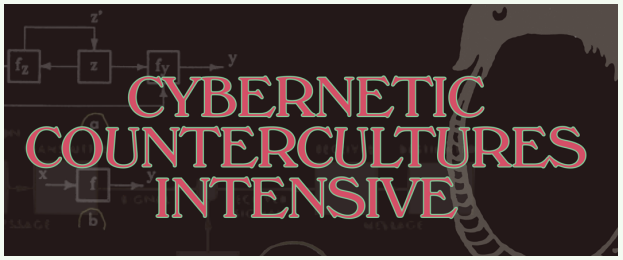
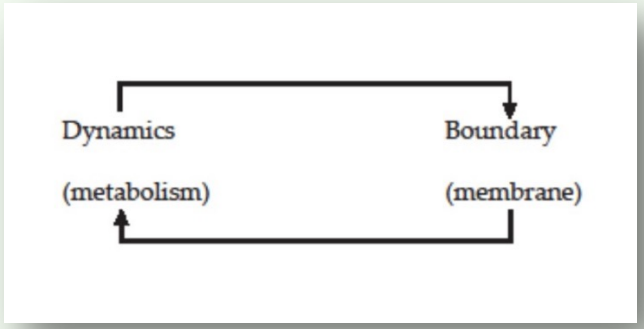
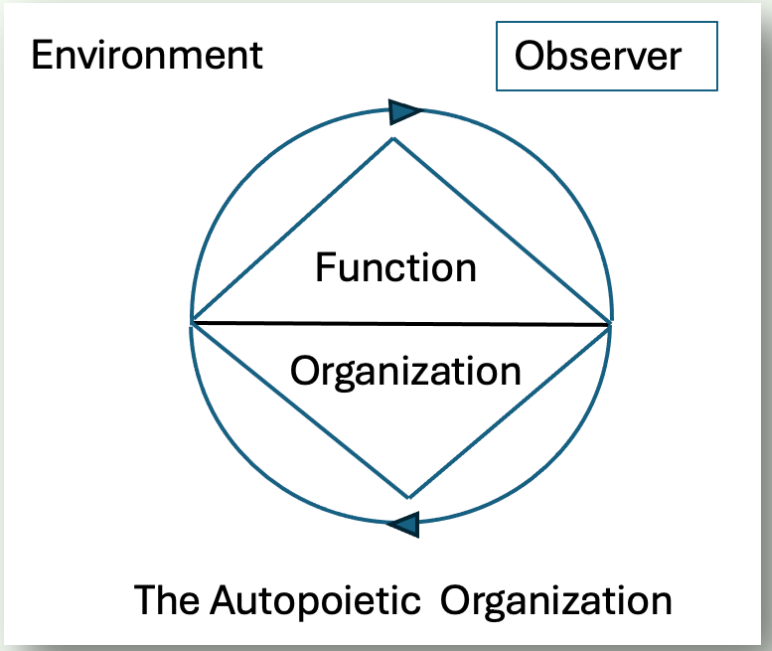


Week 3. Approaching Autopoiesis: Maturana and Varela

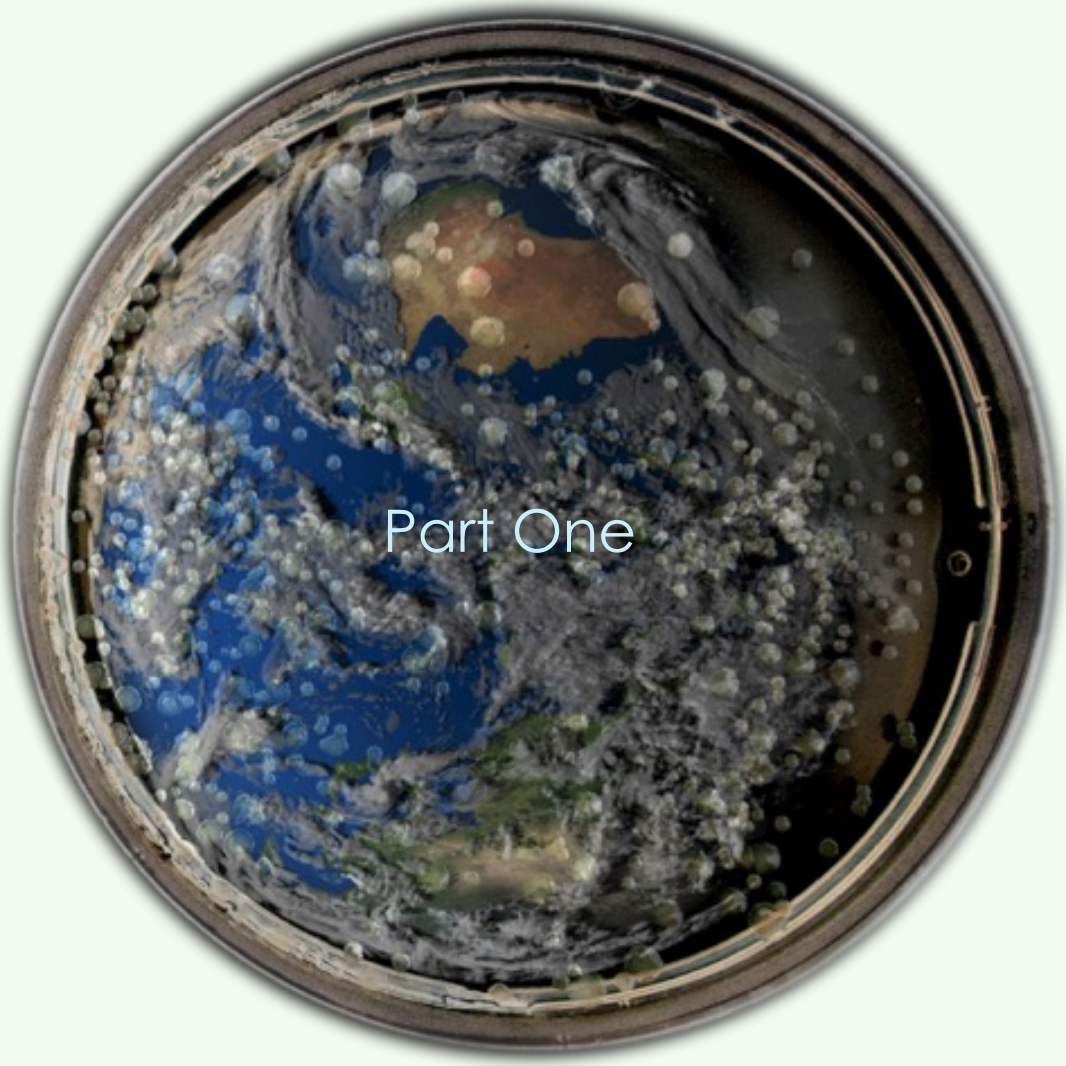
Bruno Clarke
brunoclarke@gmail.com





CYBERNETIC COUNTERCULTURES INTENSIVE

Week 3. Approaching Autopoiesis: Maturana and Varela

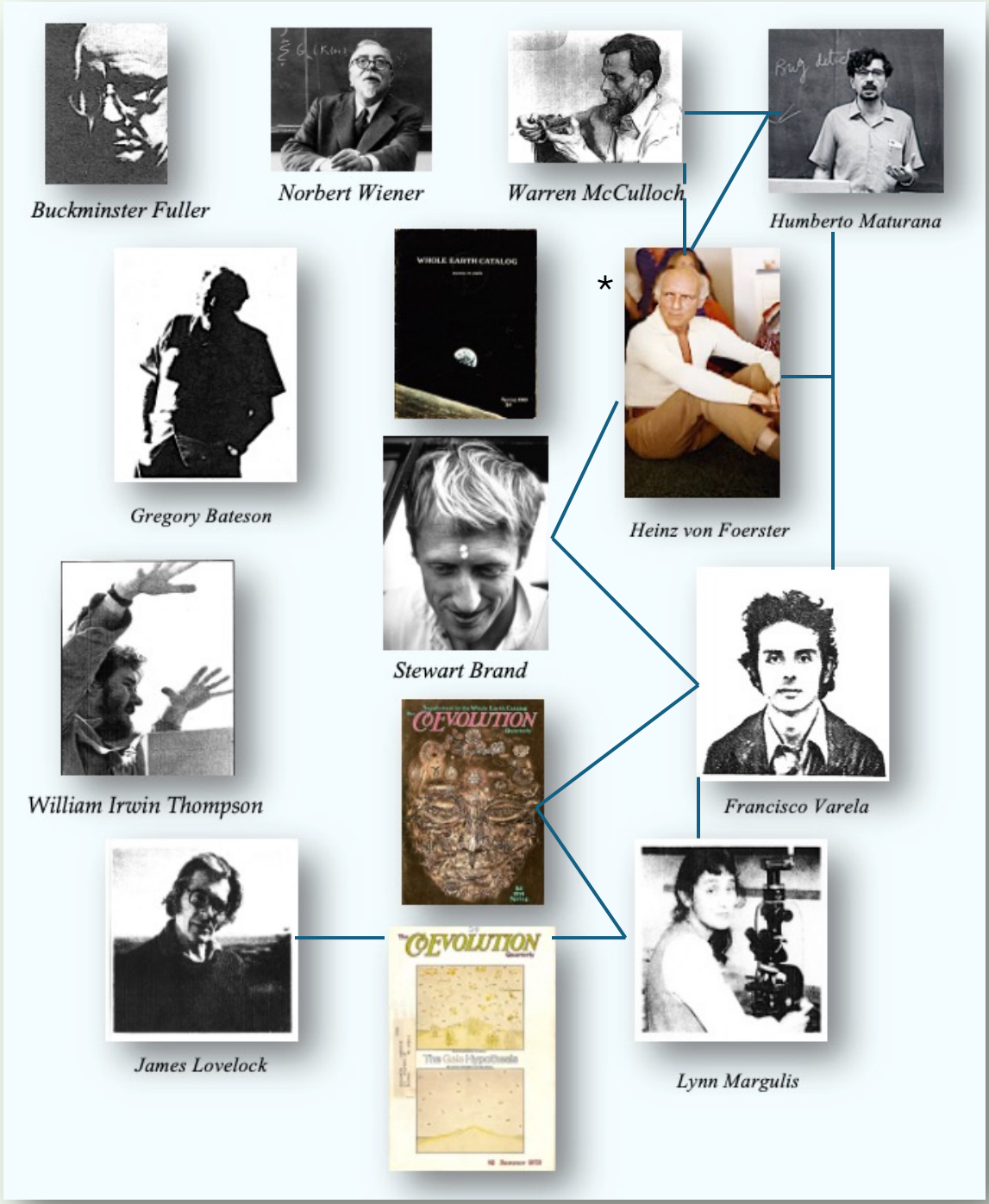


Incubating Autopoiesis: From the Biological Computer Lab to *CoEvolution Quarterly*

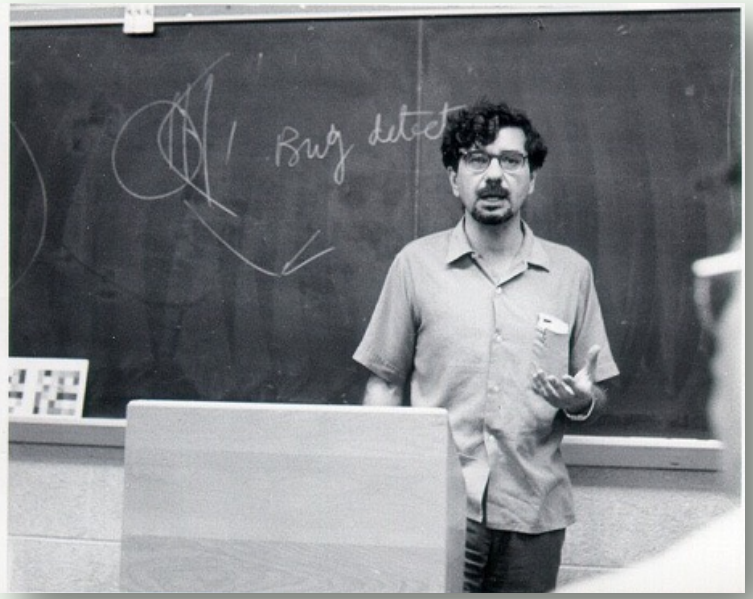
Bruno Clarke
brunoclarke@gmail.com

Cybernetic Countercultures Network

To tell this story right we have to work on the Heinz von Foerster portion of the network and his consequential collaborations with Humberto Maturana and Francisco Varela.



The concept of autopoiesis was born in the laboratory of the Chilean scientist Humberto Maturana. After completing doctoral training at Harvard in neurophysiology, he took a post-doctoral fellowship at MIT in the lab of the cognitive scientist Jerome Lettvin.



Humberto Maturana in Jerry Lettvin's lab

Their paper of 1959, "What the Frog's Eye Tells the Frog's Brain," mutually co-authored with Warren McCulloch and Walter Pitts, "one of the earliest papers in the realm of neuroethology" (Wikipedia), become a classic early-cybernetic treatment of epistemological constructivism.

Precise mapping of neuronal activity in the frog's eye indicated that the frog's sensorium has evolved, restated in an autopoietic idiom, to "bring forth" not a raw or neutral world but one predisposed to make its preferred prey stand out sharply from its environmental surround. The better to prosper as a living being, the frog constructs a reality that foregrounds immediately available nutritious affordances—that is, flies.

What the Frog's Eye Tells the Frog's Brain*

J. Y. LETTVIN†, H. R. MATURANA‡, W. S. McCULLOCH||, SENIOR MEMBER, IRE, AND W. H. PITTS||

Summary—**In this paper, we analyze the activity of single fibers in the optic nerve of a frog. Our method is to find what sort of stimulus causes the largest activity in one nerve fiber and then what is the exciting aspect of that stimulus such that variations in everything else cause little change in the response. It has been known for the past 20 years that each fiber is connected not to a few rods and cones in the retina but to very many over a fair area. Our results show that for the most part within that area, it is not the light intensity itself but rather the pattern of local variation of intensity that is the exciting factor. There are four types of fibers, each type concerned with a different sort of pattern. Each type is uniformly distributed over the whole retina of the frog. Thus, there are four distinct parallel distributed channels whereby the frog's eye informs his brain about the visual image in terms of local pattern independent of average illumination. We describe the patterns and show the functional and anatomical separation of the channels. This work has been done on the frog, and our interpretation applies only to the frog.**

Introduction

Behavior of a Frog

A FROG hunts on land by vision. He escapes enemies mainly by seeing them. His eyes do not move, as do ours, to follow prey, attend suspicious events, or search for things of interest. If his body changes its position with respect to gravity or the whole visual world is rotated about him, then he shows compensatory eye movements. These movements enter his hunting and evading habits only, *e.g.*, as he sits on a rocking lily pad. Thus his eyes are actively stabilized. He has no fovea, or region of greatest acuity in vision, upon which he must center a part of the image. He also has only a single visual system, retina to colliculus, not a double one such as ours where the retina sends fibers not only to colliculus but to the lateral geniculate body which relays to cerebral cortex. Thus, we chose to work on the frog because of the uniformity of his retina, the normal lack of eye and head movements except for those which stabilize the retinal image, and the relative simplicity of the connection of his eye to his brain.

The frog does not seem to see or, at any rate, is not concerned with the detail of stationary parts of the world around him. He will starve to death surrounded by food if it is not moving. His choice of food is determined only by size and movement. He will leap to capture any object the size of an insect or worm, providing it moves like one. He can be fooled easily not only by a bit of dangled meat but by any moving small object. His sex life is conducted by sound and touch. His choice of paths in escaping enemies does not seem to be governed by anything more devious than leaping to where it is darker. Since he is equally at home in water and on land, why should it matter where he lights after jumping or what particular direction he takes? He does remember a moving thing providing it stays within his field of vision and he is not distracted.

Anatomy of Frog Visual Apparatus

The retina of a frog is shown in Fig. 1(a). Between the rods and cones of the retina and the ganglion cells, whose axons form the optic nerve, lies a layer of connecting neurons (bipolars, horizontals, and amacrines). In the frog there are about 1 million receptors, $2\frac{1}{2}$ to $3\frac{1}{2}$ million connecting neurons, and half a million ganglion cells [1]. The connections are such that there is a synaptic path from a rod or cone to a great many ganglion cells, and a ganglion cell receives paths from a great many thousand receptors. Clearly, such an arrangement would not allow for good resolution were the retina meant to map an image in terms of light intensity point by point into a distribution of excitement in the optic nerve.

There is only one layer of ganglion cells in the frog. These cells are half a million in number (as against one million rods and cones). The neurons are packed together tightly in a sheet at the level of the cell bodies. Their dendrites, which may extend laterally from 50 μ to 500 μ, interlace widely into what is called the inner plexiform layer, which is a close-packed neuropil containing the terminal arbors of those neurons that lie between receptors and ganglion cells. Thus, the amount of overlap of adjacent ganglion cells is enormous in respect to what they see. Morphologically, there are several types of these cells that are as distinct in their dendritic patterns as different species of trees, from which we infer that they work in different ways. The anatomy shown in the figures is that found in standard references. Further discussion of anatomical questions and additional original work on them will appear in a later publication.

Physiology as Known up to This Study

Hartline [2] first used the term *receptive field* for the region of retina within which a local change of brightness would cause the ganglion cell he was observing to discharge. Such a region is sometimes surrounded by an annulus, within which changes of brightness affect the cell's response to what is occurring in the receptive field,

* Original manuscript received by the IRE, September 3, 1959. This work was supported in part by the U. S. Army (Signal Corps), the U. S. Air Force (Office of Sci. Res., Air Res. and Dev. Command), and the U. S. Navy (Office of Naval Res.); and in part by Bell Telephone Labs., Inc.

† Res. Lab. of Electronics and Dept. of Biology, Mass. Inst. Tech., Cambridge, Mass.

‡ Res. Lab. of Electronics, Mass. Inst. Tech., Cambridge, Mass., on leave from the University of Chile, Santiago, Chile.

|| Res. Lab. of Electronics, Mass. Inst. Tech., Cambridge, Mass.

Conclusion. "We have been tempted . . . to call the convexity detectors 'bug perceivers.' Such a fiber responds best when a dark object, smaller than a receptive field, enters that field, stops, and moves about intermittently thereafter. The response is not affected if the lighting changes or if the background (say a picture of grass and flowers) is moving, and is not there if only the background, moving or still, is in the field. Could one better describe a system for detecting an accessible bug?"

•

BC] Quickly moving peripheral specks were preferentially delivered to the frog's attention, as these were likely to be flies within reach of its long tongue, like a retractable missile hitting its target. This neurological study of animal vision showed experimentally that the frog's sensory apparatus generated its *Umwelt*—the world as attuned by its cognitive apparatus to its maintenance in being.

Stephen Nachmanovitch, "All About Frogs," in *The Art of Is: Improvising as a Way of Life* (2019)

. . . One of the seminal papers that came out of this research was called "What the Frog's Eye Tells the Frog's Brain." Previously **we had thought of the eye as though it were a camera that passively takes in patterns of light; the information about the light is transferred up into the brain**, which then does processing on it and distinguishes faces, letters of the alphabet, all the things we are used to recognizing. [However,] In the case of the frog, the recognition happens before the signals even get to the brain, in the nerve cells of the retina at the back of the eye. These cells are predisposed to fire most strongly when they detect small, dark dots moving around. This, of course, is because frogs eat flies. Finding flies is vitally important to frogs, and what the frog's eye tells the frog's brain is whether or not flies seem to be present. Everything else is secondary. The researchers put various types of stimuli in front of the frogs — big, open areas of color or different shapes with different rates of movement — and they would all produce some mild excitation in the nerve cells in the eye. But the nerve cells would really start jumping around when something was presented that could have been a fly: a moving black dot that subtends about one degree of angle.

Before the information even gets to the brain, the frog's eye has an epistemology. . . .

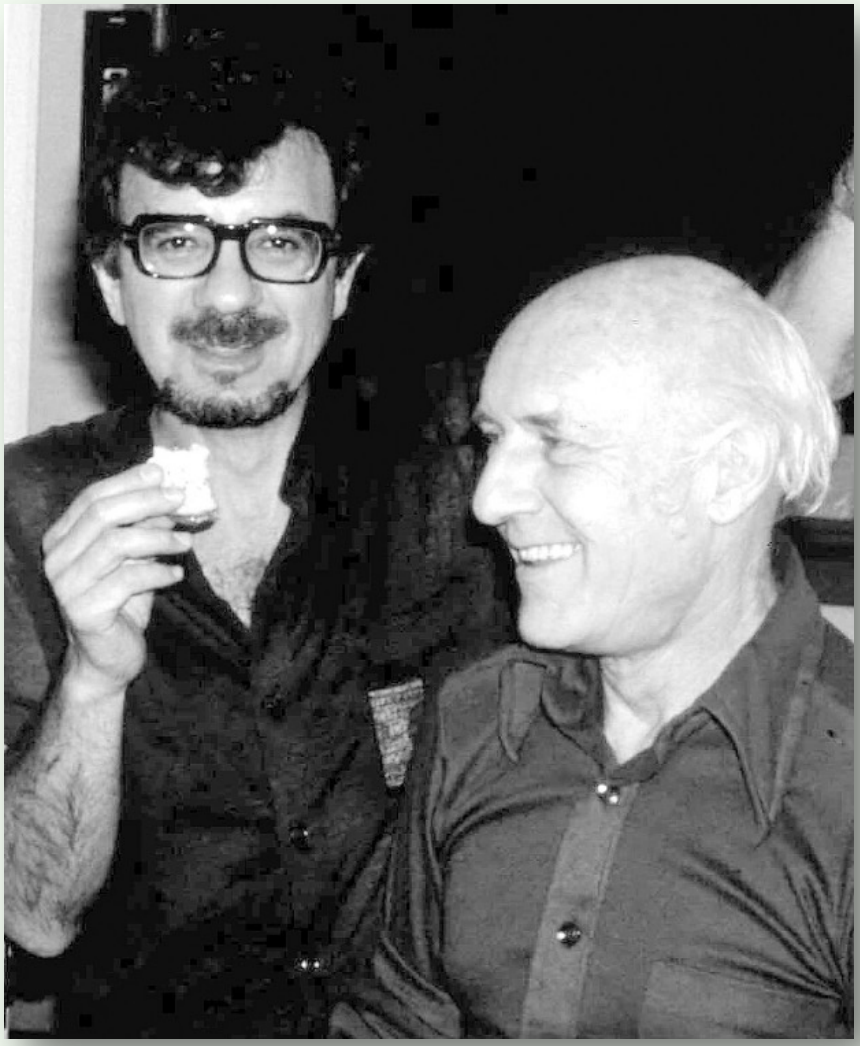
BC] This way of describing perceptual cognition is an instance of what Varela et al call *representationalism*, the narrow epistemological paradigm inherited from the empirical wing of the mechanistic worldview.

Hence, the cybernetic line of "experimental epistemology."

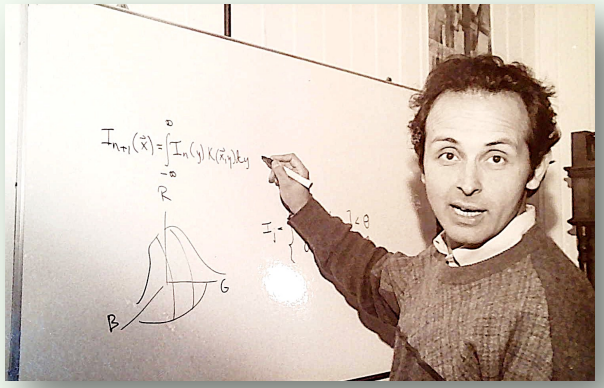
The Three Amigos of Autopoiesis. Maturana and von Foerster bonded playing hooky at an academic conference in 1962. They became close friends and supportive colleagues, both making visits to the other's lab throughout the '60s. Their work converged toward a shared neocybernetic turn that came to fruition in the theory of autopoiesis and the discourse of second-order cybernetics.

Heinz was keenly interested in Maturana's dedicated experimental work on vision and color perception, a line of investigation his medical student Francisco Varela would also pursue, at first experimentally under Maturana's supervision and then as developed toward his own later discourse of neurophenomenology.

In due time, Varela too would be invited to the BCL. Immediately after a three-day visit there in January 1968, Varela applied for a fellowship in the doctoral program in physiology at Illinois, giving as his prior academic experience "research in neurophysiology of vision" at the Faculty of Sciences in Santiago between 1966-68 and his receipt of the scholarship at Harvard University that brought him to the US at that moment.



Maturana and von Foerster at the Biological Computer Lab, 1974



Varela's statement of purpose in his application to the University of Illinois, listing Maturana as his director and von Foerster as a reference. As it happened, Varela was welcome at the BCL but remained on scholarship at Harvard. By his own account, he was frustrated by their program and took his doctorate in two years in order to get out of there and back to Maturana's lab in Chile.

Insert below a statement of not more than three hundred words concerning your past work in your proposed or allied fields of study, including non-course educational experiences, teaching or other relevant employment, publications, and your plans for graduate study and a professional career.

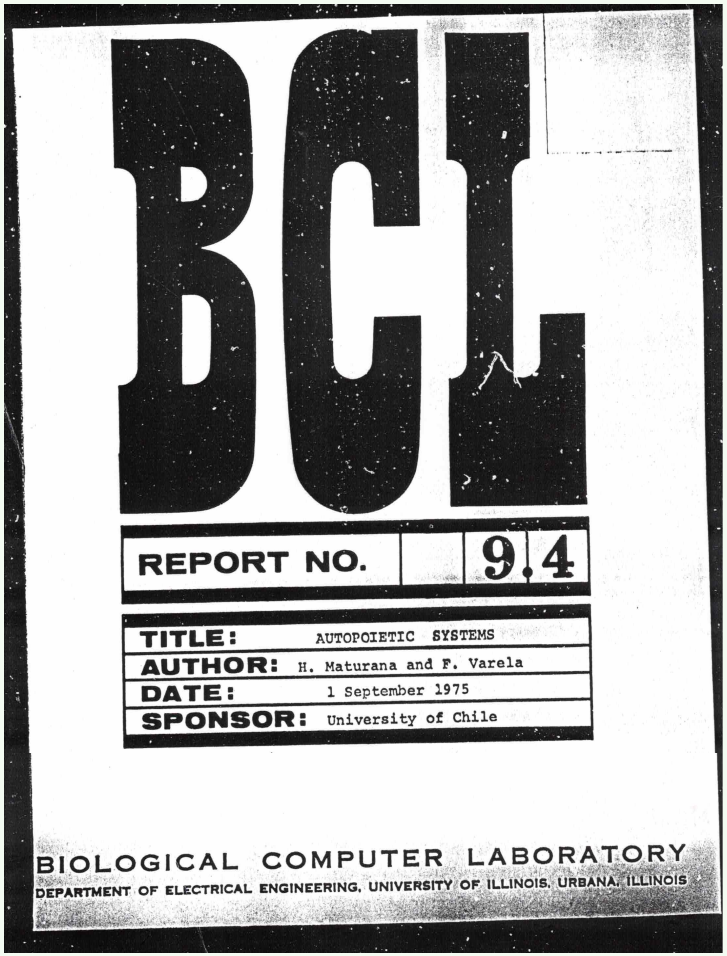
My major professional goal is the understanding of the nervous system, both from the physiological and the theoretical point of view. It is my intention to concentrate in the neuron-to-neuron interaction and to develop a mathematical apparatus to describe these interactions as a first step towards a more broad theoretical (mathematical) frame for the biological sciences. During 1966-67 I worked under the direction of Dr. H.R. Maturana in vision physiology. A final report on this work is ready for publication. A paper entitled, "Interactions between Excitatory and Inhibitory Processes in Single Ganglion Cells" by F.G. Varela and H.R. Maturana has been accepted for publication. I have the intention to join the Faculty of Sciences (Univ. of Chile), for research and teaching sometime after I have received my Ph.D.

Harvard doctorate in hand, Varela returned to Chile and rejoined Maturana as a colleague at the University of Chile. By 1971 their newly-developed application of the concept of self-reference to biological systems received the name *autopoiesis*. Here is a passage from Varela's "The Early Days of Autopoiesis," written for a 1995 festschrift for von Foerster. (A more detailed account is Varela, "Preface to the 2nd ed. of *De Maquinas y Seres Vivos*.")

Entry Into Experimental Epistemology

Apprenticeship for the trade of neurobiologist wasn't the only thing going on in the laboratory. Humberto had entered a period of frank questioning of certain dominant ideas in neurobiology; discussion, reading and debate were daily events, spurred on by the presence of Gabriela Uribe, a physician of clear epistemological leanings who was working with Maturana at that time. Those were times of search and discussion focusing on what seemed a dissatisfaction, an *anomaly*. A basic dissatisfaction was the notion of information as the key to understanding the brain and cognition; the idea didn't appear to play an explicit role in the biological process. Humberto's intuition was that living beings are, as he said in those days, 'self-referred', and in some way the nervous system was capable of generating its own conditions of reference. It was a question of reformulating an orientation into an 'experimental epistemology', a wonderful term introduced by McCulloch.

By 1972 Maturana and Varela had completed the 100-page typescript, *De Maquinas y Seros Vivos* (*Of Machines and Living Beings*) but could only get it published by a Chilean university press, in Spanish. The full original statement of the theory of autopoiesis as later transmitted to and internationally disseminated in *Autopoiesis and Cognition* (1980) is already extant in this text. The BCL released its English typescript on September 1, 1975, as Report No.9.4. For five years this was the version that circulated through the cybernetic underground.



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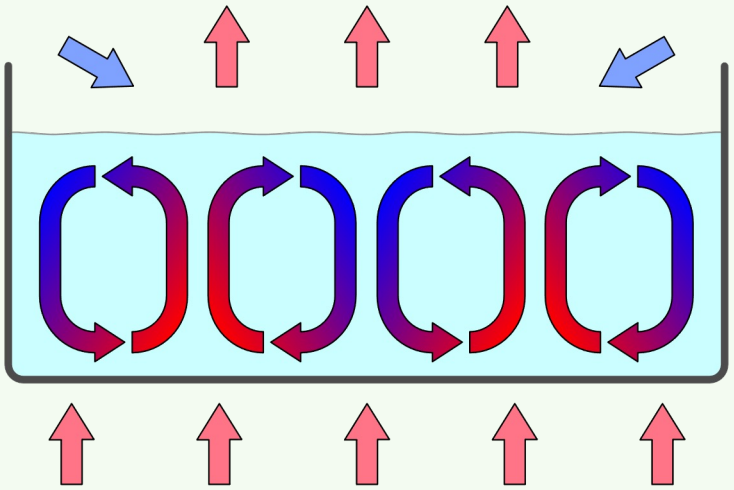
The main thing to note here is that the basic theory of autopoiesis had been fully worked out by the early 1970s, when Varela was still in his mid-twenties. That the theory was not buried in a Chilean library but went on in the next decade to earn a serious international audience owes a great deal to the acumen and promotional efforts of Heinz von Foerster. Varela himself soon proceeded to develop further ramifications of the organizational theory regarding the productivity of operational closure in fields beyond biology proper: we'll come back to this in Week 6.

Sidebar: Self-Organization vs. Autopoiesis

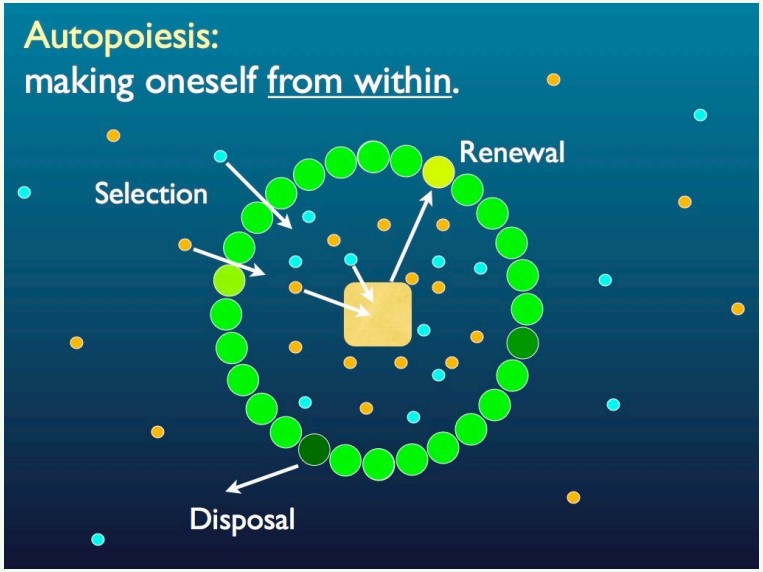
A *self-organizing system* can emerge from an energy flow through certain configurations of physical systems. Recall Morowitz on the cover of the *WEC*: "The flow of energy through a systems acts to organize that system." Self-organization here concerns transient patternings arising with the reduction of energy gradients. Such order typically decays as soon as the energy is spent.



By I, Eyrian, CC BY-SA 3.0, https://commons.wikimedia.org

An example of *self-organization in a dissipative system*: the emergence of convection cells in a heated vessel of fluid.

In contrast, an *autopoietic system* closes upon itself in order to transform its components into an operational unity that functions to perpetuate its organization. The autopoietic organization has "a network of productions of components which participate recursively in the same network of productions of components which produced these components."



A diagram of autopoiesis from http://www.whatlifeis.info/pages/Themes/Origins/Autopoiesis.html

Meanwhile, there is also the saga of the first autopoiesis article. After it was rejected by the *Journal of Theoretical Biology*, Varela et al sought the counsel of their friend and colleague Heinz von Foerster.

They sent Heinz their readers' reports and a further revision with the title of the eventually published article, "Autopoiesis: The Organization of Living Systems: Its Characterization and a Model."

Santiago, December 13.
1972

Varela

Dear Heinz:

Enclosed you will find two versions of a paper on autopoietic systems, together with the referee's commentaries. The paper has been finally rejected by the editor of Theoretical Biology.

It is our impression however that, as seen by the criticisms and objections, the referee's are not talking about the same paper we are writing. Thus there are two possibilities: either we have not expressed ourselves clearly, or they are too blinded by their own epistemological prejudices. We would like to have your opinion on this,

Hope that your sabbatical will start soon, so that you can be with us next year. Affectuously,

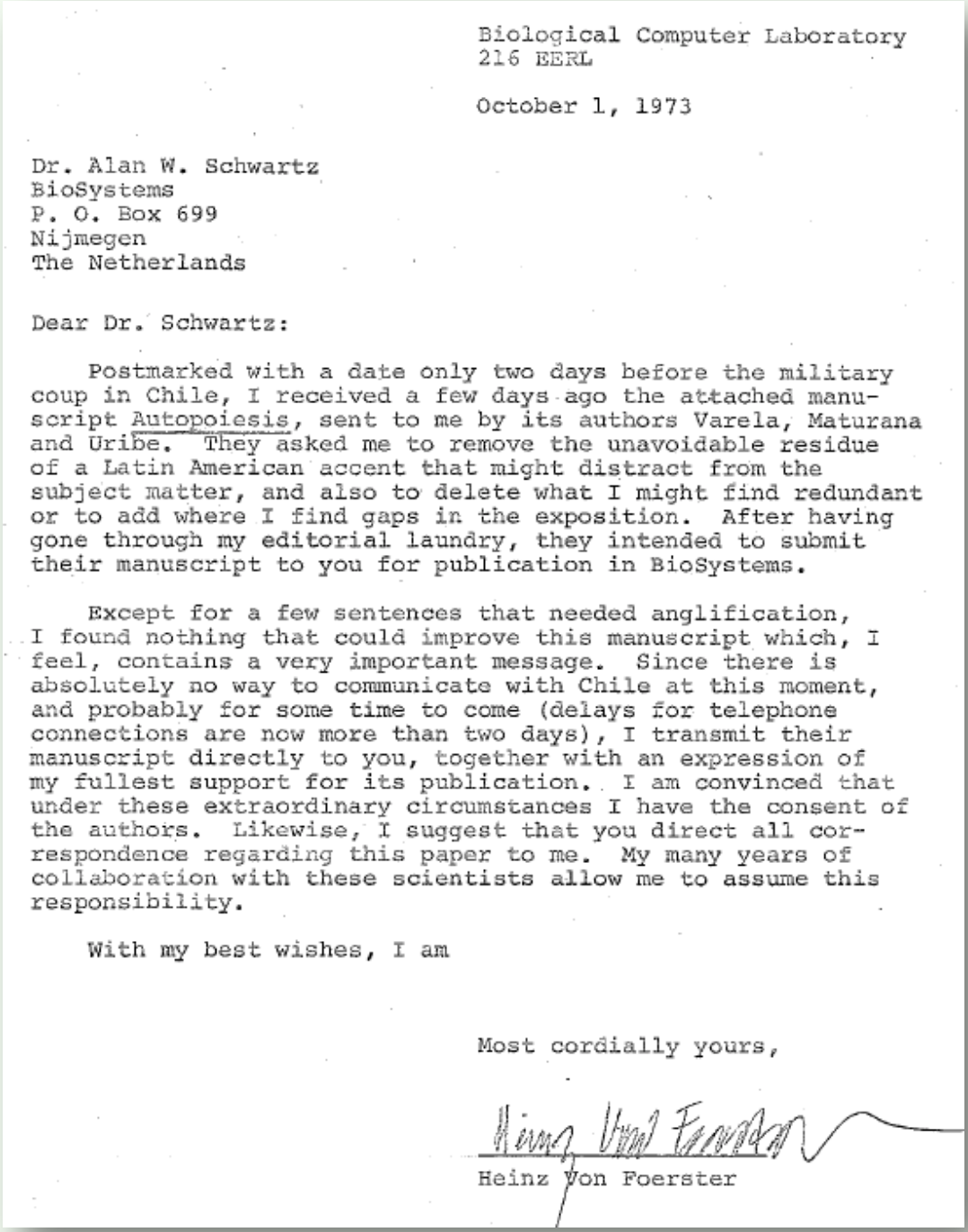
Maturana

Hymberto & Francisco.

Dear Heinz, if you think in a journal that might publish it please pay it or send it. Also, if you would like to publish it as a BCL report, please do it.
I am glad that your eye is getting better. Please take care. Love to you and Nai

The article-length narration of the autopoiesis concept got workshopped in English, with Heinz's own emendations, between 1972-73.

That version went to Dr. Alan Schwartz at the journal *BioSystems* just weeks after the coup that toppled the Allende regime in Chile. Heinz's cover letter explained the reason for his intercession in this correspondence: the turmoil of Pinochet's counter-revolution blocked regular mail with the authors.



Biological Computer Laboratory
216 EERL

October 1, 1973

Dr. Alan W. Schwartz
BioSystems
P. O. Box 699
Nijmegen
The Netherlands

Dear Dr. Schwartz:

Postmarked with a date only two days before the military coup in Chile, I received a few days ago the attached manuscript Autopoiesis, sent to me by its authors Varela, Maturana and Uribe. They asked me to remove the unavoidable residue of a Latin American accent that might distract from the subject matter, and also to delete what I might find redundant or to add where I find gaps in the exposition. After having gone through my editorial laundry, they intended to submit their manuscript to you for publication in BioSystems.

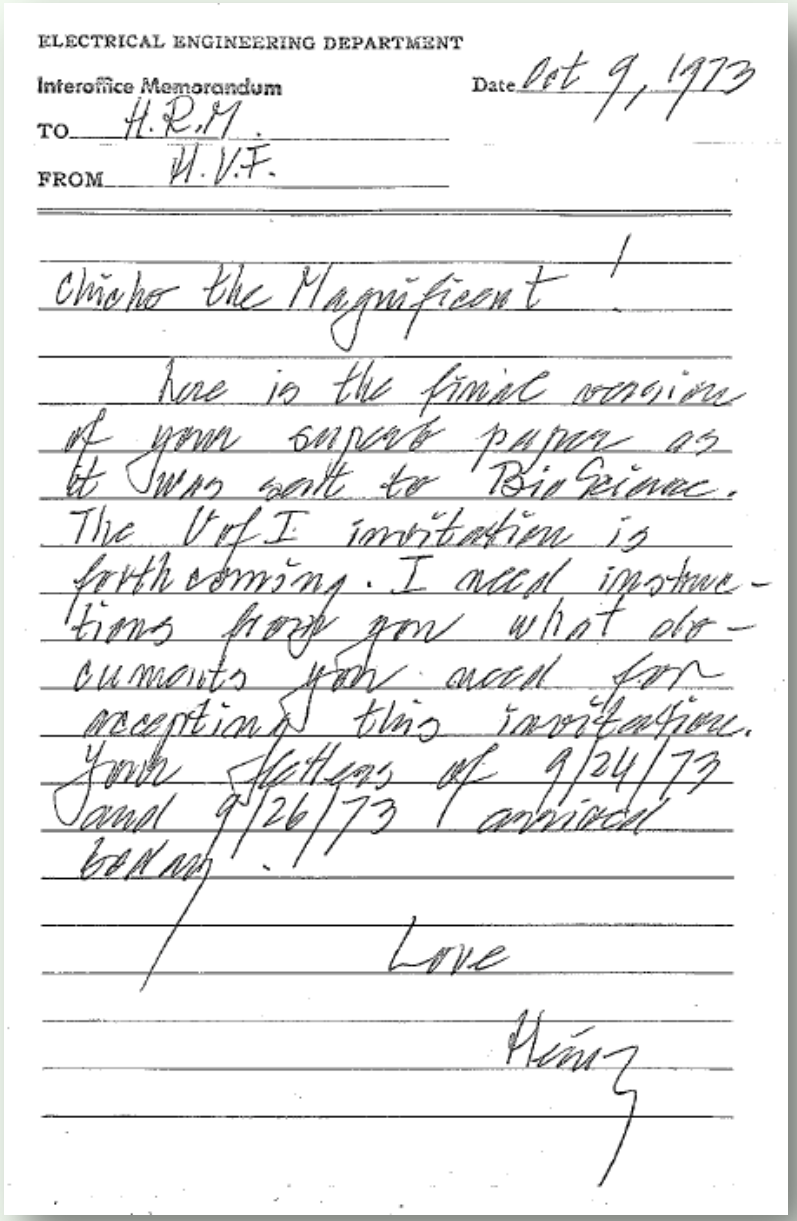
Except for a few sentences that needed anglification, I found nothing that could improve this manuscript which, I feel, contains a very important message. Since there is absolutely no way to communicate with Chile at this moment, and probably for some time to come (delays for telephone connections are now more than two days), I transmit their manuscript directly to you, together with an expression of my fullest support for its publication. I am convinced that under these extraordinary circumstances I have the consent of the authors. Likewise, I suggest that you direct all correspondence regarding this paper to me. My many years of collaboration with these scientists allow me to assume this responsibility.

With my best wishes, I am

Most cordially yours,

Heinz von Foerster

Heinz kept his Chilean colleagues up to date on his efforts on behalf of their autopoiesis essay. He sent them the finished version after final preparations of the manuscript were carried out at the BCL.



ELECTRICAL ENGINEERING DEPARTMENT

Interoffice Memorandum

Date Oct 9, 1973

TO H.R.M.

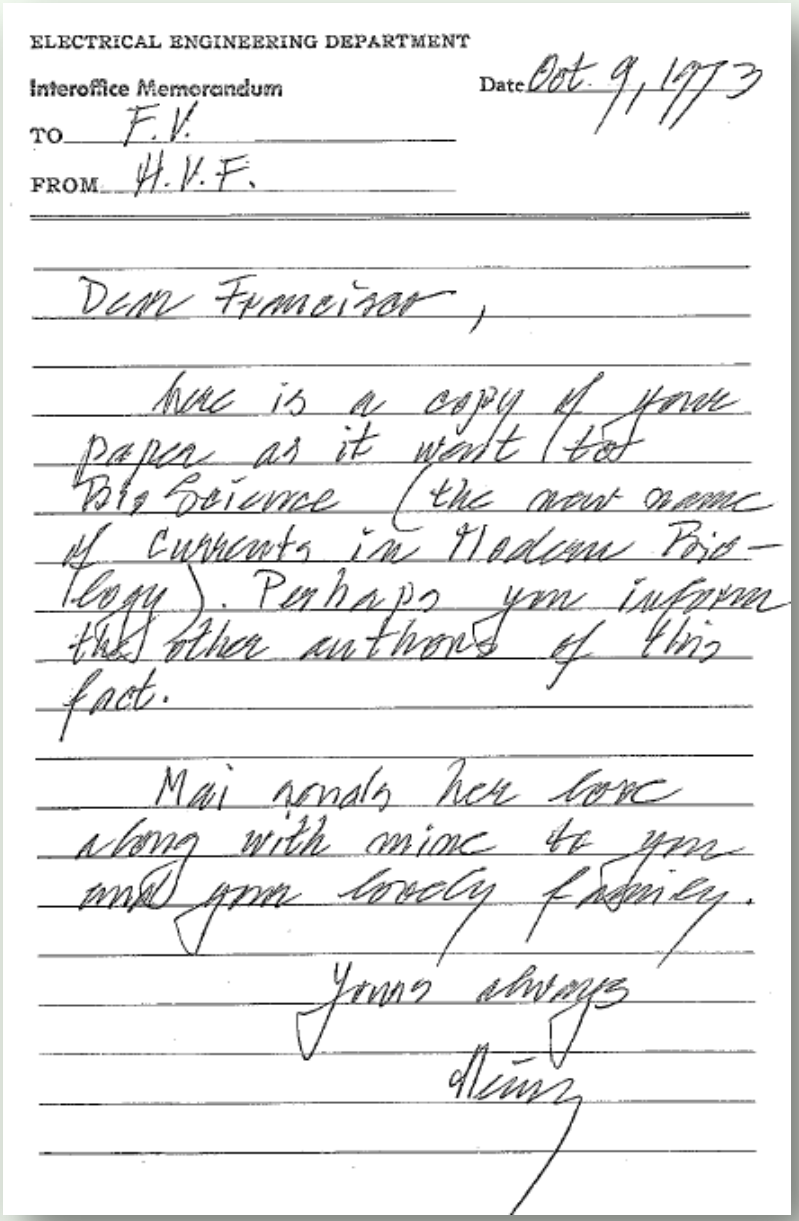
FROM H.V.F.

Chicho the Magnificent!

Here is the final version of your superb paper as it was sent to BioScience. The U of I invitation is forthcoming. I need instructions from you what documents you need for accepting this invitation. Your letters of 9/24/73 and 9/26/73 arrived both.

Love

Heinz



ELECTRICAL ENGINEERING DEPARTMENT

Interoffice Memorandum

Date Oct. 9, 1973

TO F.V.

FROM H.V.F.

Dear Francisco,

here is a copy of your paper as it went to BioScience (the next issue of Currents in Modern Biology). Perhaps you inform the other authors of this fact.

Mai sends her love along with mine to you and your lovely family.

Yours always

Heinz

Schwartz accepted the essay on the strength of von Foerster's recommendation. A week later *BioSystems* sent von Foerster a formal notice of acceptance for "Autopoiesis: The Organization of Living Systems, its Characterization and a Model."

EDITOR!

[redacted]

Direct all correspondence, including proofs, galleys, reprint orders, etc., regarding this paper

AUTOPOIESIS
by
F. Varela, H. R. Maturana, R. Uribe B.
University of Chile, Santiago

to

Heinz Von Foerster
216 EERL
University of Illinois
Urbana, Illinois 61801

BIOSYSTEMS Journal of Molecular, Cellular and Behavioral Origins and Evolution
P.O.B. 699 Nijmegen, The Netherlands

Dr. H. von Förster
Dept. of Electrical Engineering
University of Illinois,
Urbana, Ill. 61803
U.S.A.

17 October 1973.

Dear Dr. von Förster:

Thank you very much indeed for sending me the manuscript by Varela et al. I shall, of course, accept it with your recommendation and will see that proofs are sent directly to you.

Sincerely yours,

Alan W. Schwartz.

Here finally is the first English-language publication of the theory of autopoiesis. Heinz inserted a self-referential BCL acknowledgement.

Acknowledgement

The authors wish to express their gratitude to the members of the Biological Computer Laboratory of the University of Illinois, Urbana, particularly to Richard Howe, Heinz Von Foerster, Paul E. Weston and Kenneth L. Wilson, for their continuous encouragement, discussions, and help in clarifying and sharpening the presentation of our notions.

However, it is still quite a ways from this modest and buttoned-down international scientific journal read only by a rarified audience of specialists to the California shores of the Cybernetic Countercultures. Fortunately, their industrious American sponsor was not done yet with his promotional contributions.

BioSystems 5 (1974) 187–196, NORTH-HOLLAND PUBLISHING COMPANY, AMSTERDAM

BioSystems 5 (1974)

AUTOPOIESIS: THE ORGANIZATION OF LIVING SYSTEMS, ITS CHARACTERIZATION AND A MODEL

F.G. VARELA, H.R. MATURANA and R. URIBE

Facultad de Sciencias e Departamento de Electricidad, University of Chile, Santiago, Chile

We formulate the organization of living organisms through the characterization of the class of autopoietic systems to which living things belong. This general characterization is seen at work in a computer simulated model of a minimal case satisfying the conditions for autopoietic organization.

1. Introduction

Notwithstanding their diversity, all living systems must share a common organization which we implicitly recognize by calling them "living". At present there is no formulation of this organization, mainly because the great developments of molecular, genetic and evolutionary notions in contemporary biology have led to the overemphasis of isolated components, e.g. to consider reproduction as a necessary feature of the living organization and, hence, not to ask about the organization which makes a living system a whole, autonomous unity that is alive regardless of whether it reproduces or not. As a result, processes that are history dependent (evolution, ontogenesis) and history independent (individual organization) have been confused in the attempt to provide a single mechanistic explanation for phenomena which, although related, are fundamentally distinct.

We assert that reproduction and evolution are not constitutive features of the living organization and that the properties of a unity cannot be accounted for only through accounting for the properties of its components. In contrast, we claim that the living organization can only be characterized unambiguously by specifying the network of interactions of components which constitute a living system as a whole, that is, as a "unity". We also claim that all biological phenomenology, including reproduction and evolution, is secondary to the establishment of this unitary organization. Thus, instead of asking "What are the necessary properties of the components that make a living system possible?" we ask "What is the necessary and sufficient organization for a given system to be a living unity?" In other words, instead of asking what makes a living system reproduce, we ask what is the organization reproduced when a living system gives origin to another living unity? In what follows we shall specify this organization.

2. Organization

Every unity can be treated either as an un-

And meanwhile, the first coauthored Margulis and Lovelock articles on the Gaia hypothesis just happen to get published in the same year of 1974. Soon enough, the *CoEvolution Quarterly* comes calling.

Atmospheric homeostasis by and for the biosphere: the gaia hypothesis

By JAMES E. LOVELOCK, *Bowerchalke, Nr. Salisbury, Wilts. England* and LYNN MARGULIS, *Department of Biology, Boston University, 2, Cummington Street, Boston, Mass. USA*

(Manuscript received May 8; revised version August 20, 1973)

ABSTRACT

During the time, 3.2×10^9 years, that life has been present on Earth, the physical and chemical conditions of most of the planetary surface have never varied from those most favourable for life. The geological record reads that liquid water was always present and that the pH was never far from neutral. During this same period, however, the Earth's radiation environment underwent large changes. As the sun moved along the course set by the main sequence of stars its output will have increased at least 30 % and possibly 100 %. It may also have fluctuated in brightness over periods of a few million years. At the same time hydrogen was escaping to space from the Earth and so causing progressive changes in the chemical environment. This in turn through atmospheric compositional changes could have affected the Earth's radiation balance. It may have been that these physical and chemical changes always by blind chance followed the path whose bounds are the conditions favouring the continued existence of life. This paper offers an alternative explanation that, early after life began it acquired control of the planetary environment and that this homeostasis by and for the biosphere has persisted ever since. Historic and contemporary evidence and arguments for this hypothesis will be presented.

It is widely believed that the abundance of the principal gases N_2 and O_2 is determined by equilibrium chemistry. One of the larger problems in the atmospheric sciences is that of reconciling this belief with the uncomfortable fact that these same gases are cycled by the Biosphere with a geometric mean residence time measured in thousands of years. The more thoroughly the inventory of an individual gas is audited the more certain it seems that inorganic equilibrium or steady state processes determine its atmospheric concentration but the same audit frequently further reveals the extent of its biological involvement. A lucid account of contemporary information on the problem of the cycle of gases is in the paper of Junge (1972).

This paper presents a new view of the atmosphere, one in which it is seen as a component part of the biosphere rather than as a mere environment for life. In this new context the incompatibilities of biological cycles and inorganic equilibria are seen as more apparent than real.

A starting point is a consideration of the profoundly anomalous composition of the Earth's atmosphere when it is compared with that of the expected atmosphere of a planet interpolated between Mars and Venus. Thus on Earth the simultaneous presence of O_2 and CH_4 at the present concentrations is a violation of the rules of equilibrium chemistry of no less than 30 orders of magnitude. Indeed so great is the disequilibrium among the gases of the Earth's atmosphere that it tends towards a combustible mixture, whereas the gases of Mars and Venus are close to chemical equilibrium and are more like combustion products.

The anomalous nature of the atmosphere has been known since Lewis & Randall (1923) first commented that at the pE and pH of the Earth the stable compound of nitrogen is the NO_3^- ion in the oceans; gaseous nitrogen should not be present. In spite of reminders by Hutchinson

ICARUS **21**, 471–489 (1974)

Biological Modulation of the Earth's Atmosphere

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AND

J. E. LOVELOCK

Department of Applied Physics, University of Reading, Reading, England

Received August 7, 1973; revised November 6, 1973

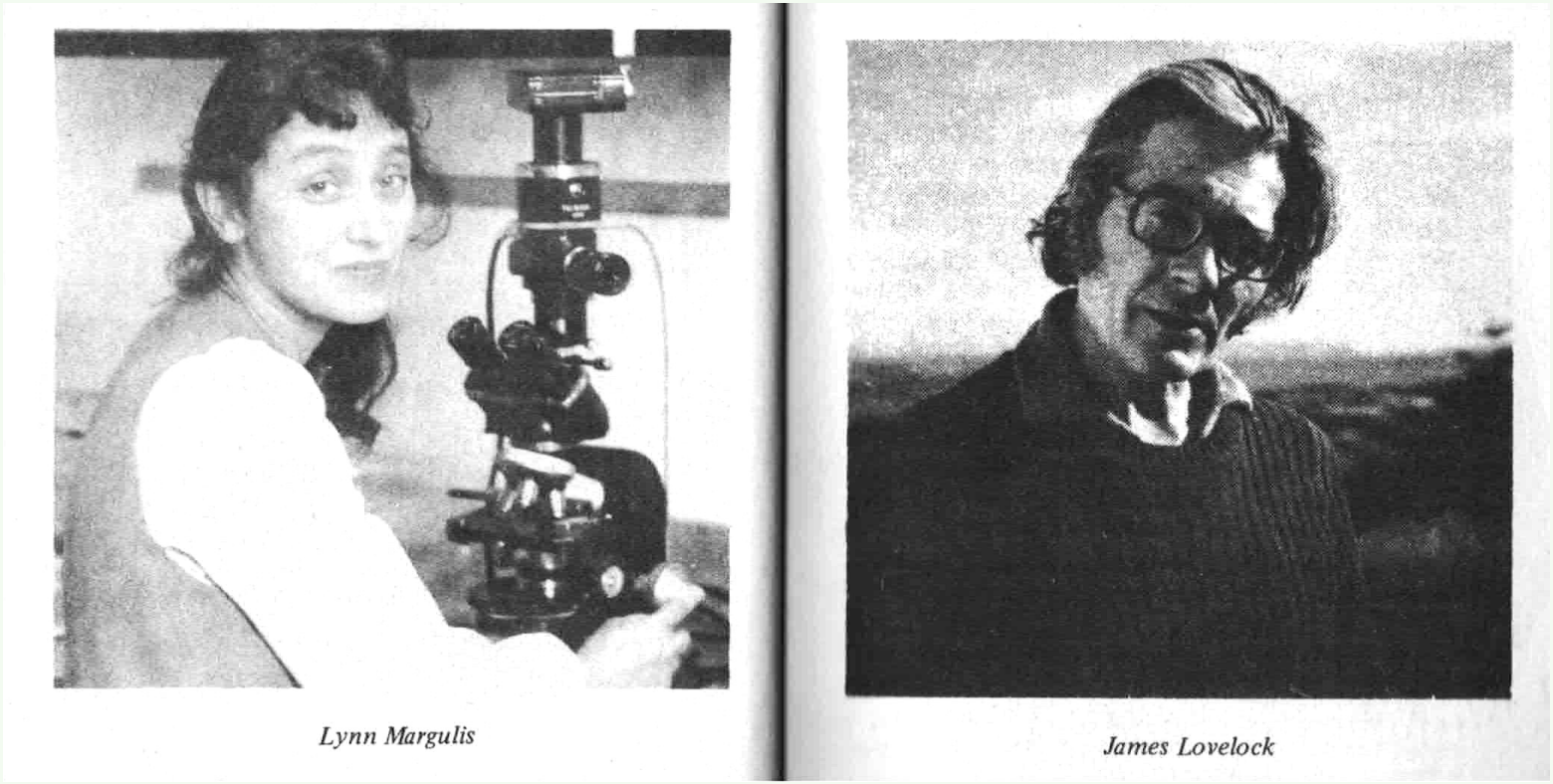
We review the evidence that the Earth's atmosphere is regulated by life on the surface so that the probability of growth of the entire biosphere is maximized. Acidity, gas composition including oxygen level, and ambient temperature are enormously important determinants for the distribution of life. We recognize that the earth's atmosphere deviates greatly from that of the other terrestrial planets in particular with respect to acidity, composition, redox potential and temperature history as predicted from solar luminosity. These deviations from predicted steady state conditions have apparently persisted over millions of years. We explore the concept that these anomalies are evidence for a complex planet-wide homeostasis that is the product of natural selection. Possible homeostatic mechanisms that may be further investigated by both theoretical and experimental methods are suggested.

> "The atmosphere, therefore, is the mysterious link that connects the animal with the vegetable, the vegetable with the animal kingdom." (Dumas and Boussingault, 1844).[1]

I. Introduction to Gaia: Le Milieu Exterior

The purpose of this paper is to develop the concept that the earth's atmosphere is actively maintained and regulated by life on the surface, that is by the biosphere. The ancient Greeks believed that all creatures on the earth, animals and plants, including man belonged to a common society. Their reference to this great communal being was "Gaia," or roughly, Mother Earth. We recognize that the earth's atmosphere differs greatly from that of the other terrestrial planets with respect to acidity, composition, redox potential, and temperature history as predicted from solar luminosity. This anomalous atmosphere has persisted over geological time periods. We believe that these properties of the terrestrial atmosphere are evidence for homeostasis on a planetary scale. In deference to the ancient Greek tradition, we refer to the controlled atmosphere-biosphere as "Gaia". We review some recent information about the terrestrial atmosphere in the light of the "Gaia hypothesis" (Lovelock, 1972; Lovelock and Margulis, 1973). First we consider the evidence that certain features of the terrestrial atmosphere (such as composition, temperature and pH) are under feedback control. We follow with suggestions for possible mechanisms involved in this complex homeostasis and ways of testing for them. We have written this paper to be comprehensible to a wide scientific audience, recognizing that an understanding of the earth's atmosphere will come only from cooperation of many scientists: planetary astronomers, geolo-

[1] See Aulie, 1970.



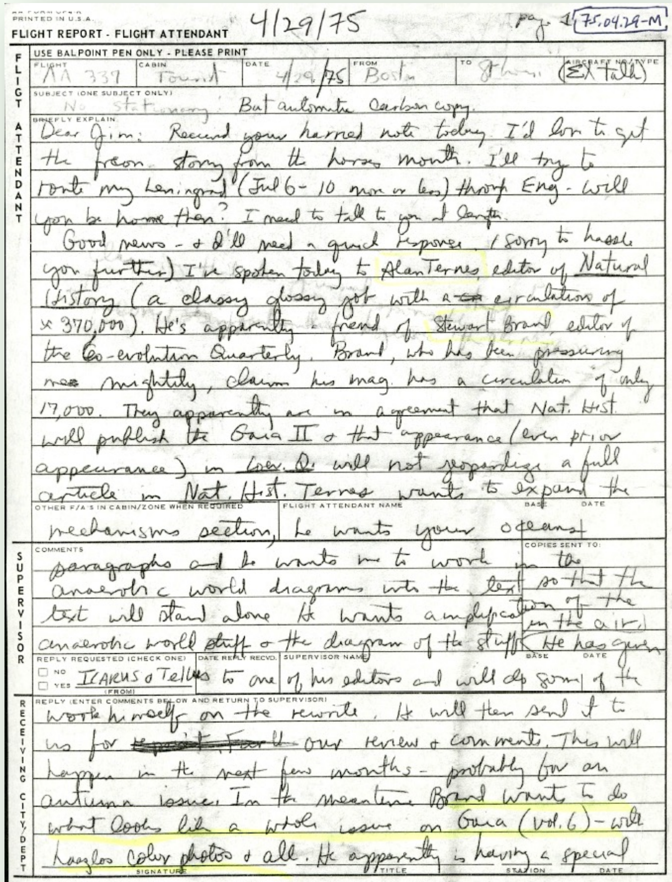
Lynn Margulis

James Lovelock

—from "The Atmosphere as Circulatory System of the Biosphere—
The Gaia Hypothesis," *CoEvolution Quarterly* 5 (Summer 1975)

We know from Margulis' correspondence that the *CoEvolution Quarterly* article came about because Brand got in touch with her first. She then cleared the idea with Lovelock.

It was Carl Sagan in 1970 who put his ex-wife Lynn Margulis in touch with James Lovelock, and it was also Carl Sagan in 1975 who brought the Gaia hypothesis to the attention of Stewart Brand.



FLIGHT REPORT - FLIGHT ATTENDANT 4/29/75 Pg. 1 75.04.29-M

USE BALPOINT PEN ONLY - PLEASE PRINT

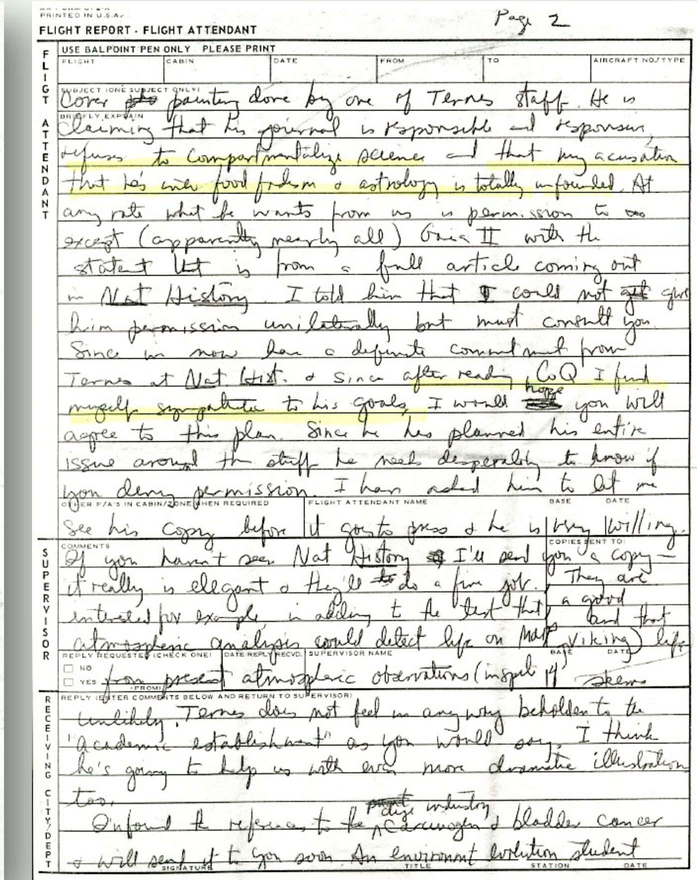
FLIGHT	CABIN	DATE	FROM	TO	AIRCRAFT NO/TYPE
AA 337	Tourist	4/29/75	Boston	Ithaca	(Ex Talk)

SUBJECT (ONE SUBJECT ONLY) No stationery! But automatic carbon copy.

BRIEFLY EXPLAIN

Dear Jim: Received your harried note today. I'd love to get the freon story from the horse's mouth. I'll try to route my Leningrad (Jul 6–10 more or less) through Eng.—will you be home then? I need to talk to you at length.

Good news—& I'll need a quick response (sorry to hassle you further) I've spoken today to Alan Ternes editor of Natural History (a classy glossy job with a circulation of @ 370,000). He's apparently a friend of Stewart Brand, editor of the Co-evolution Quarterly. Brand, who has been pressuring me mightily, claims his mag. has a circulation of only 17,000. They apparently are in agreement that Nat. Hist. will publish the Gaia II & that appearance (even prior appearance) in Coev. Q. will not jeopardize a full article in Nat. Hist. Ternes wants to expand the mechanisms section, he wants your oceans paragraphs and he wants me to work in the anaerobic world diagrams into the text so that the text will stand alone. He wants amplification of the anaerobic world stuff & the diagram of the stuff (in the air.) He has given ICARUS & Tellus to one of his editors and will do some of the work himself on the rewrite. He will then send it to us for our review & comments. This will happen in the next few months—probably for an autumn issue. In the meantime Brand wants to do what looks like a whole issue on Gaia (vol. 6)—with hazelnut color photos & all. He apparently is having a special



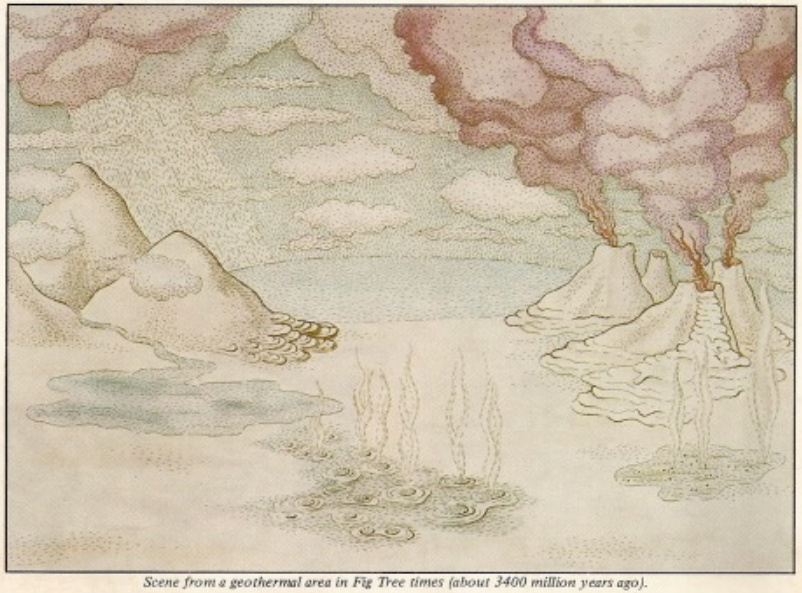
FLIGHT REPORT - FLIGHT ATTENDANT Page 2

Cover painting done by one of Ternes staff. He is claiming that his journal is responsible and responsive, refuses to compartmentalize science and that my accusation that he's into food fadism & astrology is totally unfounded. At any rate what he wants from us is permission to (except (apparently nearly all) Gaia II with the statement that it is from a full article coming out in Nat History. I told him that I could not give him permission unilaterally but must consult you. Since we now have a definite commitment from Ternes at Nat. Hist. & since after reading CoQ I find myself sympathetic to his goals, I would hope you will agree to this plan. Since he has planned his entire issue around the stuff he needs desperately to know if you deny permission. I have asked him to let me see his copy before it goes to press & he is very willing.

If you haven't seen Nat History I'll send you a copy—it really is elegant & they'll do a fine job. They are interested for example in adding to the text that a good atmospheric analysis could detect life on Mars (and that Viking) life from present atmospheric observations (in spite of) skews unlikely. Ternes does not feel in any way beholden to the "academic establishment" as you would say. I think he's going to help us with even more dramatic illustration too.

I've found the reference to the dye industry carcinogen & bladder cancer & will send it to you soon. An environment evolution student

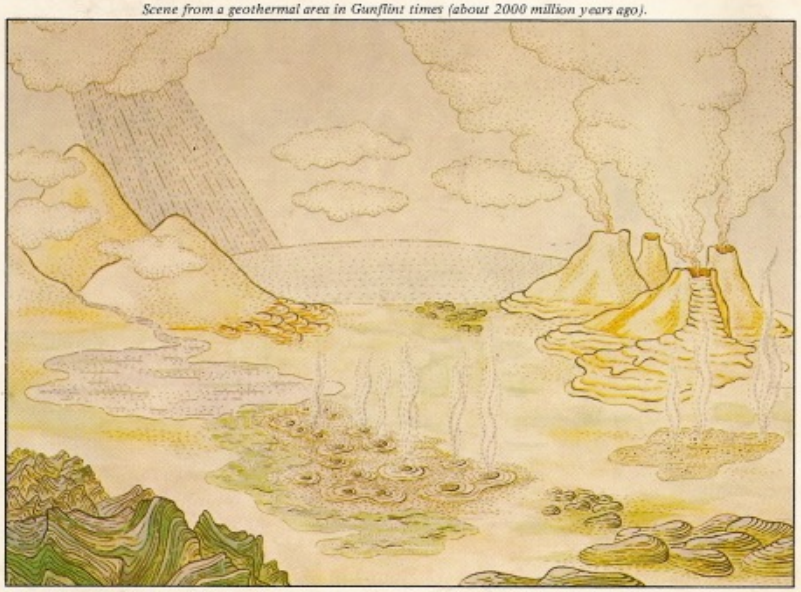
"... Good news—and I'll need a quick response (sorry to hassle you further) I've spoken today to Alan Ternes, editor of *Natural History* (a classy glossy job with a circulation of @ 370,000). He's apparently a friend of Stewart Brand, editor of the *Co-Evolution Quarterly*. Brand, who has been pressuring me mightily, claims his mag. has a circulation of only 17,000. ... Brand wants to do what looks like a whole issue on Gaia (vol. 6) .... He is claiming that his journal is responsible and responsive, refuses to compartmentalize science and that my accusation that he's into food faddism and astrology is totally unfounded. ... I told him that I could not give him permission unilaterally but must consult you." (Lynn Margulis to James Lovelock, April 29, 1975)



Scene from a geothermal area in Fig Tree times (about 3400 million years ago).

The Gaia Hypothesis

Scene from a geothermal area in Gunflint times (about 2000 million years ago).



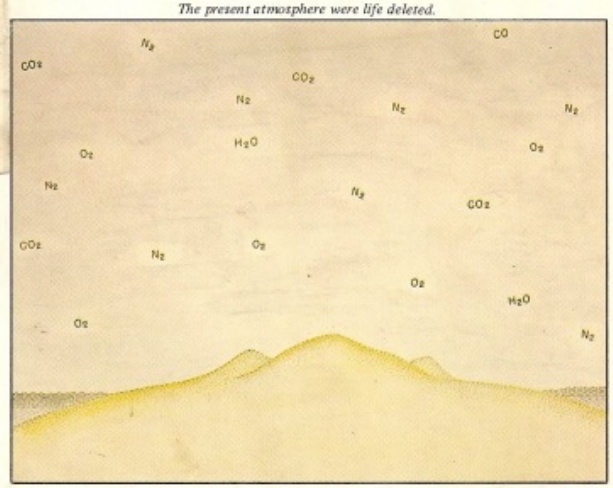
29

The COEVOLUTION Quarterly

Earth's atmosphere at present.

The Gaia Hypothesis

The present atmosphere were life deleted.



$2 Summer 1975

It was also Lynn who secured the article's frontispiece, Sachs von Lewenheimb's 1664 engraving "Oceanus Macro-Microcosmicus." Her aim was to illustrate the analogy between the discovery of the circulation of the blood in the human body and the realization expressed as the Gaia hypothesis, that the circulation of the atmosphere is part of the "physiology" of a self-regulating planetary "body."

FIGURE 1. Frontispiece* to Sachs von Lewenheimb, 1664, Oceanus Macro-Microcosmicus. This illustration stresses the analogies between the circulation of the blood and the circulation of water. According to W. Pagel (1), *"The subtitle of the dissertation (which addresses itself to the famous anatomist Thomas Bartholinus) explains that it deals with the analogies between the circular motion of the water from and back to the sea, on the one hand, and that of the blood from and back to the heart, on the other. This motion is "circular," not because it describes the geometrical figure of a circle, but because it reverts to its point of departure. The earth resembles the human body in that, like the latter, it is pervaded by canals and harbours an internal fire. The sea lets water rise by evaporation and return in the form of rain whereby the rivers and subterranean waters are nourished and these finally return the same water to the sea. The latter thereby acts not unlike the heart from which the blood goes out to the organs, starting on its way attenuated by the influx of heat and 'perfected' in the 'workshops' of the organs; finally, after its absorption and assimilation by the organs, its residue is drawn back into the heart in order to be attenuated again – just as the waters are diluted by joining the sea."*

*From the original treatise in the Wellcome Library by courtesy of the trustees.

The Atmosphere as Circulatory System of the Biosphere— The **Gaia** Hypothesis

BY LYNN MARGULIS AND JAMES E. LOVELOCK

We would like to discuss the Earth's atmosphere from a new point of view – that it is an integral, regulated, and necessary part of the biosphere. In 1664 Sachs von Lewenheimb, a champion of William Harvey, used the analogy shown in Figure 1 to illustrate the concept of the circulation of blood. Apparently the idea that water lost to the heavens is eventually returned to Earth was so acceptable in von Lewenheimb's time that Harvey's theory was strengthened by the analogy (1).

Three hundred and ten or so years later, with the circulation of blood a universally accepted fact, we find it expedient to revive von Lewenheimb's analogy – this time to illustrate our concept of the atmosphere as circulatory system of the biosphere. This new way of viewing the Earth's atmosphere has been called the "Gaia" hypothesis (2). The term Gaia is from the Greek for "Mother Earth," and it implies that certain aspects of the Earth's atmosphere – temperature, composition, oxidation reduction state, and acidity –

The Gaia Hypothesis ("Gaia" is pronounced to rhyme with papaya) treats the anomalous Earth atmosphere as an artifact of life and comprehends the planet itself as a single life.

The two old puzzles – 1) How does the bizarre Earth atmosphere maintain itself? and 2) How does fragile Earth life maintain itself? – solve each other. It took two remarkable scientists – Margulis & Lovelock – meeting outside their specialties to discover that convergance.

Lynn Margulis is a microbiologist at Boston University. Her best-known contribution is the symbiotic theory of the origin of complex cells (her book Origin of Eukaryotic Cells *is reviewed on p. 41). Popularization of that theory in* The Lives of a Cell *won Lewis Thomas a National Book Award last month. He even perpetuated Dr. Margulis' misspelling – "Myxotricha paradoxa" (should be Mixotricha, she notes).*

James Lovelock is the envy of every scientist, a successful free-lancer. Working out of a thatched cottage in the Salisbury Plain, England, this biospheric chemist has accumulated some 69 patents – most of them in what he calls "gas pornography" – chromatographic analysis of gases at the parts-per-billion level. The New Scientist *recently wrote of him, "In some ways, Jim Lovelock – begetter of the Gaia hypothesis – is one of the last of the old-style natural philosophers. A scientist who works from his own home because he believes that lack of security encourages creativity, he has invented – among other things – 'a magnificent Pandora's box', the electron capture detector gas chromatograph. Most sensitive of the analytical chemist's tools, it has been responsible for arousing concern about pesticide residues and Freons in the stratosphere, and may yet help to show that, thanks to Gaia, our fears of pollution-extermination are unfounded."*

It is an honor for The CoEvolution Quarterly *to be the first non-specialist American publication to carry the Gaia Hypothesis. Margulis and Lovelock will doubtless take some flak for appearing in suspect company – condom evaluations, poetry, and such – but both seem comfortable that their science is sound enough to withstand the science-plus context. We are grateful to Carl Sagan, who put us in touch with Lynn Margulis, and to* Natural History *editor Alan Ternes, who will publish an expanded version of this article in his magazine in September or October.*

Gaia is an old idea. She is one of the four primary divine beings of the Ancient Greeks – Chaos (Space), Gaia (Earth), Tartarus (the Abyss), and Eros (Love). But Gaia is still a new hypothesis, containing more questions than answers.

It is too early for proofs, conclusions, or morals, beyond the one incressingly obvious, that as long as human activity works against the self-balancing of biosphere and atmosphere there is no Teilhardian noosphere in evidence, just a damned human cartel.

In Gaia we are – all – Tangled Up In Blue.

– SB

With Brand contributing an extensive epigraph, *CQ* devotes ten lively pages to Lynn's lead-authored presentation. Over the next decade, *CQ* will repeatedly promote the Gaia hypothesis for a Whole-Earth inclined and ecologically knowledgeable audience.

TABLE 2. Composition of the atmosphere: gases in disequilibrium

Gas	Abundance	Flux (moles/yr x 10^{13})	Disequilibrium factor	Oxygen used up in the oxidation of these gases (moles/yr x 10^{13})	abiological process	Source of gas % contribution by biological process	
						human	gaia*
Nitrogen	78%	3.6	10^{10}	11	.001	0	>99
Methane	1.5 ppm	6.0	10^{30}	12	0	0	100
Hydrogen	0.5 ppm	4.4	10^{30}	2.2	?	0	?
Nitrous oxide	0.3 ppm	1.4	10^{13}	3.5	.02	0	>99
Carbon monoxide	0.08 ppm	2.7	10^{30}	1.4	.001	10	90
Ammonia	0.01 ppm	8.8	10^{30}	3.8	0	0	100

*gaia = nonanthropogenic biological sources; for details see Table 1.
? = some quantities not known. ppm = parts per million

TABLE 3. Some critical biological elements that may be naturally limiting

Element	Use in biological systems	Possible form of fluid transport
MAJOR ELEMENTS		
C (carbon)	all organic compounds	CO_2; food; organic compounds in solution; biological volatiles; carbonate, bicarbonate, etc.; usually not limiting
N (nitrogen)	all proteins and nucleic acids	N_2, N_2O, NO_3^-, NO_2^- (often limiting)
O, H (oxygen, hydrogen)	H_2O in high concentration for all organisms	rivers, oceans, lakes
S (sulfur)	nearly all proteins (cysteine, methionine, etc.); key coenzymes	dimethyl sulfide; dimethyl sulfoxide, carbonyl sulfide
P (phosphorus)	all nucleic acids; adenosine triphosphate	unknown (biological volatiles? spores? birds? migrating salmon?)
Na, Ca, Mg, K (sodium, calcium, magnesium, potassium)	membrane and macromolecular function	usually not limiting except in certain terrestrial habitats (27)
TRACE ELEMENTS		
I (iodine)	limited to certain animals (e.g., thyroxine)	methyl iodide
Se (selenium)	enzymes of fermenting bacteria (production of ammonia, hydrogen; animals (26))	unknown (dimethyl selenide?)
Mo (molybdenum)	nitrogen fixation enzymes of bacteria & blue green algae; carbon dioxide reductase (*Clostridium*)	unknown

Gaia – the Greek personification of Earth as a goddess. Terra cotta statuette from Tanagra; in the Musee Borely, Marseille. From Encyclopedia Britannica.

Table 2 shows that given the quantity of oxygen in the atmosphere not only the major gases such as nitrogen and methane but also the minor atmospheric components are far more abundant than they ought to be according to equilibrium chemistry. Even though the minor constituents differ greatly in relative abundance, they sustain very large fluxes – comparable to those of the major constituents. The Earth's atmosphere is certainly not at all what one would expect from a planet interpolated between Mars and Venus. It has too little CO_2, too much oxygen, and is too warm. We believe the "Gaia" hypothesis provides the new approach that is needed to account for these deviations.

A new framework for scientific thought is justified if it guarantees new observations and experiments.

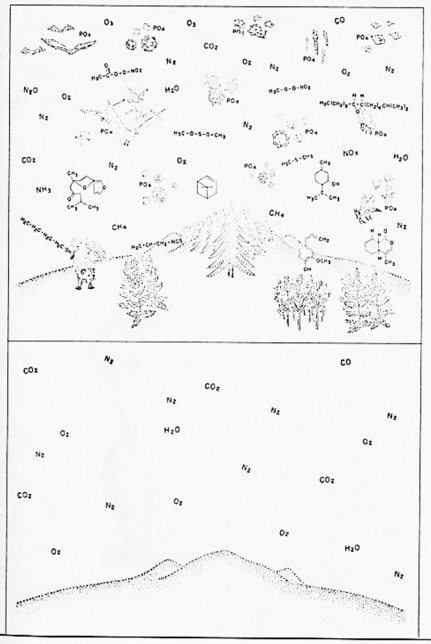


FIGURE 2. Earth's atmosphere at present: examples of major volatiles. (Key: the following compounds and spores are in the picture. It is left to the reader to identify them. See 28 for many details.) Spores of: ferns, club mosses, zygomycetes, ascomycetes, basidiomycetes, slime molds, bacteria. All contain nucleic acids and other organic phosphates, amino acids and so forth. Animal products: butyl mercaptan, plant products: myoporum, catnip (nepetalactone), eugenol, geraniol, pinene, isothiocyanate (mustard); unknown; PAN (paroxacetyl nitrate), dimethyl sulfide, dimethyl sulfoxide; gases: nitrogen, oxygen, methane, carbon monoxide, carbon dioxide, ammonia.

FIGURE 3. The present atmosphere were life deleted. *[Also see CQ cover.]*

The recognition that blood in mammals circulates in a closed, regulated system gave rise to meaningful scientific questions such as: How is blood pH kept constant? By what mechanism is the temperature of mammalian blood regulated around its set point? What is the purpose of bicarbonate ion in the blood? What is the role of fibrinogen? If the blood were simply an inert environment (as the atmosphere is presently viewed) such questions would seem irrelevant and never be asked at all.

Let us consider another analogy. Bees have been known to regulate hive temperatures during midwinter at about 31°C, approximately 59°C above ambient (10). Under threat of desiccation they also maintain high humidities. While the air in the hive is not alive, it maintains an enormous disequilibrium due to the expenditure of energy by the living insects – ultimately of course, solar energy. How is the hive temperature maintained? How does the architecture of the hive aid to reduce desiccation? How does the behavior of the worker bees alter temperature? These are all legitimate scientific questions, generated by the circulatory system concept.

The Gaia hypothesis of the atmosphere as a circulatory system raises comparable and useful scientific questions and suggests experiments that based on the old paradigm would never be asked, for example: How is the pH of the atmosphere kept neutral or slightly alkaline? By what mechanism(s) has the mean midlatitude temperature remained constant (not deviated more than 15°C) for the last 1000 million years? Why are 0.5 x 10^9 tons nitrous oxide (N_2O)

This early Gaia article is still highly technical, with charts, tables, figures, and diagrams, along with a modicum of narrative. I speculate that the terra cotta statuette of the goddess Gaia is Stewart Brand's contribution, exercising the generally irresistible urge to personify the idea of Gaia.

Oops!

Then Heinz von Foerster checks Lovelock's math as transmitted in the *CQ* article and finds problems, including a printers' error that garbles one of the equations.

Moreover, Lovelock's foray into Erwin Schrödinger's *What is Life?* and its physical equation of life with negentropy gives von Foerster the opportunity to question the premises of these information-theoretic descriptions of living systems, and to propose both methodological and theoretical alternatives.

Gaia's cybernetics badly expressed.

My dear Stewart,

CQ's Summer issue found its way to me in the boondocks where in a natural ecology I enjoyed CQ's fabulous bits and pieces of ecological nature. All of us who wish to see or to help healing the wounds cut by reductionism shall be grateful to you for having brought together people whose visions, concepts, and language are much needed medication. Your authors' unity of intent is evident everywhere in this issue, and give CQ a coherence that in itself is a potent remedy.

On the other hand, unity is still absent in the use of a terminology that by necessity pervades CQ's universe of discourse. Should we all be right, then such unity will co-evolve when this terminology is being kicked around in our "conversation pit."

However, it is difficult to converse if too much noise enters the conversation as, for instance, through the three equations in your excerpt from "Atmospheric Homeostasis by and for the Biosphere: The Gaia Hypothesis" by Lovelock and Margulis which appears in the box on Summer '75 CQ's pages 36 and 37:

1. Conceptual Noise (?):

$$\rho \frac{dS}{dt} + div\, S = \Theta \text{ "}$$

is incomprehensible on purely syntactic grounds:

(i) Each of the three terms involved has a different physical dimension, hence they cannot be added [a(apples) + b(bananas) = c(cherries) ?] .

(ii) Divergence (div) is a differential vector operator operating on vectors only; but entropy has no direction.

(iii) Entropy is not a point function as, e.g., temperature, barometric pressure, etc. (otherwise its additivity would give for any finite volume an infinite value), hence entropy cannot appear in a "continuity equation" of the form suggested.

2. Printing Noise (?):

$$\text{"} I = (E + PV - TS - \Sigma N_i N_i)/T \text{ "}$$

The right hand side of this equation looks to me like a Gibbs Free Energy with a malignant tumor attached to it (ΣN, N_i). Maybe this tumor is benign when transformed into

$$\Sigma \mu_i N_i$$

with μ_i and N_i representing the chemical potentials and the number of molecules of species "i" respectively.

I am unable to (re)-construct the proper representation of these equations' intent, for their intent is to be read from their representations. Moreover, sitting in the boondocks I have no way to find out who is to be charged with these booboos: CQ who misprints Lovelock and Margulis; Lovelock and Margulis who misquote Denbigh (1951) and Evans (1969); or Denbigh and Evans who misunderstand. But this is not my job. On the other hand, I found Lovelock's and Margulis' ideas too important to see them becoming vulnerable because of deficiencies of a different kind. As a comment on their — or anybody else's — classification of Life I suggest that you reproduce "Autopoiesis: The Organization of Living Systems, its Characterization, and a Model" by Francisco Varela, Humberto Maturana, and Ricardo Uribe, from **Biosystems**, 5 (4), 187-196 (1974).

3. Epistemological Noise (?):

"Thus the information (I) of a system can be defined as

$$I = S_0 - S$$

where S_0 is the entropy of the components of the system at thermodynamic equilibrium and S the entropy of the system assembled."

Now, dear Stewart, if I tell you (and you listen) that I have here on my desk a system whose volume is about 200 cubic centimeters, and whose entropy is very roughly a few kilowatthours per degree centigrade, you may take this to

be some information about my system. These numbers are now your information of my system, and neither the volume nor the entropy are the information of my system. In fact, my system has no information: it is a can of lighter fluid. This can remains uninformed even if someone were to define its volume or its entropy to be its "curiosity" or its "information," invoking cognitive faculties at places where there are none.

I would hope that we shall never tire of reminding ourselves and each other that "complexity," "disorder," "entropy," "information," "order," "organization," "simplicity," etc., are not names for properties of things, but those for properties of descriptions, or — if you wish — are names reflecting properties of the observer (describer), his vocabulary, his natural or chosen limits of discrimination, etc., in short, his idiosyncrasies at the time of his observations (see Lars Lofgren: "Recognition of Order and Evolutionary Systems" in **Computer and Information Science 2**, J. Tou (editor), 165-175 (1976)). With this in mind it may be amusing to read again the various conjectures on pages six and seven of your Summer issue, or other related pieces.

Cheers and Congratulations to all CQ-ers
ever yours
Heinz Von Foerster
Pescadero, California

Heinz Von Foerster is in the process of retiring as head of Biological Computer Laboratories at the University of Illinois. Last week someone wrote a letter to Science *noting that his population equation of some ten years ago — which predicted a population of infinity during the second decade of the 21st century — is right on schedule.*

—SB

I am going to build a church some day. It will have a holy of holies and a holy of holies of holies. And in that ultimate box will be a random number table.

—Gregory Bateson

Sent by Judith van Slooten

CQ 6 (Fall 1975)

Von Foerster seizes his platform at *CQ* to deliver a highly technical message within the "conversation pit" of the Cybernetic Countercultures. We know that Lovelock and Margulis saw this criticism: Lovelock wrote Margulis an irate letter concerning it. He may not have grasped Heinz's style of intellectual humor. But Margulis, one thinks, would have taken notice of his recommendation of autopoietic theory of living organization.

Gaia's cybernetics badly expressed.

My dear Stewart,

CQ's Summer issue found its way to me in the boondocks where in a natural ecology I enjoyed CQ's fabulous bits and pieces of ecological nature. All of us who wish to see or to help healing the wounds cut by reductionism shall be grateful to you for having brought together people whose visions, concepts, and language are much needed medication. Your authors' unity of intent is evident everywhere in this issue, and give CQ a coherence that in itself is a potent remedy.

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These remarks directly indicate the completion of von Foerster's turn to the second-order cybernetics of *observing systems*. At the same time, their publication in *CQ* marks the moment when a young theory of autopoiesis earned its Cybernetic Countercultural spurs, with a little help from an older hand.

I would hope that we shall never tire of reminding ourselves and each other that "complexity," "disorder," "entropy," "information," "order," "organization," "simplicity," etc., are not names for properties of things, but those for properties of descriptions, or — if you wish — are names reflecting properties of the observer (describer), his vocabulary, his natural or chosen limits of discrimination, etc., in short, his idiosyncrasies at the time of his observations

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