Is Earth Alive?

Gaia as an Analogy, Abduction, Induction, and Deduction

Rasmus Grønfeldt Winther

Professor, University of California, Santa Cruz

Affiliate Professor, University of Copenhagen

www.rgwinther.com; rgw@ucsc.edu

28.7.24

[Book Chapter for volume based on “Coloquio Universitario de Evolución: Diálogo entre Ciencias y Humanidades,” Seminario Universitario de Evolución, volume edited by Rosaura Ruiz Gutiérrez and Ricardo Nogera Solano, Facultad de Ciencias, UNAM, Mexico City, MX]

Abstract

Some of the richness and depth of scientific reasoning can be captured by four key, logical types of inference: analogy, abduction, induction, and deduction. This chapter engages in a sustained comparative exploration of these forms of scientific inference in the service of answering a provocative question: Is Earth alive? Four possible, particular answers (one geological and three biological) are specified, all falling under a general Gaian Claim. Unraveling the Gaia theory of James Lovelock and Lynn Margulis, particularly their 1974 triptych of co-authored papers, gives us a unique window into the role played by each inference type in the three proper biological Gaian claims. Fascinating ontological, theoretical, and methodological disagreements between Lovelock and Margulis about Gaia give us insight into, for example, differences between analogy, perhaps Lovelock’s favorite logical tool, and abduction, so essential to Margulis’s scientific work.

1. Introduction

Is Earth alive? If so, in what sense? Surely Earth *hosts* life, and its organic systems contribute to geological or Earth system processes. But how important is this influence? Does life as a whole set limits or equilibrium conditions to, for example, atmospheric composition, marine chemistry, or average global temperature? How would we measure and empirically assess this? More radically, given the character of geological, physical Earth systems, is it defensible to claim that Earth is itself an individual, living organism?

The stance that Earth might, somehow, be considered alive evokes strong sentiments, in favor and against this consideration. Whether viruses are alive hardly awakens the same level of feeling. And we all agree that biological individuals from the prokaryotic cell up are alive.[1] One reason for the conflicting reactions seems to be that the question "Is Earth alive?" is intimately tied to political, ethical, and social issues about ecology and biodiversity, biosphere collapse and climate catastrophe, and the role and responsibility of humans on this vulnerable planet. There are serious sentimental, moral, and cultural issues involved with the idea of a living Earth.

Recognizing these high stakes, this chapter seeks to answer a series of questions regarding the general and ambiguous claim that Earth is alive: What is the exact content and nature of the claim, and what might its different components of "increasing strengths" be? What are the sources of, and justification for, such a belief? How can we confirm or falsify it?

In order to dive into the Gaian Claim (GC) that Earth is alive (cf. Winther, 2024), I will explore the interweaving of analogy, abduction, induction, and deduction—four types of inference according to which we can analyze (but not wholly reduce) complex practices of scientific reasoning. Focusing on these four kinds of inferences simultaneously helps us see a form of pluralism in scientific practice, which I shall call "inferential pluralism," which is rarely, if ever, considered in extant literature on scientific pluralism or styles of scientific reasoning (e.g., Hacking, 2002; Longino, 2002, 2013; Winther, 2012). Scientific inference is also explored in light of a particularly surprising and controversial conclusion from scientific inferences, that is, the GC. The Gaia hypothesis James Lovelock, an atmospheric chemist and inventor, and Lynn Margulis, a microbiologist and evolutionary biologist, co-developed in the 1970s helps clarify the contrast among the four types of scientific inference. Conversely, this chapter also seeks to understand the cradle, content, and validation of the general GC by appealing to, and mapping out, the modes of inference that it grew out of, and that bolster it. For instance, while the GC can be coherently read as an analogy—most simply between organisms and a planet—I also show that the GC's conceptual content can be usefully understood as produced and justified by abduction. In short, the claim that Earth is alive illuminates the abstract, logical apparatus of scientific inference, and vice versa.

Given the intertwined nature of its philosophical (Section 2) and scientific (Section 3) analyses, this chapter should appeal to at least two audiences: first, those concerned with the nature and logic of scientific reasoning, in particular with the four types of logical and epistemological inference essential to science (developed by figures such as Aristotle, David Hume, Immanuel Kant, and—in more modern times—Charles S. Peirce, J. Robert Oppenheimer, Nelson Goodman, Mary Hesse, Paul Bartha, and Douglas Hofstadter);

[1] Here I set aside the comparison of the boundaries of life with the boundaries of consciousness or rationality, although in impressive artificial intelligence times, whether such artificial systems should be considered conscious or rational, etc., also evokes strong feelings.

and, second, those concerned with Gaia theory as one particular case—not the only possible one, but a central and historically powerful one—of the claim that Earth is alive.

2. Deduction, Induction, Abduction, and Analogy: Types and Relations of Scientific Inference

Let us explore each of the four types of scientific inference in turn. Their order in this section mirrors their order of importance, at least implicitly, in philosophy (e.g., logic and epistemology) and in the scientific and popular imagination. But their order of centrality in this chapter is as presented in the title—the chapter is a plea for the simultaneous importance of analogy and abduction in science.

2.1. Teach Your Children Well? Deduction versus Induction

Many undergraduate courses in philosophy, science, and engineering teach scientific inference as a basic contrast between *deduction* and *induction*—period. Deduction moves from a general, abstract statement to more particular statements or concrete consequences. In a deductive argument, the truth of the premises guarantees the truth of the conclusion. Moreover, a deductive argument is indefeasible in that new information cannot defeat (i.e., deny or negate) a valid deduction—that is, novel information cannot deny the move from the truth of the premises to the truth of the conclusion. This kind of reasoning is common to mathematics and physics.

In contrast, induction is taught as moving from a set of particular claims or observations to a more general claim that includes or subsumes the particular claims or observations. An induction is highly defeasible in that the truth of the premises (e.g., a set of observations about objects or processes, linguistically represented) does not guarantee the truth of the conclusion (e.g., a general claim about properties—both observed and unobserved—of the relevant objects or processes). Thus, deduction is touted as truth-preserving, while induction is not. However, induction produces synthetic or ampliative knowledge—new factual and fallible knowledge about the world—which is something deduction cannot claim. A good or powerful inductive argument is one where the premises provide reasonable to good probabilistic warrant for the conclusion. Empirical sciences of all kinds amply engage in induction.

Deduction and *induction* as highly abstract and capacious idealizations of scientific reasoning help us (and the undergraduates!) understand how scientists might (deductively) derive novel predictions from theories and (inductively) generalize about new objects or processes from experiments. But, despite the undergraduate courses—and a standard, cardboard history of philosophy to the contrary—deduction and induction are also not the only types of scientific inference available. In addition to induction, there exist two other—important, in my view—types of synthetic, ampliative, defeasible, and non-necessary inference: *abduction* and *analogy*.[2]

2.2. Abduction

Abduction comes from the work of Charles S. Peirce and is also called "inference to the best explanation" (Harman, 1965), though some interlocutors wish to make a strong distinction between these (e.g., Harman, 1965; Minnameier, 2004). In a classic piece from 1878, Peirce identifies a kind of inference he calls "hypothesis" and enthusiastically distinguishes it from both induction (both of which he deems synthetic) and deduction. He writes:

> Induction is where we generalize from a number of cases of which something is true, and infer that the same thing is true of a whole class. … Hypothesis is where we find some very curious circumstance, which would be explained by the supposition that it was a case of a certain general rule, and thereupon adopt the supposition. (Peirce, 1878/1986, p. 326)

In the same essay, he writes:

> The great difference between induction and hypothesis is, that the former infers the existence of phenomena such as we have observed in cases which are similar, while hypothesis supposes something of a different kind from what we have directly observed, and frequently something which it would be impossible for us to observe directly. (Peirce, 1878/1986, pp. 335–336)

To clarify the contrast, both induction and hypothesis start with empirical evidence and observation, but hypothesis is an extrapolation, a jump, to try to formulate a theory, a hypothesis, an explanation for the (strange) empirical evidence. By way of illustration rather than argument, here is a vibrant example from Peirce about hypothesis: "Fossils are found; say, remains like those of fishes, but far in the interior of the country. To explain the phenomena, we suppose the sea once washed over this land. That is another hypothesis" (Peirce, 1878/1986, p. 326).

---

[2] Classical literature and names are associated with each form of ampliative reasoning: David Hume and Nelson Goodman, for instance, with induction; C. S. Peirce and Gilbert Harman with abduction and inference to the best explanation; Mary Hesse and Paul Bartha with analogy. (Deduction traces back to the Ancient Greeks, including, of course, Euclid and Aristotle; cf. Netz, 1999.) The four types of inference are fairly isolated in their respective modern analyses and literature. For instance, Igor Douven's 2021 *Stanford Encyclopedia of Philosophy* entry on "abduction" makes no reference to analogy or analogical reasoning, and Paul Bartha's 2022 entry on "analogy and analogical reasoning" on the same platform has no discussion of abduction or inference to the best explanation. Deduction is almost always backgrounded as a default form of inference, and induction is sometimes considered in respective discussions of abduction and analogy. Sources placing all four forms of inference under the same umbrella are rare but include Brewer (2011) who "recognize[s] four distinct, irreducible modes of logical inference" (pp. 177–178) and an editorial introduction to a special issue on "defeasible and ampliative reasoning" (Booth, et al., 2019). Interestingly, Minnameier (2010a), after quoting a brief, cryptic remark by Peirce—"Analogy (Aristotle's {paradeigma}) combines the characters of Induction and Retroduction" (*Collected Papers* 1.65, 1896; Minnameier, 2010a, p. 110)—attempts to reduce analogy to abduction and induction.

Throughout his career, Peirce fully accepted that abduction (also called "hypothesis" or "retroduction" by Peirce) is fallible, error-prone, and synthetic. He also saw it as an informed "guessing" or a kind of "instinct" (cf. Minnameier, 2010b, p. 239; Pietarinen & Belluci, 2014, p. 360). Indeed, "Deduction proves that something *must* be; Induction shows that something *actually is* operative; Abduction merely suggests that something *may be*" (Peirce, *Collected Papers* 5.171, 1903). Abduction is creative and produces possible explanations for surprising situations.[3] Although Peirce, early in his career, saw deduction, induction, and abduction primarily as distinct, almost independent modes of inference, he later came to understand each of these as an iterative part of a larger picture of scientific inquiry.

I here set aside debates about the justification of abduction (e.g., Belluci & Pietarinen, 2020), the logical form of abduction (e.g., Hintikka, 1998), and many other heated matters, including the role of abduction in the scientific realism debates (e.g., Winther, 2020, Chapter 9). What I wish to emphasize is a broad-stroke view of abduction as a creative process of hypothesis formation—a kind of highly educated, intuitive, and informed guessing—and a Sherlock Holmes–like inference to the best explanation of a certain state of affairs. Neither deduction nor induction as inference forms tell us much about *how* the theory or explanation was guessed at or formulated. This kind of "context of discovery," which involves the rampant production of surprising and strange guesses, without which science could not progress—as well as attempts to both justify this mode of inference and to understand how abduction or inference to the best explanation itself justifies new hypotheses and theories (i.e., the "context of justification")—are often missing from the fuller picture of scientific inference in those Introduction to Philosophy undergraduate courses.

2.3. Analogy

Whereas deduction, induction, and abduction typically operate within a single domain of discourse or scientific discipline, analogy permits comparison *across* domains or disciplines, potentially wildly different—for example, from projectile motion to planetary orbits (Galileo, Isaac Newton) or from oceanography/floating icebergs to geology/floating continental plates (Alfred Wegener). Analogy, in the domain of language, is akin to the literary notions of simile and metaphor. But here I analyze analogy as a type of scientific inference, that is, analogical inference. Thus, I articulate it with deduction, induction, and abduction, rather than with literary and poetic devices, as important as these latter are.[4]

---

[3] In his 1878 essay, Peirce presented formal syllogisms where the premises of a deduction were "rule" and "case," with the "result" as conclusion, while the premises for an induction (abduction) were case and result (rule and result) and the conclusion rule (case). Peirce later mostly abandoned such syllogistic presentation of those inference types.

[4] A brief, accurate contrast from a linguist is as follows: "The *metaphor* term comes from the literary analysis tradition, the *analogy* term comes from the philosophic tradition, most recently via Kant and Peirce" (Givón, 1986, p. 100).

In making an analogical inference, we compare—explicitly or subconsciously—an object or process from one domain or discipline to a similar object or process from another domain or discipline. In a thoughtful article titled "Analogy in Science," Robert Oppenheimer characterized analogy thusly:

> [A]nalogy is indeed an indispensable and inevitable tool for scientific progress. Perhaps I had better say what I mean by that. I do not mean metaphor; I do not mean allegory; I do not even mean similarity; but I mean a special kind of similarity which is the similarity of structure, the similarity of form, a similarity of constellation between two sets of structures, two sets of particulars, that are manifestly very different but have structural parallels. (Oppenheimer, 1956, p. 129)

In analogical inference, we map or match-up properties and relations, one to one, best we can (e.g., Gentner & Jeziorski, 1993; Bartha, 2010; Hofstadter & Sander, 2013; Winther, 2020, Chapter 2). Because some properties and relations are readily comparable, analogical scientific reasoning intends to infer that additional properties from the *source domain* (e.g., selective breeding) would also tell us something further about the *target domain* (e.g., natural selection, to allude to Darwin's analogy in his famous 1859 book). Target and source domains should neither be conflated nor confused—they should not be reified (Winther, 2020; cf. Hesse, 1966; Bartha, 2010).

2.4. How Are These Kinds of Scientific Inferences Related?

Unfortunately, each primarily philosophical literature associated with each respective form of inference has a tendency, at least implicitly, to isolate and universalize that inference type (e.g., "abductivists" read abduction as strongly distinct from, and more creative and perilous than, induction, and then interpret analogy as reducible to a combination of abduction and induction). Although the four types of scientific inference are distinct, it will not do to universalize any one of them. I believe it is crucial to simultaneously understand each of them, their respective role, their context of application, and, ultimately, at least try to investigate how they are related. We must also accept that they interact—in both science and everyday reasoning—perhaps in unclear and surprising ways that we have yet to discover.

For Peirce, abduction, deduction, and induction were stages of scientific inquiry. Pietarinen and Bellucci (2014) describe what I shall call "Peirce's ouroboros": "[F]irst comes abduction, the process of forming an explanatory conjecture, then follows deduction which calculates the consequences of the hypothesis, and finally comes induction, in which the consequences of the hypothesis are put to the experimental test" (pp. 353–354). This is a valiant model of scientific inquiry, but of course it is highly idealized, and in actual historical cases it is not easy to point out exactly when and where which of these three scientific reasoning patterns occurred.

Another model of how these types of scientific inferences are related is to think of analogy as bringing in theory, questions, and creativity from entirely different, new domains, thereby not only supplementing the power of abductive inference to grow new hypotheses, but also suggesting new ways to combine inferences, both of the same kind and of different kinds, in both theoretical and experimental contexts. By focusing especially on the GC—and its four constituent GCs—we can also see how analogy conditions Peirce's ouroboros and other potential models of the relations among the other three within-domain inferences (including pair-wise relations such as abduction–induction and abduction–deduction).

3. Gaia Theory

Let us now investigate Gaia theory by turning to four possible, specific answers (one geological and three biological) to the question of this piece's title. Explicit brief definitions and characterizations of each of these four answers is given in the first subsection below, while the types of scientific inference adopted by Gaia's parents are sketched abstractly in the second subsection. In the third subsection, we shall see how the three proper biological GCs rely, in interestingly diverse manners, on the four types of scientific inference. Captivating ontological, theoretical, and methodological disagreements between Lovelock and Margulis also illuminate differences between analogy, arguably Lovelock's favored logical tool, and abduction, so critical to Margulis's scientific work.

3.1. The Gaian Claims

To say that Earth is alive, could, in my view and very roughly, mean two general things: the metaphorical *geological* GC and the proper *biological* GCs.

First, as a geologically, hydrologically, glaciologically, oceanographically, atmospherically, and astronomically complex phenomenon, Earth could be interpreted as alive, with dynamic movement and activity, including volcanoes and earthquakes, as well as with immense, ordered crystals growing in massive underground caves.[5] This is, I argue, an interpretation and reification of some biological processes, including animated movement and cyclical processes, into geology. This is the idea that somehow geology—grouped here with closely related physical sciences such as hydrology, oceanography, and atmospheric science, etc.—embodies life-like processes. After all, similar to an organism, Earth undergoes movement, and parts of it grow and change—even develop—in complex and fairly reliable manners, cyclical as well as linear.

[5] Artist Marie Raffn (personal communication, May 2024) reacted instinctively and immediately to the GC by stating that Earth was alive in that it moved with earthquakes and developed and grew via, for example, uplifting mountain ranges and volcanoes, on land and in the oceans, all caused by plates drifting in various ways. Evolutionary biologist, geneticist, and philosopher Eva Jablonka, while entering the geological Teck Suite of Galleries at the Royal Ontario Museum in Toronto exclaimed something close to "I believe in Gaia when I see crystals like this" (personal communication, September 2023).

However, there may not be anything like *symbiosis* (intimate cross-species or cross-kind cooperation that can lead to higher-level individuality) or *homeostasis* (regulation and maintenance of conditions such as temperature around a set point or within a set range)—two properties among several that are practically definitional of "life" (and thereby of "organism")—involved in Earth's movement, activity, or development. But this is a reasonable perspective and does have historical antecedents (especially the ancient microcosm–macrocosm analogy, also adopted by medieval neo-Platonism and by Renaissance thinkers, that there are resemblances and similitudes of body to planet; cf. Foucault, 1966; Merchant, 1980, Chapter 4, "The World an Organism"). Roughly put, I shall state the first, geological, highly metaphorical version of the GC as follows:

> GC.1 *In its geological (including oceanographic and atmospheric, etc.) processes, Earth is like a living organism.*

Once the proper GC has been established, this GC can be understood as a subset of it.[6]

Notably, the standard *geologistic* view of the relation between physical Earth system processes and biological processes does not generally accept GC.1, let alone the proper GCs. According to the geologistic view, geological, oceanographic, and atmospheric features and processes are the stage upon, and setting in, which life acts—and, moreover, life does not affect geology. The evolutionary play takes place on a large, independent, and sovereign geological stage. In other words, neither the quantity nor quality of life has any significant effect on the physical Earth system. For instance, in a passage critiquing Lovelock's and Margulis's Gaia theory, in which two geoscientists and an astrophysicist accept that the biota is somewhat important and plays some role in, for example, the carbon cycle, Kasting, Toon, and Pollack write: "[W]e nonetheless suggest that the fundamental controls on atmospheric carbon dioxide levels are physical rather than biological" (Kasting, et al., 1988, p. 93). The geologistic view is analogous to the "organism is a passive object" view that Levins and Lewontin critique, a view which emphasizes that while organisms evolve in response to their environment, "autonomous change of the environment [is a] function only of environmental variables" (Levins & Lewontin, 1985, pp. 104–105). Similarly, autonomous change of Earth is a function only of physical, geological, oceanographic, and atmospheric processes and mechanisms—life is irrelevant.[7]

In direct contrast to this orthodox geologistic view, the proper biological GC is that life is an integral part of Earth's overarching processes. It could be stated thus:

---

[6] Admittedly, this is an ancient claim—"Gaian" *avant la lettre*, as it were. However, it resonates so energetically with the modern proper GCs that I have chosen to keep the name. Perhaps an alternative nomenclature for the "general GC" of Earth being alive would be a "general Living Planet Claim."

[7] Margulis describes the geologistic view thusly: "Scientists assume the environmental conditions are determined by geological and climatological factors and that life is forced to adapt or perish" (Margulis, 1993a, p. 364).

GC.2. *Geological processes and life are inextricably intertwined, and life may even be the ultimate, determining factor of Earth's past, present, and future. The Earth system must be studied as a whole and includes the biosphere.*[8]

This proper GC, as I analyze it, consists of three increasingly strong claims, the second (and third) of which can be added to the prior one(s). In being mindful of other significant research on the history and philosophy of Gaia (e.g., Ruse, 2013; Latour, 2017; Latour & Lenton, 2019; Lenton, et al., 2020; Dutreuil, 2024), I here primarily wish to be specific about three types of claims that could be intended as answers to the question: Is Earth alive?

First, life affects overarching geology, for instance, by producing certain gases, such as oxygen and methane, in an atmosphere that is far from chemical equilibrium. The first biological GC can be summarized thus:

GC.2i. **Life's Touch: The Weak Thesis**. *Life can influence—usually to a limited extent—certain features of Earth (e.g., atmospheric gases), but not necessarily Earth as such (n.b., the boundary between auxiliary features and essential object is admittedly challenging to draw*[9]*).*

Second, life is and becomes an integral part of geological processes, broadly construed, such as cyanobacteria fundamentally and completely altering ancient atmospheric composition, or limestone produced, for example, by corals or coccolithophores (the latter being the source of, e.g., the White Cliffs of Dover). The second proper GC can be stated thus:

GC.2ii. **Life's Touch: The Strong Thesis**. *Furthermore, life can influence—often significantly and perhaps greatly—particularly intimate or essential geological aspects of Earth, including geological formations (e.g., sedimentary rocks of various kinds) and processes (e.g., marine chemistry and continental drift), such that biology and geology are interwoven.*

These first two claims are accepted today by many, although to varying degrees, in Earth sciences or geoscience. Finally, and perhaps most importantly yet controversially, there is the claim that life influences and partly comprises Earth in such a way so as to *optimize conditions* (e.g., temperature ranges, acidity conditions, or the rate of change of such conditions over evolutionary and geological time) for its very existence and flourishing. To be clear:

---

[8] Approximately 20 years after the 1974 triptych, on March 15, 1993, Lovelock wrote the following to Margulis: "I think it best to look on Gaia as a coupled system involving both the biota and the material world. Something that cannot usefully be separated into parts" (Clarke & Dutreuil, 2022a, p. 324).

[9] To be clear, our analytical object in this chapter is Earth not as an *entire* planet—the entire rock hurtling through space—but rather Earth from the asthenosphere and up (i.e., the planet's crust, oceans, and atmosphere). This is where the action is for *all* disciplines of the Earth sciences. More astrophysical concerns such as celestial mechanics, orbitals, and gravity do not depend, in any sense, on the presence of life—unless humans or next-phase intelligence could somehow affect, for example, the geomagnetic field (but see van Thienen, et al., 2007).

GC.2iii. **The Truly Living Planet**. *In so influencing Earth, life actually and materially "scales up" its own properties including homeostasis, self-organization, and symbiosis to the highest level, that is, Earth itself, or Gaia herself.*

In a nutshell, I believe the proper GC (GC.2) is a full combination of the latter three increasingly strong claims, while the geological GC (GC.1) is metaphorical yet potentially subsumable under the proper GC.

3.2. James Lovelock and Lynn Margulis

The parents of Gaia theory, James Lovelock and Lynn Margulis, were each impressive scientists in their own right. Together they were a formidable force, as they co-developed Gaia theory in the 1970s. Literary theorist Bruno Clarke and historian and philosopher of science Sébastien Dutreuil illustrate how Lovelock was a creative, "out of the box" and "larger-than-life" thinker, theorist, and tinkerer. In the 1960s, after twenty years at the United Kingdom's National Institute for Medical Research, Lovelock:

> established himself as a scientific entrepreneur, consulting for private corporations such as Shell and Hewlett Packard, and scientific institutions such as NASA's Jet Propulsion Laboratory and the US National Oceanic and Atmospheric Administration. Thanks to one of his inventions, the electron capture detector (ECD), he made the first measurements of the chlorofluorocarbons (CFCs) later determined to be responsible for the depletion of ozone in the stratosphere. (Clarke & Dutreuil, 2022c, p. xviii; cf. Clarke & Dutreuil, 2022b, "Careers and Personae: Lovelock," pp. 2–5)

Margulis, an imaginative and exceptional evolutionary biologist and microbiologist about 20 years Lovelock's junior, went on to empirically prove the initially controversial Serial Endosymbiosis Theory (SET), whereby distinct and independently living ancient prokaryotes eventually came to live cooperatively one within the other (e.g., mitochondria or chloroplasts within eukaryotic cells). As a prescient observation related to Gaia theory, already on the first page of her second paper—written before she had any contact with Lovelock—Margulis argued:

> Immense biochemical virtuosity exists in prokaryote microbes which, as a whole, are still probably the most important biological agents of geochemical change. It is highly probable that Precambrian prokaryote activity caused large deviations in the amounts and types of compounds in both the atmosphere and the sediments from those expected on physical and chemical grounds alone. (Margulis, 1969, p. 606, footnotes suppressed)

To Gaia theory, Lovelock contributed the framework of cybernetics (e.g., homeostasis) and a concern for measuring and interpreting atmospheric chemistry and composition, while Margulis emphasized the workhorses of Gaia: microbes (e.g., bacteria).[10] *Cybernetics meets microbes*. Or, to cite from Lovelock's autobiography: "She [Margulis] put biological flesh on the bare bones of my physical chemistry" (Lovelock, 2000, p. xi).

Following ampliative inference forms laid out above, I perceive Lovelock as more analogical, as in the fruitful analogy of Gaia as a self-regulating organism, while Margulis, in her work on endosymbiosis, was guided more by abductive inference: serial endosymbiosis was the best explanation for the origin of mitochondria and chloroplasts.[11] Let us now look at further details of their arguments for Gaia theory, and Lovelock's and Margulis's real disagreements, with respect to the three components of the second, proper biological GC.

3.3. Analogy, Abduction, Induction, and Deduction in the Gaian Claims

Let us explore each of the biological GCs in order, interpreting them as moving from more inductive to more abductive and analogical. In so doing, I shall also appeal to arguments from Lovelock's and Margulis's three key collaborative papers from 1974, which set the tone and frame for Gaia theory.

3.3.1. *GC2.i. Life's Touch: The Weak Thesis*

Even just the three titles of Lovelock's and Margulis's 1974 triptych captures three key elements with which Gaia theory was forged: the atmosphere, the biosphere, and homeostasis. Lovelock was originally interested in atmospheric composition both as the planetary signature of life and as a way to track pollution.[12] (I shall return to homeostasis in the third proper GC.) Regardless of the origins of why he wished to measure atmospheric composition, Lovelock expressed a strong inductive drive to measure gas composition of the (planetary) atmosphere(s)—for example, via spectrometry or gas chromatography[13] (e.g., Lovelock & Giffin, 1969). And this drive captures the impetus of the weak thesis, GC2.i: life *at least* has an effect on the gas composition of the atmosphere.[14]

---

[10] "We emphasize the microbial contribution for two reasons: their metabolic versatility leading to profound environmental effects and because the regulation of the planetary environment was apparently proceeding long before the evolution of the larger (eukaryotic) life forms" (Margulis & Lovelock, 1974, p. 476).

[11] "That Margulis brought microbial ecology to the development of the Gaia hypothesis is generally known, but that she also contributed her knowledge of the deep geology of Earth's history is less often recognized" (Clarke & Dutreuil, 2022b, p. 13).

[12] Betsey Dexter Dyer (2022) recounts "Jim [Lovelock] declaring to NASA that he didn't need to travel through space to discover life on another planet, he only needed a spectrograph of the planet's atmosphere to see if its gas chemistry was in thermodynamic disequilibrium or not" (p. 396). Sébastien Dutreuil (2024) argues that "the historical, scientific, and philosophical origins of Gaia are not to be found in NASA's search for life on other planets, and certainly not in a biological tradition of altruism and cooperation, but in an *anthropological reflection on pollution*" (p. 14; my translation).

[13] "During the heyday of his collaboration with Margulis, Lovelock was *the* international expert in gas chromatography" (Clarke & Dutreuil, 2022b, p. 5).

[14] There is, of course, a fuller story to be told about the role of the oceans in Gaia. Already on April 11, 1973, Lovelock wrote the following to Margulis: "If you can bear it maybe later on we can do a thing on the oceans" (Clarke & Dutreuil, 2022a, p. 117), a

One way to trace the inference pattern of induction here is by exploring two kinds of tables the authors provide. First, Lovelock and Margulis collated richly complex tables of Earth's atmospheric composition, with many gas types such as nitrogen, oxygen, carbon dioxide, methane, nitrous oxide, hydrogen sulfide, sulfur dioxide, etc., together with the sources of these gases, presented both quantitatively ("[i]norganic sources," "[b]iological sources: Gaian," and "[b]iological sources: Human") and qualitatively ("[p]rincipal origins," such as "[d]enitrifying bacteria" for N_2). This can be seen especially in Table II "Reactive Gases of the Earth's Atmosphere" (Margulis & Lovelock, 1974, pp. 476–477), and Table 1 "Principal sources and sinks" (Lovelock & Margulis, 1974b, pp. 96–98), which also has bibliographic references for each gas type. Very roughly and abstractly, this information is all inductively determined. Now, a highly simplified Table 2 of "Gases in the Earth's atmosphere with origins in the Biosphere" (Lovelock & Margulis, 1974a, p. 5) shows only five gas types and has two columns unique to this table as compared to the other two tables: "Anticipated equilibrium concentration" and "Departure from equilibrium." Admittedly, collating this information would require some deductive calculations based on assumptions about gas type reactivity, thermodynamics, and so forth, but, again, knowledge of initial gas composition of the contemporary atmosphere would be inductively determined. (Each of these three tables has residence time for each gas—ranging roughly from days or weeks to thousands of years—also requiring some calculations.)

Second, the first table in Lovelock and Margulis (1974a, Table 1, "The partial pressures in millibars of CO_2, N_2 and O_2 on Mars, Earth and Venus and on two model abiological Earth[s]," p. 4) and Margulis and Lovelock (1974, Table I, "Atmospheres of the Terrestrial Planets (Pressures in Millibars)," p. 472) compare the atmospheres of Venus and Mars to Earth today (for just a few gas types) and to two kinds of "abiological" Earth models, one in which life was deleted, either in that it never evolved (Margulis & Lovelock, 1974, p. 472) or is imagined as deleted today (Lovelock & Margulis, 1974a, p. 4), and one for which gas composition values are interpolated between Venus and Mars.[15] Induction (measurement,

suggestion that never bore fruit, despite Margulis's repeated attempts to interest Lovelock, much later during the 1990s, in questions about the oceans, including: "[I]s water retention itself a Gaian phenomenon?" (Clarke & Dutreuil, 2022a, p. 294). Given my own interests in the oceans, and in analogy, one ongoing project of mine is understanding the ocean from a Gaian perspective (cf. Harding & Margulis, 2010; Winther, 2019, 2024; Döring & Winther, 2022).

[15] Admittedly, Margulis and Lovelock (1974) have two instructive illustrations presenting (1) the deep history of gases (with pressure represented in bars on a logarithmic scale) in Earth's atmosphere with (Fig. 1b, p. 473) and without (Fig. 1a, p. 473) life evolving, and (2) the deep history of Earth's (average) temperature with respect to solar luminosity (Fig. 2a, p. 475) as well as its "probable history derived from the fossil record" (Fig. 2b, p. 475), in both cases comparing scenarios of Earth with and without life. These four figures visually depict how life has stabilized, for example, N_2 and O_2 partial pressures, over the course of the planet's history (p. 473) and how life has stabilized temperatures over at least the last 3.5 billion years on an otherwise much cooler planet (p. 475).

experiment, generalization, etc.) is important here, but again deduction with assumptions is involved in, for example, calculating the idealized thermodynamic equilibrium conditions if life were deleted.[16]

GC.2i is highly empirical and inductive. The idea of this GC is that life can influence, at least to an extent, readily measurable features of Earth. Indeed, the presence of these gases is itself a signature of life: "The simultaneous and large fluxes of N_2, CH_4, NH_3, N_2O and O_2 are all inconsistent with an abiological model" (Lovelock & Margulis, 1974a, p. 5). Although gas measurement is inductive, there is also an abductive element here. After all, contrasting explanations must be considered regarding whether physical features of Earth alone could produce those gases even close to those partial pressures (i.e., the geologistic view) or whether atmospheric composition must be considered a signature of life, at least to an extent. We know which side Gaia theory was on, and that is indeed also the main current, modern perspective.

3.3.2. *GC.2ii. Life's Touch: The Strong Thesis*

By way of distinguishing the weak and the strong theses of the biological GC, in the sense of distinguishing auxiliary and causally minor aspects of Earth from the essential and causally constitutive aspects, consider two somewhat conflicting metaphors about the atmosphere used by Lovelock and Margulis. On the one hand, they write: "[T]here is overwhelming evidence that the atmosphere apart from its content of noble gases is a biological product. It may also be a biological contrivance; not living but as essential a part of the biosphere as is the shell to a snail or the fur to a mink" (Lovelock & Margulis, 1974a, p. 6). In this sense, and in thinking about Gaia's ontology, the atmosphere is here considered not part of Gaia's body per se, but more an adaptation and an epiphenomenon to Gaia herself. The atmosphere is a biological product (GC.2i) and perhaps even an adaptation (cf. GC.2iii), but the atmosphere itself is not a *part* of Gaia's living body, *sensu stricto*. This is the only paper of the triptych with this shell/fur metaphor, although in Gaia's 1972 "birth certificate," Lovelock made exactly these points: "[T]he air is not to be thought of as a living part of Gaia but rather as an essential but non-living component which can be changed or adapted as the needs require. Like the fur of a mink or the shell of a snail" (Lovelock, 1972, p. 580). Indeed, this was his metaphor.

On the other hand, the same paper with the snail/fur metaphor also views the atmosphere "as a component part of the biosphere rather than as a mere environment for life" (Lovelock & Margulis, 1974a, p. 2). In another paper of the triptych, they paint the following picture: "The atmosphere, far from being an

[16] If life today were utterly deleted: "…the atmospheric composition … expected … was derived as follows: nitrogen reacts under the influence of solar UV, electrical discharges … with both O_2 and CO_2 to give oxides of nitrogen. By such processes in time all nitrogen would be converted to the stable [nitrate] ion dissolved in the oceans [and so forth]" (Lovelock & Margulis, 1974a, pp. 4–5).

inert sink, we regard as a regulated fluid component of the biosphere, a contrived circulatory system to assure the perpetuation of conditions optimal to the whole of the interconnected living organisms" (Lovelock & Margulis, 1974b, p. 95). A new metaphor is here invoked: the atmosphere is a kind of circulatory system. Just as nutrients are moved around in blood vessels, so are reactive elements, simple compounds, human-made synthetic chemicals, etc., cycled within fairly stable wind current systems (e.g., mid-latitude and Hadley cells, westerlies at mid-latitudes, etc.).

Now, even if the snail/fur and circulatory system metaphors are themselves instances of an overarching organismic analogy guiding them, note that I leave the full organismic—and cybernetic—analogies of Gaia to the truly living planet thesis of the next section. Here I appeal to these metaphors in order to focus on system boundaries and the interface between living (biosphere) and non-living aspects of Gaia.[17] In so doing, the metaphor of the circulatory system, in contrast to that of a snail's shell or a mink's fur, implies a much more intimate nature of the atmosphere with respect to Gaia, and points to that part of Gaia as being alive. That is, if we understand Gaia according to the first snail/fur metaphor, then the non-living atmosphere belongs under the weak thesis (GC.2i). In contrast, if we are guided by the circulatory system metaphor, then the atmosphere is an integral part of Gaia and is best described by the strong thesis (GC.2ii).

The strong thesis is closely linked to what Dutreuil calls *extension vitale*, in which Earth is alive not because of an analogy, or relations of similarity, to organisms, "but because she is a vital extension of organisms" (Dutreuil, 2024, p. 326; my translation). This is his preferred version of the GC, which he traces back to "Margulis's bacterial ecology and Lovelock's frozen cells [from his early days researching cryobiology]" (Dutreuil, 2024, p. 326; my translation). Indeed, for Dutreuil, even Lovelock's claim about the snail's shell is a blunt ontological assertion concerning how life's effects extend beyond its typical boundaries of cell membrane, bark, or skin/fur, etc. This extended causal ontology is what eventually gives rise to, and grounds, the snail's shell, mink's fur, *and* circulatory system metaphors. Because of the ubiquity and force of Dutreuil's extension vitale, I would place his view under the strong thesis of life's touch.

Other examples of our strong thesis here might be organic material becoming, over the ages, limestone, oil (e.g., from sedimented marine phytoplankton), or coal (e.g., from Carboniferous or Permian wetland forests, filled with ancient ferns and mosses); or life changing the late Archean (Neoarchean) atmosphere to having significant amounts of oxygen (the so-called "oxygen revolution" starting

[17] A provocative presentation of the biosphere or biota and its relation to Earth can be found in Margulis and Lovelock (1974): "The most conspicuous difference on the earth relative to the other terrestrial planets is the ubiquitous scum of the planet (and mostly lying within a few meters of the air, rock, water interface), namely the biota. Presumably it is this living system that is responsible for the phenomenon we are calling Gaia" (p. 473).

approximately 2.5 billion years ago and powered by ancient cyanobacteria); or evolving land plants changing, for example, atmospheric composition and continental weathering (e.g., Dahl & Arens, 2020). There are much wilder and more controversial examples, including the idea that "limestone-generating life" is a cause of plate tectonics (Anderson, 1984, p. 348; cf. Lovelock, 1988/1995, p. 99; Margulis, 1993b, p. 366; Lenton, et al., 2020, p. 259) and the obvious point that humans have changed Earth in multiple and nearly unimaginable ways—captured in the controversial notion of the Anthropocene—which I leave to the reader to list out.

While there are clear features of induction in this second proper GC, such as the measurement of elements and compounds of sedimentary layers or of marine biochemistry, inferential features of abduction and, to a lesser extent, of analogy, are also at play. After all, we are making a strong assertion now: non-biosphere parts of the planet are *also* alive (or are *part of* the living planet?), and this requires argumentation, inference, and hypothesis formation and justification. Moreover, complex theses and hypotheses about the origin and change of geological, atmospheric, and oceanographic phenomena must be explained by processes and mechanisms from a variety of fields. The exact role of life for particular phenomena must be assessed by contrasting distinct hypotheses and making inferences to the best explanation. Yes, oil has a biological origin, but not only is it very hard, if not conceptually impossible, to demarcate where biology ends and geology starts (or vice versa), we must also provide tried-and-true explanations for how oil got to be the way it is, and how life's touch reaches to the most intimate parts of Earth, of Gaia. Without abduction (and analogy), we wouldn't get very far in our efforts of tracing life's touch or, to follow Dutreuil, of understanding Gaia as a vital extension of life (of the biosphere).

3.3.3. GC.2iii. *The Truly Living Planet*

But the thesis for which abduction and analogy as inference types come to the fore (induction doesn't really get us very far at all), is the third proper GC, the truly living planet thesis.

This is Lovelock's and Margulis's early definition of Gaia:

> We believe that Gaia is a complex entity involving the earth's atmosphere, biosphere, oceans and soil. The totality constitutes a feedback or cybernetic system which seeks an optimal physical and chemical environment for the biota (Lovelock, 1972). The maintenance of relatively constant conditions by active control is conveniently described by the word "homeostasis," which we shall use henceforward for this purpose. (Margulis & Lovelock, 1974, pp. 473–474; a very similar version can be found in Lovelock, 1979, p. 11)

We can now do some justice to "homeostasis" as one of the three elements of the titles of Gaia's parents' 1974 triptych. Perhaps the key concept for a cybernetic system is the idea of a negative feedback loop in which a sensor of the cybernetic device detects the actual state of the entire system under regulation, and the device assesses the difference between the actual systemic state and the desired systemic state (or range). This difference is then encoded as part of a message sent to the device's controller that initiates action such that the difference between actual and desired states is decreased to the extent possible. Homeostasis is this entire integrative process of sensing the state of the system and acting so as to maintain desired, optimal systemic conditions. Think of a thermostat in your house during the cold winter, or body temperature in a healthy mammal.[18]

It was the concept of homeostasis that governed much of Lovelock's thinking on how the biosphere played a significant role in maintaining relatively stable and optimal planetary conditions for its own evolution. Lovelock was making a kind of analogical inference from a cybernetic system to an interdisciplinary, complex planetary object. Returning to the tables of Lovelock's and Margulis's 1974 triptych, consider Table II "Possible biological mechanisms to achieve homeostasis of the present terrestrial atmosphere" (Lovelock & Margulis, 1974b, pp. 100-101), which lists mechanisms such as "[t]rapping and precipitation of sediments such as $CaCO_3$, carbon black, iron sulfides" and "[s]ome organisms directly excrete acids and bases (lactic, acetic, uric, nitric, etc.)" for the "[q]uantity contro[l]" of temperature and pH, respectively. These homeostatic mechanisms were explicitly considered "control systems" or "potential devices our [planetary] engineer has at his disposal" (Margulis & Lovelock, 1974, pp. 479–480) and were discussed extensively and textually under subheadings such as different kinds of "[t]emperature [c]ontrol" as well as "[c]ontrol of [a]cidity" and "[c]ontrol of [r]edox [p]otential" (Margulis & Lovelock, 1974, pp. 479–486). Thus, cybernetics, homeostasis, and large-scale regulatory systems play a crucial role as an analogical source, especially for Lovelock.[19]

Margulis never accepted Lovelock's other big analogy, that Gaia was an organism (or, perhaps, superorganism). Margulis always insisted that "Gaia is not an individual, it is an ecosystem" (Margulis, 1993a, p. 745).[20] But Lovelock was enamored with the organismic analogy, and he repeatedly deployed biological, organismic terms and thinking:

---

[18] Clarke and Dutreuil contrast Lovelock and Margulis on homeostasis and its home paradigm, cybernetics: "Lovelock's systems thinking was fastened on the first-order cybernetics of self-organizing systems, self-regulation through negative feedback, and the closely allied discourses of energy and entropy . . . Margulis endorsed the second-order cybernetics of Maturana and Varela and their concept of autopoiesis" (Clarke & Dutreuil, 2022b, p. 22; cf. Haraway, 2016, especially Chapter 3; Clarke, 2020). Indeed, in a letter to Lovelock dated December 7, 1985, Margulis writes: "I still think the smallest autopoietic system we know is a bacterial cell and the largest is Gaia" (Clarke & Dutreuil, 2022a, p. 257).

[19] An important qualification: "We are not claiming that a 'planetary engineer' was actually commissioned but rather that Neodarwinian mechanisms of natural selection that have operated in the origin and evolution of the examples of local environmental control have also operated in the origin of these larger scale modulation mechanisms" (Margulis & Lovelock, 1974, p. 486).

[20] Despite Margulis's claim to the contrary in 1993a, this sentence is not found in the "Gaia and the Extant Biosphere" section of 1993b, pp. 363–367; but that book does contain another lovely sentence: "Gaia is only symbiosis as seen from space" (1993b, p.

> Although Gaia is often portrayed as a complex system, specifically as a complex adaptive system, this broad category fails to distinguish some of its unique features. As an engineer/inventor, Lovelock naturally reaches for cybernetic language to describe the workings of Gaia, such as *feedback*, *homeostasis*, *self-regulation*, and *optimization.* But he equally reaches for biological language to describe the perceived entity and its functioning, such as *super-organism* and *geophysiology*. All the while, Margulis explicitly and repeatedly reminds him that Gaia is not an organism. (Latour & Lenton, 2019, p. 665, footnotes suppressed; cf. Latour, 2017)

We see this organismic analogy and concomitant language in one of the papers of the triptych, where Lovelock and Margulis frame important questions:

> If the atmosphere is a functioning part of the biological cybernetic system which sustains homeostasis, it is appropriate to question the purpose of its various components. Just as it is reasonable to ask of honeybees: By what mechanisms is hive temperature controlled, or of mammals: What is the function of bicarbonate ion in the blood, it becomes reasonable to ask: What is the function of nitrous oxide or methane? Why are these gases released into the atmosphere in quantities of 10^9 tons yr^{-1}? Such questions would be rightfully considered illogical if the atmosphere were an open system, a product of steady state chemistry only; but if we consider the atmosphere to be in homeostasis … . (Lovelock & Margulis, 1974b, pp. 99, 101)

It is difficult to imagine a clearer and more powerful appeal to an analogy from organisms (and superorganisms), as source domain, to Gaia, as target domain.[21] This is the cybernetic, organismic truly living planet. Was this organismic analogy necessary? Dutreuil notes that Gaia theory had tremendous influence in Earth and environmental sciences, regardless of the fate, coherence, and strength of the organismic analogy, and that "in a larger cultural appropriation … everybody was already convinced that Earth is an organism" (personal communication, May 2024). Even so, Lovelock's thinking about Gaia was consistently suffused with analogy, from two source disciplines: cybernetics and organismic biology.

To understand the role of abductive inference, we need to take a step back, I believe, to Margulis's other key research program. In Winther (2009), I compared Margulis's SET to autogenous theories and

---

367). More importantly, "Lovelock would say that Earth is an organism. I disagree with this phraseology. No organism eats its own waste. I prefer to say that Earth is an ecosystem, one continuous enormous ecosystem composed of many component ecosystems" (Margulis, 1995, p. 140). Moreover, in a letter to Lovelock and his wife Sandy dated October 19, 1995, Margulis wrote: "Gaia as a worldwide ecosystem (a 'superecosystem' not a 'superorganism') is utterly dependent on bacterial transformations and interactions for its persistence" (Clarke & Dutreuil, 2022a, p. 349).

[21] Many readers of Gaia theory interpreted her as a superorganism, but Lovelock was in fact more comfortable with organismic language (cf. Winther, 2005 for an extensive discussion of the superorganism metaphor of both social insect colonies and populations, in general; and Latour, 2022, who critiques the facile superorganismic interpretation of Gaia).

showed how Margulis was explicitly appealing to predictions; in so doing, I now believe, she ultimately adopted abductive inference. In one of her classic papers on SET, written while she was working with Lovelock on Gaia, Margulis lists 15 predictions of the theory. Although she accepts that "several" of the "experimentally verifiable predictions … are not absolute requirements of the theory," she argues that "the phenomena listed here would be much more likely consequences of the serial endosymbiotic theory than other suggested models of eukaryote organelle origin (e.g., Raff & Mahler [1975])" (Margulis, 1975, p. 28). As I analyze her argument (Winther, 2009, pp. 895–897), she cherished surprising and risky (novel) predictions, that is, predictions that hadn't been considered before (i.e., surprising) and that, if *not* borne out, would be detrimental to the theory that had made them (i.e., risky). With respect to SET, many of her predictions were both surprising and risky and, ultimately, abductive. In other words, we have a set of phenomena that is best explained according to SET, in contrast to "autogenous theories" of the origin of all eukaryote organelles, which held that in single prokaryote lineages, over evolutionary time, membranes were pinched off to make organelles—Raff & Mahler (1975) developed this alternative hypothesis. No analogy is at play here, but an explicit contrast of alternative hypotheses is. Thus, I interpret Margulis as deploying abduction, or inference to the best explanation—and, in fact, Peirce's ouroboros of abduction-deduction-induction—in presenting, arguing for, and justifying SET. I also see the hand of abduction in some of the argumentation of the 1974 triptych. The organismic and cybernetic analogies are central to the development of Gaia theory. But the source and justification of Gaia are also an abduction to a novel hypothesis—with deductively inferred surprising and risky predictions—that explains much and that can be tested via induction. Gaia theory helps us understand why the atmosphere and the ocean are as they are: far from thermodynamic and chemical equilibrium, relatively stable, and finely tuned to optimize conditions for life. Life bootstrapped these conditions into existence in order to make a better home for itself. Why else, asks the Gaia theorist, would thermodynamic and chemical disequilibrium, stability, and optimality for life be the case?

> To those who are convinced that the atmospheric gases are biological products but are reluctant to accept the notion of homeostasis we say: if life has merely a passive role in cycling the gases of the air then the concentrations will be set by equilibrium chemistry; in fact they most certainly are not. If life actively cycles the gases then we ask how could such a system be stable in the long run without homeostasis? (Lovelock & Margulis, 1974a, p. 9)

This question is a marvelous case of an appeal to abduction and, I might add, to Peirce's ouroboros.

In short, while Lovelock's Gaia was cybernetic and organismic, and was largely borne out of analogical inference, Margulis's Gaia was autopoietic and largely borne out of *abductive* inference. Either way, this last GC saw the entire planet as truly alive, in many senses. Inductive inference was hardly sufficient to make and justify this claim, and we need to understand GC.2iii in terms of analogical as well as abductive inference.

4. Conclusion

Different aspects of the richness and depth of scientific reasoning can be captured by four key, logical types of inference: analogy, abduction, induction, and deduction. A simultaneous analysis of these inferential types—each of which is itself an idealization and simplification of the kind of scientific reasoning it attempts to capture—helps us understand scientific pluralism and practice. I have here tried to bring the four forms of scientific inference alive by turning to Gaia theory, especially as presented in the three papers published by Lovelock and Margulis in 1974, their annus mirabilis. Deduction I have left somewhat aside, although it is clearly present in mathematical calculations.[22] Instead, I have exalted both analogy and abduction, two lesser-known inference types rarely given much time in undergraduate courses. As we move from the weak thesis to the strong thesis to the truly living planet claim, induction becomes more peripheral, and analogy and abduction take progressively central roles. To say that life has *some* impact on Earth is the weak thesis (GC.2i), premised on induction; to say that life is more intimately tied to and part of Earth is a strong thesis (GC.2ii), premised increasingly on abduction and analogy; and claiming that the entire planet is actually alive (i.e., GC.2iii) certainly clearly requires analogy and abduction, that is, inference to the best explanation.[23]

Tracing the four types of scientific inference thus sheds light on a theory or hypothesis—Gaia theory—that may be one of the most controversial and interesting of the last 50 years or so. Indeed, it is potentially our guiding light as we continue stumbling dangerously into the Anthropocene.

Acknowledgements

Thank you to Ricardo Noguera Solano and Rosaura Ruiz Gutiérrez for inviting me to present at the UNAM conference on evolution ("Coloquio Universitario de Evolución: Diálogo entre Ciencias y Humanidades") in November 2023, and to Victor Hernández Marroquín for support during the visit. Some of the ideas in this paper were also presented at the Instituto de Investigaciones Filosóficas, UNAM, also in November 2023—thank you to Sergio Martínez Muñoz and Kirareset Barrera García for that invitation and

[22] Deduction was also central in the mathematical modeling surrounding Daisyworld (Watson & Lovelock, 1983), which provided rigor and impetus to Gaia theory. The Daisyworld model was to Gaia theory what the Lotka–Volterra equations were to theoretical ecology.

[23] My distinctions among GCs resonate with questions Lovelock asked, in 1979: "How, then, do we identify and distinguish between the works of Gaia and the chance structures of natural forces? And how do we recognize the presence of Gaia herself?" (p. 34) The first question relates to GC.2i and GC.2ii, the second to GC.2iii.

kind attention. Dina Theleretis copy edited expertly. Sébastien Dutreuil, Claus Emmeche, Marie Raffn, Lucas McGranahan, and Victor provided critical feedback on the manuscript, and to Seb for many conversations and correspondence regarding Gaia theory.

Bibliography

Anderson, D. L. (1984). The Earth as a Planet: Paradigms and Paradoxes. *Science*, *223*(4634), 347–355.

Bartha, P. (2010). *By Parallel Reasoning: The Construction and Evaluation of Analogical Arguments.* Oxford University Press.

Bartha, P. (2022). Analogy and Analogical Reasoning. *The Stanford Encyclopedia of Philosophy* (E. N. Zalta, Ed.). https://plato.stanford.edu/archives/sum2022/entries/reasoning-analogy/

Bellucci, F., & Pietarinen, A.-V. (2020). Peirce on the Justification of Abduction. *Studies in History and Philosophy of Science, 84*, 12–19.

Booth, R., Casini, G., Klarman, S., Gilles, R., & Varzinczak, I. (2019). Editorial: Defeasible and Ampliative Reasoning. *International Journal of Approximate Reasoning*, *112*, 1–3.

Brewer, S. (2011). Logocratic Method and the Analysis of Arguments in Evidence. *Law, Probability and Risk*, *10*, 175–202.

Clarke, B. (2020). *Gaian Systems: Lynn Margulis, Neocybernetics, and the End of the Anthropocene*. University of Minnesota Press.

Clarke, B, & Dutreuil, S. (Eds.). (2022a). *Writing Gaia: The Scientific Correspondence of James Lovelock and Lynn Margulis*. Cambridge University Press.

Clarke, B., & Dutreuil, S. (2022b). Introduction. In B. Clarke & S. Dutreuil (Eds.), *Writing Gaia: The Scientific Correspondence of James Lovelock and Lynn Margulis* (pp. 1–31). Cambridge University Press.

Clarke, B., & Dutreuil, S. (2022c). Preface. In B. Clarke & S. Dutreuil (Eds.), *Writing Gaia: The Scientific Correspondence of James Lovelock and Lynn Margulis* (pp. xvii–xxiii). Cambridge University Press.

Dahl, T. W., & Arens, S. K. M. (2020). The Impacts of Land Plant Evolution on Earth's Climate and Oxygenation State: An Interdisciplinary Review. *Chemical Geology*, *547*, 119665. https://doi.org/10.1016/j.chemgeo.2020.119665

Döring, A., & Winther, R. G. (2022). The Human Condition Is an Ocean: Philosophy and the Mediterranean Sea. In S. Wuppuluri and A. C. Grayling (Eds.), *Metaphors and Analogies in Sciences and Humanities* (pp. 383–398). Springer. https://doi.org/10.1007/978-3-030-90688-7_19

Douven, I. (2021) Abduction. *The Stanford Encyclopedia of Philosophy* (E. N. Zalta, Ed.). https://plato.stanford.edu/archives/sum2021/entries/abduction/

Dutreuil, S. (2024). *Gaïa, Terre vivante: Histoire d'une nouvelle conception de la Terre*. La Découverte.

Dyer, B. D. (2022). Gaia at the Margulis Lab. In B. Clarke & S. Dutreuil (Eds.), *Writing Gaia: The Scientific Correspondence of James Lovelock and Lynn Margulis* (pp. 394–399). Cambridge University Press.

Foucault, M. (1966). *Les Mots et les choses. Une archéologie des sciences humaine*. Gallimard.

Gentner, D., & Jeziorski, M. (1993). The Shift from Metaphor to Analogy in Western Science. In A. Ortony (Ed.), *Metaphor and Thought*, 2nd ed. (pp. 447–480). Cambridge University Press.

Givón, T. (1986). Prototypes: Between Plato and Wittgenstein. In C. G. Craig (Ed.), *Noun Classes and Categorization* (pp. 77–102). John Benjamins B. V.

Hacking, I. (2002). *Historical Ontology*. Harvard University Press.

Harding, S., & Margulis, L. (2010). Water Gaia: 3.5 Thousand Million Years of Wetness on Planet Earth. In E. Crist and H. B. Rinker (Eds.), *Gaia in Turmoil: Climate Change, Biodepletion, and Earth Ethics in an Age of Crisis* (pp. 41–59). MIT Press.

Haraway, D. (2016). *Staying with the Trouble: Making Kin in the Chthulucene*. Duke University Press.

Harman, G. (1965). The Inference to the Best Explanation. *The Philosophical Review*, *74*(1), 88–95.

Hesse, M. (1966). *Models and Analogies in Science*. University of Notre Dame Press.

Hintikka, J. (1998). What is Abduction? The Fundamental Problem of Contemporary Epistemology. *Transactions of the Charles S. Peirce Society*, *34*(3), 503–534.

Hofstadter, D., & Sander, E. (2013). *Surfaces and Essences: Analogy as the Fuel and Fire of Thinking*. Basic Books.

Kasting, J. F., Toon, O. B., & Pollack, J. B. (1988). How Climate Evolved on the Terrestrial Planets. *Scientific American*, *258*, 90–97.

Latour, B. (2017). *Facing Gaia: Eight Lectures on the New Climatic Regime*. Polity Press

Latour, B. (2022). Gaia as a Problem of Social Theory. In B. Clarke and S. Dutreuil (Eds.), *Writing Gaia: The Scientific Correspondence of James Lovelock and Lynn Margulis* (pp. 404–407). Cambridge University Press.

Latour, B., & Lenton, T. M. (2019). Extending the Domain of Freedom, or Why Gaia Is So Hard to Understand. *Critical Inquiry*, *45*(Spring), 659–680.

Lenton, T. M., Dutreuil, S., & Latour, B. (2020). Life on Earth is Hard to Spot. *The Anthropocene Review*, *7*(3), 248–272.

Levins, R., & Lewontin, R. (1985). *The Dialectical Biologist*. Harvard University Press.

Longino, H. E. (2002). *The Fate of Knowledge*. Princeton University Press.

Longino, H. E. (2013). *Studying Human Behavior: How Scientists Investigate Aggression and Sexuality*. University of Chicago Press.

Lovelock, J. E. (1972). Gaia as Seen Through the Atmosphere. *Atmospheric Environment*, *6*, 579–580.

Lovelock, J. E. (1979). *Gaia: A New Look at Life on Earth*. Oxford University Press.

Lovelock, J. E. 1988(1995). *The Ages of Gaia*. Norton.

Lovelock, J. E. (2000). *Homage to Gaia: The Life of an Independent Scientist*. Oxford University Press.

Lovelock, J. E., & Giffin, C. E. (1969). Planetary Atmospheres: Compositional and Other Changes Associated with the Presence of Life. In O. L. Tiffany and E. Zaitzeff (Eds.), *Advanced Space Experiments* (Advances in the Astronautical Sciences: Volume 25, pp. 179–193). American Astronautical Society.

Lovelock, J. E., & Margulis, L. (1974a). Atmospheric Homeostasis by and for the Biosphere: the Gaia Hypothesis. *Tellus*, *26*(1–2), 2–10.

Lovelock, J. E., & Margulis, L. (1974b). Homeostatic Tendencies of the Earth's Atmosphere. *Origins of Life*, *5*, 93–103.

Margulis, L. (1969). New Phylogenies of the Lower Organisms: Possible Relation to Organic Deposits in Precambrian Sediment. *The Journal of Geology*, *77*(5), 606–617.

Margulis, L. (1975). Symbiotic Theory of the Origin of Eukaryotic Organelles: Criteria for Proof. *Symposia of the Society for Experimental Biology*, *29*, 21–38.

Margulis, L. (1993a). Gaia in *Science*. *Science*, *259*(5096), 745.

Margulis, L. (1993b). *Symbiosis in Cell Evolution: Microbial Communities in the Archean and Proterozoic Eons* (2nd ed). W. H. Freeman.

Margulis, L. (1995). Gaia Is a Tough Bitch. In J. Brockman (Ed.), *The Third Culture* (pp. 129–151). Touchstone.

Margulis, L., & Lovelock, J. E. (1974). Biological Modulation of the Earth's Atmosphere. *Icarus*, *21*, 471–489.

Merchant, C. (1980). *The Death of Nature: Women, Ecology, and the Scientific Revolution*. HarperCollins.

Minnameier, G. (2004). Peirce-Suit of Truth: Why Inference to the Best Explanation and Abduction Ought Not to Be Confused. *Erkenntnis*, *60*(1), 75–105.

Minnameier, G. (2010a). Abduction, Induction, and Analogy. In L. Magnani, W. Carnielli, & C. Pizzi (Eds.), *Model-Based Reasoning in Science and Technology. Studies in Computational Intelligence* (Vol. 314, pp. 107–119). Springer. https://doi.org/10.1007/978-3-642-15223-8_5

Minnameier, G. (2010b). The Logicality of Abduction, Deduction and Induction. In M. Bergman, S. Paavola, A.-V. Pietarinen, & H. Rydenfelt (Eds.), *Ideas in Action: Proceedings of the Applying Peirce Conference* (pp. 239–251). Nordic Studies in Pragmatism 1. Helsinki: Nordic Pragmatism Network. https://www.nordprag.org/nsp/1/Minnameier.pdf

Netz, R. (1999). *The Shaping of Deduction in Greek Mathematics: A Study in Cognitive History*. Cambridge University Press.

Oppenheimer, J. R. (1956). Analogy in Science. *American Psychologist*, *11*(3), 127– 35.

Peirce, C. S. 1878(1986). "Deduction, Induction, and Hypothesis." In C. J. W. Kloesel, M. H. Fisch, N. Houser, L. A. Ziegler, D. D. Roberts, A. Houser, & E. C. Moore (Eds.) *Writings of Charles S. Peirce: A Chronological Edition, Volume 3*, 1986 (pp. 323–338). Indiana University Press.

Peirce, C. S. (1931–1958). *Collected Papers of Charles Sanders Peirce* (C. Hartshorne & P. Weiss, eds., Vols. 1–6; A. W. Burks, ed. Vols. 7–8). Harvard University Press.

Pietarinen, A.-V., & Bellucci, F. (2014). New Light on Peirce's Conceptions of Retroduction, Deduction, and Scientific Reasoning. *International Studies in the Philosophy of Science*, *28*(4), 353–373.

Raff, R. A., & Mahler, H. (1975). The Symbiont That Never Was: An Inquiry into the Evolutionary Origin of the Mitochondrion. *Symposia of the Society for Experimental Biology*, *29*, 41–92.

Ruse, M. (2013). *The Gaia Hypothesis: Science on a Pagan Planet*. University of Chicago Press.

van Thienen, P., Benzerara, K., Breuer, D., Gillmann, C., Labrosse, S., Lognonné, P., & Spohn, T. (2007). Water, Life, and Planetary Geodynamical Evolution. *Space Science Reviews 129*, 167–203.

Watson, A. J., & Lovelock, J. E. (1983). Biological Homeostasis of the Global Environment: The Parable of Daisyworld. *Tellus B*, *35*(4), 284–289.

Winther, R. G. (2005). An Obstacle to Unification in Biological Social Science: Formal and Compositional Styles of Science. *Graduate Journal of Social Sciences*, *2*(2), 40–100.

Winther, R. G. (2009). Prediction in Selectionist Evolutionary Theory. *Philosophy of Science*, *76*(5), 889–901.

Winther, R. G. (2012). Interweaving Categories: Styles, Paradigms, and Models. *Studies in History and Philosophy of Science, Part A*, *43*(4), 628–639.

Winther, R. G. (2019). Mapping the Deep Blue Oceans. In T. Tambassi (Ed.), *The Philosophy of GIS* (pp. 99–123). Springer.

Winther, R. G. (2020). *When Maps Become the World*. University of Chicago Press.

Winther, R. G. (2024). Diving into the Unconscious: Beyond the Archaeological Analogy. *The American Psychoanalyst.* https://tapmagazine.org/all-articles/diving-into-the-unconscious