano.

Since the soil bacteria are more active in high temperatures, the removal of carbon dioxide is accelerated when the planet is hot. This has the effect of cooling the planet. Therefore the whole massive cycle forms a feedback loop. Lovelock and Margulis identified a number of other feedback loops which operate in a similar way. An interesting feature of these loops is that, like the carbon dioxide cycle, they often combine living and non-living components. The importance of biological processes on the planet was pointed out by the Russian scientist Vernadsky, who as early as 1929 said:

"Life appears as a great, permanent and continuous infringer on the chemical 'dead-hardness' of our planet's surface ... Life therefore is not an external and accidental development on the terrestrial surface. Rather, it is intimately related to the constitution of the Earth's crust, forms part of its mechanism, and performs in this mechanism functions of paramount importance, without which it would not be able to exist." (1929)

Vernadsky showed, for example, that living organisms are the primary transformer of solar energy to chemical energy, and stressed the importance of biotransport systems. An example of a biotransport system is birds which feed on marine life, hence transferring an enormous amount of matter from the oceans back to the land. In order to understand how the planet works, one has to take into account the effect of life - exactly what Lovelock and Margulis say.

The Gaia Hypothesis immediately created a lot of interest. The idea that the Earth was alive had been expressed several times before, but it gained special resonance in the early 60's because of the space flights which allowed the Earth to be viewed for the first time as a complete entity from outer space. In a way these photographs were to the Gaia idea what computers were to chaos theory; they allowed one to see what was going on, and therefore brought the subject alive to a great many people.

The intellectual climate was also becoming amenable. A lot of work was being done at that time on self-organising systems. Ilya Prirogine had been studying systems far from thermal or chemical equilibrium which nevertheless showed a high degree of order, for example the Belousov-Zhabotinskii reaction which produces amazing periodic oscillations. He realised that there was a close association between self-organisation at states far from equilibrium, and the nonlinearity of the system. This tied in well with Lovelock's observation that the Earth is chemically far from equilibrium, and the nonlinearity of the feedback loops such as the carbon dioxide cycle.

Meanwhile the Chilean neuroscientists Maturana and Varela were developing their autopoietic (literally self-making) definition of life. There is no single definition of life that is accepted by all fields, however one of the most successful has been their definition, which states that living beings produce, by their own rules, the components, including their own boundary, that specify it and realise it as a concrete unit in space and time (Maturana and Varela 1987). What is important in this definition is not so much the material structure of life as the process, organisation and set of relations between the components. Life is a network which constantly makes itself. The simplest autopoietic system is the living cell. For something to be alive by this definition, there is no requirement that it grow or reproduce or pass on DNA. Since, as Vernadsky observed, 99.9% of the different molecules on Earth have been created in the life process of Earth, the Earth would seem to qualify as a self-making organism.
While the Gaia Hypothesis attracted a lot of interest, it also received a great deal of criticism. Lovelock had attached great weight to the idea that the Earth seemed to regulate itself. Some took this to imply that the Earth was behaving with a sense of purpose, that it was a teleological being.

Teleology, from the Greek word telos (purpose), asserts that there is an element of purpose or design behind the workings of nature. It is part of a very old debate between mechanists who believe that nature essentially behaves like a machine, and vitalists who believe there is a non-causal life force. Critics thought Lovelock was saying that the planet had a life force which was actively controlling the climate and so on. However this wasn't Lovelock's intention. He stated that 'Neither Lynn Margulis nor I have ever proposed that planetary self-regulation is purposeful ... Yet we have met persistent, almost dogmatic, criticism that our hypothesis is teleological.' (1991)

Another loudly voiced objection was that Gaia had evolved without any recourse to natural selection - an impossibility, according to the Darwinists. If the Earth is alive, where is its Selfish Gene, and who will it pass it onto?
As a response to these criticisms, Lovelock, together with Andrew Watson, developed the Daisyworld model - an imaginary planet, which maintains conditions for its survival simply by following its own natural processes. This simple model has since become an integral part of the debate about the Gaia Hypothesis.

The Daisyworld planet contains only two species of life: light daisies and dark daisies. Light daisies tend to reflect light, which has a cooling effect, while dark ones absorb radiation, and therefore warm the planet. Growth of the daisies depends on the present population, the natural death rate, the available space and the temperature (the equations that Lovelock used to model them were based on the dynamics of real daisy growth). The planet revolves around a sun, from which it absorbs energy at a rate which depends on the sun's luminosity and the albedo of the planet. It also radiates heat out to the universe, at a rate determined by the Stefan-Boltzmann Law. Interestingly, when the model is run with the sun's luminosity gradually increasing, the population of the light and dark daisies adjust themselves naturally so as to keep the temperature constant at the optimal level for daisy growth. Daisyworld is an example of a self-regulating system. Feedback loops between the daisies and the planet temperature, contained in the equations relating growth rate to albedo, somehow conspire to maintain the conditions suitable for life. Daisyworld is only a kind of thought experiment, but demonstrates the principle of self-regulation very convincingly. It's a viable ecosystem which regulates its temperature, without any recourse to selection or teleology.

One of the main ideas to come out of the Daisyworld model is that the species in an ecosystem can be concerned with nothing more than their own survival, yet as a consequence of their actions they help not only themselves but the whole system. We could say that the self-regulation is an emergent property of the system. There isn't any need for the white and black daisies to get together and agree quotas for each other's populations, and fix growth rates and argue over how much land should be left uncovered. They just do their own thing and the planet takes care of itself. All that is needed is that the daisies give positive and negative feedback to the temperature, and they are happiest at a particular temperature, so they tend to keep the planet around that temperature. They make the planet suit them. Daisyworld addresses the dichotomy that exists between the reductionist approach, which attempts to understand systems by breaking them down to their smallest components, and the holistic approach which views systems as complete entities that must be understood in their entirety.

A consequence of the Daisyworld model is that it has opened people's eyes to similar systems. An example is the salinity of the oceans, as described by Hinkle [see Bunyard, 1996]. Living organisms maintain a salinity which is roughly equal to that of the oceans. Previously it was thought that this was because natural selection tended to assist those organisms which were in balance with their surroundings. The question remained, why has the ocean managed to maintain a constant level of salinity? The ocean's present salinity is around 3.4%. If it were to go much above 4%, then basic cell functions such as the maintenance of membrane potential would fail. There would be mass extinctions of life in the oceans. And yet there is no evidence of such extinctions in the last 500 million years. This is quite strange, because salt is constantly being deposited in the oceans through the weathering of rocks, yet its concentration is only 10% of saturation levels. Furthermore, there has been a multitude of cataclysmic events such as meteorite impacts, periods of glaciation and so on which one might expect to abruptly alter salinity. Indeed, attempts to model the salinity regulation using chemistry or physics have failed. So what is regulating the oceans?

From Daisyworld we might predict that the answer is the organisms that live in the oceans. In fact, bacteria play a particularly important role in the running of the oceans (as in most life processes). Although they constitute only 10-40% of the ocean biomass, their high surface area to volume ratio means that they make up 70-90% of the biologically active surface area. And they all pump salt. Looking at the problem from the point of view of Gaia Theory breaks down the barriers between what we have traditionally seen as living and non-living systems.

Daisyworld and the Gaia Hypothesis are controversial because they touch on the definition of what constitutes life. If we think that life is about the selfish gene, competition, and survival of the fittest, then it is hard to see where the Earth fits in. However, it isn't necessary to think that the Earth is alive in order to appreciate that it is a highly complex system. And, if we say it is alive, why is that so threatening? No one doubts that plants are alive, but they don't do anything nearly as complicated as the Earth does.

Gaia theory has already had a huge impact on science, and has changed the way we view our place in the world. By making us more aware of the damage we are doing to the eco-system, it may also help us to survive. One of the lessons of Daisyworld is that, due to the effect known as hysteresis, damage once done is very difficult to undo. Our experiment with global warming cannot be halted when we are uncomfortable with the effects; by then it may be too late. And once a species is extinct, it cannot be restored. We are just one part of a larger system, and are reliant on that system for our continued existence. We harm it at our peril.

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See also:
Orrell, D. 2007. The Future of Everything: The science of prediction. Thunder's Mouth Press, New York. (Published in Canada by HarperCollins as Apollo's Arrow.) Includes a discussion of the relation of Gaia theory to climate prediction.