

The dialectic between nature and culture in the interplay between the discrete and the continuum¹

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Abstract: In an attempt to contribute to the debate between nature and culture, we will explore a specific "cultural" sphere, thus attempting to enrich the many often profound but abstract philosophical reflections. The interplay between discrete and continuous mathematics will be a site of analysis of a dialectic within a scientific debate, beginning with that between Einstein and Bohr in the 1930s. This will allow us to construct knowledge of our animal actions in the world, in the space-time continuum, and to better differentiate ourselves from machines. Mathematics is in fact written in a "natural language" - we will gradually give a possible meaning of this elusive notion - and it is not, as Galileo says, nature that is written in mathematical language. Seeing mathematics as a symbolic-cultural praxis, we will analyse its rootedness in primary gestures of us animals, constrained in and rich in our biological bodies, emphasizing how it continually returns to find "meaning" in spatio-temporal activities. At the heart of such a path, alphabetic writing, another fundamental rupture and link with nature, discretizes the continuous song of language and re-proposes in other terms the nature-culture dialectic we seek to identify in this text.

Causality, between continuous and discrete descriptions

From Aristotle to Einstein, every event possesses a "cause." The same could be said for Darwin who looks for the "causes" of phylogenetic (evolutionary) changes in the permanent production of diversity proper to living reproduction and eco-systems' dynamics. Our entire scientific culture, at least the Western one, has been based on an intelligibility of nature largely built on the "search for causes." These were then framed, in physics, in "principles of symmetry", as we will argue. A "then," however, that goes back as far as the Greek world: for Aristotle, the Earth, formed by the aggregation of heavy bodies around the center of the universe toward which they converge, is round "for reasons of symmetry"; for Archimedes, a balance with equal weights is in equilibrium and a body in water receives a push from bottom to top equal to the weight of the displaced water, "for reasons of symmetry." This is what "causes" the sphericity of the Earth, the balance of a scale and the stability of a body in water. Hermann Weyl, will explain that "every fundamental principle of physics is a principle of symmetry." But what are these symmetries? Aristotle and Archimedes think of rotational or reflection (mirror) symmetries, Euclid works with translations and rotations of the plane - all of Euclid's axioms maximize symmetries in the construction (the axioms say, "*draw a straight line...build a circle...*"), they are continuous gestures on the plane². And this is the crux: continuous hand movements that draw justify and ground Euclidean geometry in terms of symmetries.

¹ Invited paper for a Special Issue (Patterns: The Discrete and the Continuous) of *Theory Culture and Society*, 2026.

² Longo G. (2025) Symmetries and Symmetry Breaking, from Geometry to Physics, via Painting, in *Proceedings "Symmetry: Art and Science"*, Crete (Gr) (Longo's papers are here: <https://www.di.ens.fr/users/longo/download.html>)

Two thousand years later, Noether's theorems (1918) show that the conservation principles of physics (of momentum or inertia, of energy...) are *continuous symmetries* in the equations³, in all existing physical theories, even those that are incompatible with each other (such as those of the relativistic and quantum field)⁴. These theorems explain why conservation principles are so fundamental in physics: they are not arbitrary rules, but consequences of the underlying symmetries of space-time⁵. Thus they unify various physical phenomena and provide a deep conceptual basis for conservation laws in classical mechanics, quantum mechanics and field theory⁶. We will correlate this enormous and beautiful cultural construction to the primary gestures of our animal body in space and time, showing the unity between the two, as our symbolic constructions in turn modify our also-bodily being in the world.

Let us return first to the scientific problem of causality. In the 1930s, Einstein and Bohr knew well and shared the role of continuous symmetries in physics (and greatly appreciated the work of Noether and Weyl). On this basis, Einstein even made it possible to understand gravitation, we mentioned in the footnote, *as the cause of the falling of a grave* (and the turning of planets), in terms of continuous symmetry: it is an inertial motion (a conservation principle, thus a "symmetry principle") in curved spaces. Thus, when confronted with the phenomena of quantum entanglement⁷ and the spin-up or down of an electron, he thinks that they must have "causes," like any event in physics, but that these may be "hidden."⁸. The former otherwise could not take place in the space-time continuum with the topological

³ Kosman-Schwarback, Y. (2010). *The Noether theorems: Invariance and conservation laws in the twentieth century*, Springer. Noether's theorems specifically link conservation laws to continuous symmetries because the proofs rely on the ability to perform infinitesimal transformations, a property of continuous groups (Lie groups). These small transformations are used to derive the conserved properties through the Euler-Lagrange equations of motion. In Biology, we need to go beyond symmetries – knowledge is grounded on "non-conservation principles", beginning with Darwin's first principle: "descent with modification", Longo, G., Montévil M. (2014). *Perspectives on Organisms: Biological Time, Symmetries and Singularities*. Dordrecht, Springer.

⁴ Quantum entanglement is a phenomenon in which two or more particles are related in such a way that the state of one particle instantaneously affects the state of the other(s), regardless of their distance. That is, measuring the property of one particle (such as spin or polarization) gives instantaneous information about the corresponding property of the other, defying classical notions of locality and separability, Aspect, A., Grangier, P., & Roger, G. (1982). Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities. *Phys. Rev. Lett.*, 49(2), 91-94.

⁵ And this subsists even when moving from Euclidean geometry to the various Riemannian geometries (elliptic, hyperbolic), spaces of intelligibility for Einstein's Relativity. In the latter, the symmetry expressed by Euclid's fifth axiom, that of parallels, does not exist-it is equivalent to saying that the sum of the interior angles of triangles of any magnitude is 180°. As is well known, this is false in triangulations between stars. On the one hand, a fundamental continuous symmetry is thus lost, by enlargements and shrinkages (homotheties of the plane); on the other hand, Einstein allows us to say that "a body falls for reasons of symmetry," since, in the "curved" spaces of Relativity, inertia and gravitation are the same thing and, the former, is a principle of (continuous) symmetry--a splendid unification of cultures, physics and mathematics, contemporary and Greek.

⁶ Noether's theorems specifically link conservation laws to continuous symmetries because the proofs rely on the ability to perform infinitesimal transformations, a property of continuous groups (Lie groups). These small transformations are used to derive the conserved properties through the Euler-Lagrange equations of motion.

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⁸ D. Bohm developed, among others, Einstein's proposal in "A Suggested Interpretation of the Quantum Theory in Terms of 'Hidden' Variables I and II," *Physical Review*, Vol. 85, Pages 166-179 (Part I) and Pages 180-193 (Part II), 1952. Hidden variables are parameters that vary in the continuum-their necessary "non-locality" makes their use ineffective as an alternative to the interpretation defended by Bohr, see Kochen, S., Specker, E. P. (1967) The problem of hidden

property essential to relativistic and classical physics: given two distinct points in space, the points and each of their observable properties must be "separable", that is contained in different "neighborhoods" - two small circles/spheres, say, that do not intersect. "Natural" topologies have this property, for Euclid and Riemann and ... for us animals who act in space and are able to "well separate" places and objects. The same applies to the phenomenon that produces a discrete observable in the act of measurement - the spin of an electron, a kind of 0 or 1, for Einstein, Bohm and others: against Bohr's view, its (hidden) *causes*, parameterized in the continuum, must be discovered and well framed by Noether's Theorems on continuous symmetries.

Bohr instead assumes the peculiarity of micro-physics, far from our senses, accessible only through complex measuring instruments that co-constitute the event in the act of accessing the quantum level, the intrinsic contingency (a-causality) of some of its phenomena, such as the spin of a quanton. Moreover, entanglement is due to an inherent holistic nature of quantum events, made objective only in and by measurement, thanks to the "artificial" (cultural) interface between us and the micro-physical reality: the measuring instrument. Since the measurement result is a co-constituent of the "friction" between (classical) instrument and micro-physics, at its scale, this value preserves the trace of correlation at the quantum level. The spin-up or down, in turn, a discrete (classical) result of measurement, a 0/1, is inherently "causeless," for Bohr, it is pure contingency, period -- useless to look for any cause at the micro-physical level. Indeterminacy is thus put back into the theoretical heart of quantum physics, as Heisenberg had proposed it in his analysis of measurement: even more radically, thus, the spin of an electron is not only unpredictable, it has no causes. But then, if Bohr and Heisenberg are right, is the world discrete and a-causal? It depends on the scale and state of the object: unlike the bound electron, *the energy spectrum of the free electron is continuous*. In general, intended space-time are described in the continuous, but, so far, there is no unity between spaces of microphysics and classical or relativistic spaces⁹. Quantum physics proposes to us an original and difficult intelligibility of the world, intricate, discrete and continuous at the same time, or, perhaps, neither. Measurement, which stands at the interface between "nature" and a theoretical-cultural construction, including that of the classical measuring instrument, produces a new entity, the measured quantum object. That is, knowledge of the "natural" quantum object presupposes the "cultural" construction of a measuring instrument, since measurement is the only form of access we have to nature, in science. The epistemological teaching of quantum physics is of extraordinary richness.¹⁰

What everyone agrees on, from Einstein and Bohm to Bohr and Heisenberg, is that when we move to a description of the world with discrete mathematics, *causality disappears*. In quantum physics, we said, the construction and use of the measuring instrument provides access to a scale far from our senses and shows the separation between classical/relativistic physics and microphysics, as theories: it adds to the determination, that frames classical causality and justifies it, a form of randomness intrinsic to quantum theory, i.e., it highlights phenomena that can "have no cause" (such as the spin up or down of an electron) or be correlated without even information passing between them (instantaneous entanglement prohibits the passage of any signal, whose speed is limited by that of light). But the two physics separate scales to understand and, for a century, attempts have been made to unify their theoretical foundations and thus propose an intelligibility of the inert that would become even richer,

variables in quantum mechanics. *Journal of Mathematics and Mechanics* **17**, 59–87. See also A. Abbott, *Value Indefiniteness, Randomness and Unpredictability in Quantum Foundations*, PhD thesis, University of Auckland and École Normale Supérieure (2015, downloadable). Supervisors C. S. Calude (UoA) and G. Longo (ENS).

⁹ Perhaps the richest attempt at quantum/relativistic unification comes through a reorganization of the space-time continuum that starts with the non-commutativity of quantum measurement, see Connes, A. (1994). *Non-commutative Geometry*, New York: Academic Press.

¹⁰ Bitbol, M. (1998). *L'Aveuglante proximité du réel ; anti-réalisme et quasi-réalisme en physique*. Paris: Flammarion.

with partial successes. The culture, of which we shall speak, that emerges from the separation of alpha-numeric, algorithmic knowledge from bodily gestures in space and time, retroacts quite differently on our relationship to nature: it subordinates it to techno-cultural artifices whose design is now all political and aims predominantly at the control of nature and the social, without caring for intelligibility¹¹. Once causality goes out, nature goes “randomly” or *follows orders* – is it the same for the social?.

The Greek alphabet, between democracy and techno-feudalism

Among our many symbolic-cultural constructions, the radical rupture between sign and meaning, which originated in the invention of the alphabet, has been particularly fruitful and rich in spin-offs, such as the current alpha-numeric machines that are changing the world. Symbolic inventions have set themselves up as a barrier and link to nature, because at the same time they remove us from it and allow us to do science, taking a distance from reality, as well as to intervene in it by knowledge and techniques. To this end, perhaps the invention of the alphabet is one of the most powerful - we see it today. Thanks to alphabetic writing, finite sequences of signs, words and phrases, belonging to a finite list of signs, the alphabet, make it possible to reconstruct meaning through phonemes, voice, were it even produced "in the head," in silence. But it also becomes possible to manipulate these sequences automatically, without any reference to their meaning in the world.

In the book with Jean Lassègue¹², we propose a conceptual history of the invention of the current "electronic reticular writing" at the heart of the computer networks that blanket the world. Developing a lead identified by Herrenschildt¹³, which we summarize here very briefly, we recall that the Greeks are the first to make the alphabetic script inherited from the Phoenicians "phonetically complete." In short, they add enough vowels to it to remove the ambiguities peculiar to languages written only with the use of consonants, called of the "abjad," such as Phoenician, classical Hebrew and Arabic. To interpret the latter, in order to understand when reading, it is necessary to complete words, composed of consonants only, by adding, for example, dots that specify the phoneme and, thus, the meaning¹⁴. This drastic reduction of ambiguities, is at the heart of the invention of Greek democracy where every literate man was able to read and interpret the written law, without the need for scribes and priests to interpret it. It is precisely this drastic reduction of interpretive ambiguities, to be deciphered, that makes it possible to read "mechanically" and arrive, distracted, at the bottom of a page and realize that we... have understood nothing. This is already impossible in the languages of abjad, even less so in Chinese or Egyptian: one has to interpret to read - and in Egypt, it probably took two or three priest-scribes who, discussing, proposed a possible understanding of the texts, sacred rebuses.

¹¹ Anderson, C. (2008). The End of Theory: The Data Deluge Makes the Scientific Method Obsolete. *Wired Magazine*; for a mathematical falsification of this claim, but accessible to all: Calude, C., Longo, G. (2017). The deluge of Spurious Correlations in Big Data. In *Foundations of Science*, Vol. 22, Issue 3, pp 595-612. For the role of the "digital" in social control, see: Garapon A., Lassègue J. (2021), *Le numérique contre le politique*, PUF, Paris.

¹² Lassègue J., Longo G. (2025) *L'empire numérique. De l'alphabet à l'IA*. PUF, Paris.

¹³ Herrenschildt, C. (2007). *Les trois écritures, Langue, nombre, code*, Gallimard.

¹⁴ For example, in an abjad, one can write " ktb " to mean " book ", " library ", " librarian ": only the context allows one to understand what the writer is referring to. Even more complex and demanding is the interpretation of hieroglyphic or ideogrammatic writings: hieroglyphs even have to be read as "rebuses," the interpretation of which was entirely in the hands of a caste of scribes, see Lassègue J., Longo G. (2025) for more details.

The automaticity of the Greek writing of which we are the heirs, already intuited by Turing¹⁵, a pioneer of algorithm theory, is the basis of today's numerical machines-systems *for re-writing writing*: algorithms are sets of instructions, written as associations of letter sequences to letter sequences, that tell how to re-write letter sequences: the rule (aa → ab) orders to re-write aacd as abcd¹⁶. All formal and numerical computation *is just* based on "sequence-matching" and "sequence-replacement" (checking identity of sequences, replacing (sub-)sequences)¹⁷. One can thus write and rewrite--without understanding anything, mechanically, following the written rules – so works the digital machine. It is in fact easy to encode with sequences of 0s and 1s, switches of an electronic machine, sequences of alphabetic letters. The separation of writing from meaning is then radical: to manipulate it, we no longer need the phoneme that evokes, by sound, meaning-a machine can do it. We, heirs of the Greek alphabet, and only we, have thus invented an alpha-numeric machine for writing and re-writing, without meaning. And we move even further away from the animal cry, rich in meaning, a cry of call, alarm, pain, joy -- at the origin of human language.

This separation of (alphabetical) sign and sense is found in another, recent form of dualism: the sharp distinction between software and hardware, fundamental to doing computing today-a dualism to put Descartes to shame and which makes some people dream of transferring the soul, well encoded in 0s and 1s, into software¹⁸. Observe instead that the "computer" of the Chinese is a very different, geometric machine: the abacus. The unity of sign (ideogram) and meaning, is found both in the inseparability of soul and body proper to classical Chinese culture and in the relationship between writing and space: houses and gardens are built in the form of ideograms or these are drawn following lines that organize space¹⁹. A synthetic, systemic worldview dominates.²⁰

Instead, alphabetical writing is the basis of an analytically effective way of thinking: like language with the letters of the alphabet, so the world is described and constructed by stacking elementary and simple components (Democritus annotated with letters the atoms and Euclid the points, "semeia," signs). Vision that would later prove most useful in making machines, all of which can be constructed by assembling elementary and simple components. A pioneer in this distinction, Leonardo da Vinci had a "holistic" (and often "turbulent," dramatic) view nature and clearly distinguished his hundreds of naturalistic drawings from technical drawings, his own invention, obtained by breaking down and re-

¹⁵ Lassègue J., Longo G. (2012) What is Turing's Comparison between Mechanism and Writing Worth? *Invited lecture*, Proceedings of "The Turing Centenary Conference (CiE 2012)," Isaac Newton Institute program, Cambridge, June 18 - 23, 2012; in *Computability in Europe, 2012*, LNCS 7318 (S.B. Cooper, A. Dawar, and B. Löwe, Eds.), pp. 451-462, Springer-Verlag Berlin (for this and GL's other articles, see <https://www.di.ens.fr/users/longo/download.html>).

¹⁶ "Programs" are algorithms implemented in specific programming languages. All programming languages, even "functional" or "Object-Oriented" languages, which are widely used in AI, are based on an underlying *imperative* structure (by Church-Rosser Theorem, Barendregt, H. (1984) *The Lambda-Calculus: its Syntax, its Semantics*. Amsterdam, North-Holland, and by Normalization, Girard, J.-Y., Taylor, P., & Lafont, Y. (1990). *Proofs and types*, Cambridge U. Press.). Moreover, compilers and operating systems are *written in imperative languages*: the deep structure of the machine can only execute orders.

¹⁷ Bezem, M, Klop, JW, and Roelde Vrijer, R. 2013. *Term Rewriting Systems*. Cambridge U. Press.

¹⁸ Bamford S. (2012). A framework for approaches to transfer of a mind's substrate. *International Journal of Machine Consciousness*. 04 (1): 23-34; Sabry F. (2022) *Mind Uploading. Fundamentals and Applications*, Apple Books. Symmetrically, in the book by a much-funded biologist, Gilbert, W. (1992) A vision of the grail. In (Kevles, Hood, eds.) *The Code of Codes: Scientific and Social Issues in the Human Genome Project*, Harvard U.P. 83-9, it is argued that once the human genome was sequenced (2001), one could transfer the genetic code to a digital memory and say, "Here is a human being, this is me!". Who knows, perhaps in time, the two compact-disks, for the mind and the body (as coded in the DNA), for now well separated, might even be reunited in just one disk....

¹⁹ The spatiality of Chinese writing is in permanent dialogue with the organization of ambient space and accompanies the fact that "early Chinese thought considered spirit and body as inseparable," Shiqiao Li (2022) *Language, Figure, Landscape in Chinese Thought*. In *Theory, Culture & Society*, 1 -18.

²⁰ Nisbett R. (2003) *The Geography of Thought: How Asians and Westerners Think Differently.... And Why*, Free Press.

composing, analytically, whole and piece-by-piece machines, drawing plane, then three-dimensional sections²¹. A little later, forgetting Leonardo's turbulent motions, "ephemeral phenomena" he himself acknowledged, the scientific revolution begins with "celestial mechanics," an analysis of perfect and eternal motions, planetary clockwork (Descartes, Kepler), and is primarily a revolution of machines²². Along these lines, the early 19th century analytical approach of Laplace and Fourier gave us a great tool of mathematical analysis: the decomposition of systems of equations into *linear* series – like in the construction of machines, complexity is obtained by composing elementary and simple parts – this is linearity. These were intended as a *complete* description of the world, as Laplace well explicated: the equations that determine a physical dynamic allow us to predict it, up to an approximation that at most grows linearly. What more, linearization allows a discretization of nonlinear processes: as we said, every process is (mathematically, linearly) decomposable into elementary and simple components. Such a view, still common today, has delayed the understanding and development of systemic views, such as Poincaré's "geometry of nonlinear dynamical systems"²³, or Prigogine's (1949) far-from-equilibrium thermodynamics²⁴, an analysis of "ephemeral phenomena," he was reproached. These have long remained, and still are, minor canons, although almost all "world systems" are nonlinear and far from equilibrium. Their unpredictability, thus results from the conjunction of the approximation of (classical) measurement and the non-linearity: in presence of bifurcations (a notion invented by Poincaré), for example, in a non-linear trajectory, a fluctuation below the best measurement does not allow to predict which path will be followed by the continuous dynamics. This is not nature "per se", but a fruitful understanding or mathematical organization of relevant phenomena, in particular of movement, of change.

Instead, the identification of thought and nature with its alphabetical discrete "writing," more precisely of the "Greek" type (in fact in English today), is not a bridge between culture and nature, but crushes nature, hides it and proposes to manipulate it thanks to a cultural construction that is highly effective, but carries with it the "bias" of a very specific artifice, imbued with mechanicality, deeply dualistic and analytical: everything thinkable and existing can be broken down into the elemental and simple of meaningless letters, atoms of knowledge and of the real. The alphabetic writing of a program makes everything intelligible. Even more deeply, against the whole scientific mountain built on the role of continuous symmetries in physics, alluded to above, illustrious computer scientists (Turing Awards!) such as Pearl and Valiant, tell us that a stone falls because it is "programmed to fall": it just follows instructions. The laws of nature would indeed be algorithms, enriched by statistical methods²⁵ or interacting (echo-rhythms²⁶). This erases two thousand years of a very rich scientific history, that of symmetries and the continuum, from Euclid and Galileo (inertial movement) to Poincaré and Einstein, but above all the rootedness of scientific culture on bodily gestures in space and time, to replace them with a very specific form of alphabetical writings, algorithms, far removed from meaning and the

²¹ Longo G., Longo S. (2021) Réinventer le corps et l'espace, in *In Defense of the Human* (edited by Boi et al.) (also downloadable in Italian: <https://www.di.ens.fr/users/longo/download.html>)

²² Rossi P. (1962) *I filosofi e le macchine*, Feltrinelli (reprinted 2002).

²³ Poincaré, H. (1892) *Les méthodes nouvelles de la mécanique céleste, Tome I*, Gauthier-Villars. After proving that simple nonlinear systems (three bodies in their gravitational fields) do not admit of solutions (integrals) and that, almost everywhere, they cannot even be approximated linearly, the end therefore of Laplace's project, Poincaré proposes a qualitative (geometric) analysis of such deterministic but unpredictable systems. In them, the discrete approximation does not follow (non-shadowing) the physical dynamics, nor its mathematical treatment (the trajectory") given in the continuum, Pilyugin, S. Y. (1999). *Shadowing in Dynamical Systems*, Springer V.. Widespread interest in Poincaré's approach will not occur until after the 1960-70s, with the various theories of "deterministic chaos."

²⁴ Nicolis G., Prigogine I. (1977). *Self-organization in non-equilibrium systems*. New York, Wiley.

²⁵ Pearl J., Mackenzie D. (2018) *The book of why. The new science of cause and effect*, Basic Books, NY.

²⁶ Valiant L. (2013) *Probably approximately correct*, Basic Books.

world. After all, as Riemann had already observed, while in the continuous, measurement, hence metric, is associated with the structure of space (its curvature, in geometry) and, conjecturally, with the "cohesive forces between bodies" (Einstein will unify gravitation and inertia just so), in the discrete "one can only count", says Riemann²⁷. In the discrete one thus loses the fundamental form of access to the real, the classical and relativistic measure, approximated, given in an interval, associated with a metric: it is reduced to counting. That is, when the world is given in the discrete, measurement is just counting one bit, one pixel after another: access to the real is exact, as to the integers, and we forget Poincaré and return to Laplace, with the addition of the quantum randomness, recognizes Pearl - who explicitly claims that this is how nature goes: it is laplacian or quantum²⁸. And so, causes, which are framed by continuous symmetries, must be replaced by "instructions/orders": that's how the world moves. And what does not obey orders is "noise"²⁹.

One finds again a vision so dear to politics to which today's top numerical leaders adhere: the real (and the social) must obey commands and woe to those who make noise. The laws of physics and the living, are programs, alphabetical writings of instructions to be executed³⁰; a living therefore to be controlled, by re-programming it³¹. This is hardly a new unity between nature and culture; rather, it erases much of the intelligibility of the physical dynamics and justifies the growing massacre of the living, a programmed machine to be manipulated at will before understanding the organism and its preferred "space," the ecosystem, with their interactions³². The development of the few functioning biotechnologies based on the notion of a "genetic program" has by no means "dissolved the traditional boundary between nature and culture and between biology and society"³³ but, with a mechanistic,

²⁷ Riemann, B. (1854) *On the hypothesis which lie at the basis of Geometry* (Engl. by W. Clifford, Nature, 1973).

²⁸ "This quasi-deterministic functional model mirrors Laplace's conception of nature [Laplace, 1814]... (only quantum mechanical phenomena exhibit associations that might conflict with the Laplacian model)", Pearl J (2000) *The Logic of Counterfactuals in Causal Inference*, *J. Amer. Stat. Assoc.*, 95, 450.

²⁹ "Evolution is due to noise," Monod, J. (1970) *Le Hasard et la Nécessité. Le Seuil* (in English, 1972)... how annoying noise is... In physics, a fine and important distinction can be made between randomness and noise, Calude, C. S., Longo, G. (2016) Classical, quantum and biological randomness as relative unpredictability. *Natural Computing*, 15(2), 263-278; Bravi, B., Longo, G. (2015) The Unconventionality of Nature: Biology, from Noise to Functional Randomness. In *Unconventional Computation and Natural Computation UCNC 2015*, edited by M. Dinneen. *Lecture Notes in Computer Science* 9252.

³⁰ "La surprise, c'est que la spécificité génétique soit écrite, non avec des idéogrammes comme en chinois, mais avec un alphabet comme en français," F. Jacob, leçon inaugurale au Collège de France, 1965, see also Jacob, F. (1974). *Le modèle linguistique en biologie*, Critique, Éd. de Min.. The most prominent theoretical text describing the living as a "Cartesian machine programmed by DNA" is that of Monod, (1970) cited above, co-recipient of the Nobel Prize in biology with J. Jacob, in 1965. J. Doudna's text cited below is still and explicitly within this framework of thought, enriched by smashing promises, advertising the "start-ups" in which she is involved.

³¹ Doudna J., Sternberg S. (2017) *A Crack in Creation: Gene Editing and the Unthinkable Power to Control Evolution*, Bodley Head, London; for a critical account of Nobel Laureate (2020) J. Doudna's book, see: Longo G. (2021). Programming Evolution: a Crack in Science. *A Review of the book by Nobel winner, J. A. Doudna, and S. H. Sternberg, in Organisms. J. Bio Sci.*, Vol. 5, No. 1.

³² Among the many texts recounting the limitations and failures of genetically modified organisms in agriculture (GMOs), see Giraud T., Amelier M. (2024) *L'attention au vivant*, L'observatoire Eds, Paris, and the many references to books and articles in <https://ensser.org/>. As for endocrine disruptors and carcinogens, casually injected into the ecosystem on the basis of a mechanistic view of the living, see Diamanti-Kandarakis E., et al. (2009). Endocrine-disrupting chemicals: an Endocrine Society scientific statement. *Endocrine Reviews*, 30(4), 293-342; for a more general critique of "genetic program" biology, see Noble D. (2024) Genes are not the blueprint for life, *Nature*, vol. 626, February; Ball P. (2024) *How Life Works: A User's Guide to the New Biology*, Pan Macmillan; Longo G. (2023), *Le cauchemar de Prométhée. Les sciences et leurs limites*, Paris, PUF.

³³ Rabinow, P., Rose, N. (2006) Biopower Today. In *BioSocieties* 1, 195-217.

monochromatic and authoritarian reading of the living, in content and management (it follows the orders/instructions written in the DNA and we can modify them), has prevented the growth of a dialectic, theoretical and practical, link between culture and nature.

It is difficult today to distinguish research orientations in AI from authoritarian political choices, those of the new techno-feudalism³⁴: the funding of the huge oligopolistic structures that hold the reins are largely oriented toward surveillance or control³⁵, from the one, for now and in our countries, mainly commercial (what do you buy and how can I sell your personal data?³⁶), to the political one in China, to the war³⁷, with its drones and automatically controlled weapons, whose "collateral damage" is part of the inevitable. AI-related techno-feudalism, made possible by alpha-numeric machines derived from "democratic" Greek writing, again relies on a caste of scribes, the programmers of lines of code, indecipherable to the layman, almost always proprietary and secret. Between us and meaning stands the barrier of a script that has become unreadable: the computer code.

This orientation of the digital was not necessary. In the 1980s and early 1990s, the first computer networks accompanied a strong growth of exchange, of new correlations between different researchers scattered over the surface of the Earth, which outweighed the risks of uniformity, a formidable tool developed far from the AI of the time. The gradual formation of huge oligopolies profoundly changed the operation and control of networks. The myth of the "singularity" (the imminent replacement of the human) and the computational reading of cognition, of the living and even of physics³⁸ have thus changed the ends and methods of research, driven by a culture aimed at crushing the human and nature all, into a single imperative paradigm.

Intelligence, movement, body gestures

It should not be forgotten that the animal brain was formed to manage the movement in space of some multicellulars. And that this is what it has mainly served for hundreds of millions of years. And even today, it allows us to drive a car as we did when we were hunting: *protensive* saccades (eye movements) precede anything that moves, thanks to the *retension* (memory or neuronal trace), at the level of retina and primary visual cortex, of a perceived trajectory. What is more, this "sticking" or "glueing" of the retension and protension of a trajectory also occurs in peripheral vision, where we are unable to recognize objects, but appreciate movement³⁹. Self-driving cars, which, for now, advance by "recognizing all possible traffic configurations," are a paradigm of artificial stupidity: they move with great difficulty and immense energy costs on the same roads as we animals, who move as when hunting or evading a predator: anticipating everything that moves. I would further say that the "sticking"

³⁴ Morozov E. (2022) Critique of Techno-Feudal Reason, *New Left Review*, 133/134.

³⁵ Zuboff S. (2019) *The Age of Surveillance Capitalism*, PublicAffairs, NY.

³⁶ Alombert A., Giraud G. (2024) *Le capital que je ne suis pas*. Fayard.

³⁷ Roucy-Rochegonde L. de (2024) *La guerre à l'ère de l'intelligence artificielle*, PUF.

³⁸ I say "even" because physics has two thousand years of a very solid history; therefore, it takes a strong ideological commitment to forget it - but it is easy: just cut off funding to theoretical physics, fund only theses and projects that are AI-oriented or use it massively, such as recent Nobel Prize winners. Instead, the writer thinks that we should go in the direction of a "naturalization" of physics, immersing it, as a singular part of theoretical biology, in the context of the relationship between living and inert, in continuity with the history of the former, Longo G. (2020) Naturalizing Physics. Or, embedding physics in the historicity and materiality of the living. In *Deleuziana*, no. 11, special issue on "Differential Heterogenesis: Deleuze, Mathematics And The Creation Of Forms" (Sarti et al. eds), April.

³⁹ Berthoz, A. (1997). *Le sens du mouvement*, Odile Jacob, Paris.

operation that is done in these anticipations (the retentions of a movement extending into protention, via an anticipatory movement, an ocular saccade) is a primary, visual and bodily practice of continuity, made rigorous by differential geometry⁴⁰, and allows mathematical physics to make causality intelligible. This is not "naive physics" as the many naive among the artificially intelligent say, but the complex cognitive entrenchment of a "geometric judgment," related to movement, visual and gestural practice of a trajectory: "this line is continuous". "Trace, produce ... a line, a circle ..." says Euclid and in language further specifies: the line is without thickness (definition beta). Only in the interplay between gesture and language, drawing and saying, or rather, in the writing that stabilizes the concept, does mathematics develop, the result of "our human activity in the spaces of our humanity."⁴¹. But it is a humanity in all its diversity.

In the great synthesis of Chinese mathematics⁴², Liu Hui calculates, too, by approximation with inner and outer polygons the length of the circumference, but he says: when "you can no longer see the difference," the calculation stops. So for the root of 2: the larger the square, the more you can calculate the length of its diagonal, convenient! We are a long way from the Greek anguish for the a-logos, the irrational, due to the line without thickness: only in this way do we catch a glimpse of the apeiron, the infinite in the finite, the a-logos in the logos, the irrational in the rational ... and upstream, Zeno's paradox. Liu Hui does engineering, mathematics serving, he does not baste a dialogue of symmetries with the gods. But these dialogues with the infinite allowed us to invent the spaces of the scientific revolution⁴³ and, then, infinitesimal calculus. On the one hand, we thus produced much knowledge and more machines and cannons, thanks in part to the "alphabetic" view of machines and the world, and, on the other hand, better analyses of trajectories, thanks to differential/ infinitesimal calculus. On the other hand, we Greeks developed for centuries a very poor algebra and theory of numbers, poorly annotated, without 0 or negative numbers, imported only in the 13th century by the Arabs, but appearing much earlier in China and India: they were essential to make merchants' accounts well, not concerned with the essence of the world, like the Greeks.

We then build from practices of and about nature and reorganize nature with culture. But in different ways. The example of continuous/discrete play, the infinite and the finite shows this. The practice of the discrete, of counting, is also part of the evolutionary story. We share with many animals the "small count," that is, counting small amounts of objects well separated in space. However, only in language, and then in number writing, do we know how to specify and stabilize the invariant, the *concept* of integer number, common to the same quantity of objects that even the newborn or many mammals know how to compare⁴⁴. Actions therefore in the world and about the world are the episteme of two symbolic structures, the continuous and the discrete mathematics, whose epistemological diversity (i.e., diversity in the analysis of the constitution of meaning) we have emphasized. In other words, conceptual constructions both rooted on natural practices, diverge in the ways of organizing the real, falling back on it in different ways. From the geodesics of physics, optimal paths in continuous spaces, we move to trajectories made of pixels, mimicking on the screen of our numerical machines the falling of a stone, by changing of state, from one color to another, following orders. Nothing moves on a

⁴⁰ Longo G. (2021). Confusing biological twins and atomic clocks. Today's ecological relevance of Bergson-Einstein debate on time. In A. Campo & S. Gozzano (Éds.), *Einstein vs. Bergson. An enduring quarrel of time*. De Gruyter.

⁴¹ Husserl E. (1933), *The Origin of Geometry*.

⁴² Liu Hui (3rd century) *Les Neuf Chapitres*, traduit en français per Karine Chemla et Guo Shuchun (2004)

⁴³ Longo G., Longo S. (2020) Infinity of God and Space of Men in Painting, Conditions of Possibility for the Scientific Revolution. In '*Mathematics in the Visual Arts*' (R. Scheps and M.-C. Maurel ed.), ISTE-WILEY Ltd, London.

⁴⁴ Starkey P, Spelke E S, Gelman R (1983) Detection of intermodal numerical correspondences by human infants. *Science*, 222:179-181. The establishment of an invariant, linguistic, conceptual, graphic... is always the result of a plurality of "practices," "acts of experience" (Weyl): for example, counting in space and the perception of a temporal rhythm, a counting in time (Brouwer), precede the concept of number, the invariant of these two practices.

computer screen, there are only changes of state of the pixels. Formidable technology, catastrophe of knowledge and action on nature, if identified to nature.

We have tried to relate, in a very cursory way, this enormous and beautiful cultural construction, mathematics, to the primary gestures of our animal bodies in space and time, showing the unity between the two, as our symbolic constructions in turn modify our also bodily being in the world. But the cognitive grounding of knowledge constructions can lead to very different outcomes, in which the choice between one or the other turns out, perhaps always, certainly today, to be eminently political. In short, the dialectic between nature and culture is not neutral. The alleged orders given to plants and animals whose DNA is claimed to be re-programmed, GMOs, are an important example of this: they are changing nature and society, from the disappearance of insects, pollinators and soil⁴⁵, to the abuse of pesticides with endocrine disrupting roles⁴⁶, to new social suffering associated with the sale of seeds to be renewed annually⁴⁷. Imperative linguistic structures are far from allowing us to control nature: they do not determine biological dynamics, but change its "constraints"⁴⁸, including such important ones as DNA, with largely unpredictable outcomes – but surely a decline in bio-diversity, a growth of cancers (see Diamanti-Kandarakis cited above). On the other hand, while they make the intelligibility of nature, from the physical to the living, lose, they make it possible to control societies, through AI, as never before.

Making the invisible visible

To return to the topic discussed further above, the invention of writing and alphabetic writing in particular, Jaynes's⁴⁹ theses in this regard are fascinating, though for many questionable. On the one hand, as Herrenschmidt also writes, cited above, writing made visible the invisible of language, of thought. Being able to say, "there, there is written what I say, what I think," has objectified speech and, perhaps, constructed human "consciousness" itself differently or made it possible in new ways. In addition, the shift from pictographic or syllabic writing systems to the phonetic alphabet profoundly changed cognitive processes and ways of thinking. Ideogrammatic or hieroglyphic writing systems, are more visual and engage both hemispheres of the brain, particularly the right hemisphere, which seems more associated with holistic, image-based thinking. The alphabet, phonetic rather than pictorial, shifts the burden of reading and writing to the left hemisphere, which is more oriented toward sequential, linear, and analytical processing. The brain's plasticity hints at its possible structural changes, in historical times: brain connectivity seems to change rapidly, for example in motorists and those who practice virtual realities for a long time, forgetting, thanks to GPS, city maps and movement in space⁵⁰.

⁴⁵ Giraud T., Amelier M. (2024), cited, and the extensive literature cited there.

⁴⁶ Storker T. et al. (2010) Pesticides as endocrine-disrupting chemicals. Robert Krieger (ed.), *Hayes Handbook of Pesticide Toxicology* (new edition). Academic Press Incorporated, Orlando, FL, 1:551-569.

⁴⁷ Bhatnagar S. (2021) Economics of Indian Farmers' Movement: A Study of Agrarian Distress and a Vicious Debt Cycle, *Yale Journal of International Affairs*, May 15.

⁴⁸ Montévil, M., Mossio, M. (2015). Closure of constraints in biological organization. *Journal of Theoretical Biology*, vol. 372: 179-19.

⁴⁹ Jaynes J. (1976) *The Origin of Consciousness in the Breakdown of the Bicameral Mind*, Mariner Books.

⁵⁰ Fajnerová I, et al. (2018) Could Prolonged Usage of GPS Navigation Implemented in Augmented Reality Smart Glasses Affect Hippocampal Functional Connectivity? *Biomed Res Int* Jun 13; Dahmani, L., Bohbot, V.D. (2020) Habitual use of GPS negatively impacts spatial memory during self-guided navigation. *Nature Sci Rep* **10**, 6310.

And the brain is only by far the most plastic organ among the components of an organism: all evolution is shaped primarily by the plasticity of development⁵¹. Genetic expression itself is modified by the ecosystem context⁵². And we, with culture, have been changing ecosystems ever since we started carving stone and lighting fires with our free hands. Evolution has along in all dimensions of the living, and these are intricate with each other⁵³. Analyses of the production of novelty, proper to all "histories," the biological, evolutionary one, and that of our symbolic cultures, must be distinguished, but grasping a dialectic, in the similarities and differences between the two, helps to enrich both.

Thus, it is misplacing the problem to ask whether (continuous) symmetries, our powerful symbolic construction, are "intrinsic" to nature, as so many "Platonist" mathematicians say. The real is very rich, we grasp fragments of it, very particular, contingent, historical perspectives. We animals need symmetries to move, not a plant, which at most has growth symmetries. In movement we practice an isomorphism between (we identify) the line identified by the vestibular system and the visual line, the one constructed by the saccade that precedes the path to be taken, the Poincaré-Berthoz isomorphism⁵⁴. This imaginary line and the vertical axis of gravitation identify a fundamental plane of symmetry, that of bilateral symmetry common to (almost) all moving organisms. These symmetries, these invariants, are not in the world, but they allow us to organize the world. Thus, we, project them onto nature, building houses and stable structures thanks to well-flat walls, right angles...but where are flat surfaces and right angles in a forest? Yet, these symmetries allow us to unify much physics. So we extend the practice of counting to negative numbers, invented very early in Asia, it was said -- today we can *see* them as a symmetry of positive numbers with respect to 0, but they did not originate that way, it is not inherent in them. Numbers, particularly negative numbers, are not "already there": one can long make splendid mathematics of edges and symmetries, like Euclid, without making much use of them. In general, numbers, integers, rationals..., are not already in nature, but result from the constitutions of invariants of counting and from measuring operations in the continuum, of gestures that relate us to the real, down to the difficult physical, relativistic and quantum measurements. The real resists, channels our measurements, our gestures of knowledge: the symbolic production that follows is not arbitrary.

Yet, different ones can be given: we have mentioned here two that differ in the constituent paths of mathematical knowledge, the discrete and the continuous - as well as the Chinese variant, with its scriptural traces of evocative spatial diagrams. Not only do they offer a different dialectic between culture and nature, but, within mathematics itself, the interplay between the discrete and the continuous is productive of new conceptual structures: from those of algebraic geometry to analytic number theory,

⁵¹ West-Eberhard M-J. (2003) *Developmental Plasticity and evolution*. Oxford U. Press, New York.

⁵² Hybridization of blind cavefish from different populations may partially restore vision in their offspring: it is possible that, in some species, the DNA necessary for producing functional eyes is present and silenced (perhaps "methylated") or that some gene expression networks have changed, including through mutations. That is, different types of mutations or control of gene expression in separate populations lead to the loss of eyes and, when re-combined through hybridization, can form new expression networks, leading to the development of functional eyes in hybrids (Borowsky R. Restoring sight in blind cavefish. *Curr Biol*. (2008) 18:23-24; Sifuentes-Romero I et al. (2020) Repeated evolution of eye loss in Mexican cavefish: Evidence of similar developmental mechanisms in independently evolved populations. *J Exp Zool B Mol Dev Evol*. Nov. 334(7-8):423-437). As West-Eberhard says "genes are mostly followers" of ecosystem changes (the cave, interspecies encounters etc.). The formation of the eukaryotic cell, by the penetration of a bacterium, which becomes the mitochondria, into an archaea, is one of the most important examples of phenotypic transformation, in the very particular ecosystem of a billion years ago, which induced subsequent radical genetic changes (Margulis L. (1970). *Origin of Eukaryotic Cells*, Yale University Press): "genes are mostly followers" of the plasticity of organisms and ecosystems.

⁵³ Jablonka E, Lamb MJ. (2008), *Evolution in Four Dimensions*, MIT Press.

⁵⁴ Teissier, B. (2006) Géométrie et Cognition: l'exemple du continu, in *Ouvrir la logique au monde*", actes de l'Ecole thématique CNRS-LIGC" *Logique et interaction; vers une géométrie du cognitif*, Cerisy Septembre, dirigée par J.-B. Joinet et S. Tronçon.

to recent theories of Topos (Grothendieck) that allow for original correlations between discrete and continuous.⁵⁵ These “bridges” make it possible to move from one structure to another, in a unifying perspective⁵⁶, without undoing the differences, indeed allowing us to highlight their different roles in applications, in physics for example. Let’s try to explain this by an analogy. Apollonius (3rd c. BC), faced with different plane curves, circles, ellipses, parabolas, hyperbolas, invented the three-dimensional cone and observed, in Grothendieck’s style: those curves are different sections of the same cone, I can pass from one to another by tilting the section-plane—and thus he sees them all at once, in his new “topos” that unifies different “sites.” The cone allows us to look at plane sites from another mathematical dimension, “from above”, within a new “topos”, a new bridging perspective. Yet, in physics, if an astronaut is happy to travel inertially on an ellipse around the hearth, he/she would change mood if from the centre of control they inform him/her that he/she is actually travelling on a hyperbole... even though they are “just” different sections of the same cone. Mathematical bridges do not erase differences in ways of “organizing” nature: in physics, missing Einstein’s understanding of inertia *and* gravitation as a *continuous* symmetry in space, and confusing them with well-separated pixels and bits changing state on a screen, makes movement unintelligible – Topos Theory may help to understand this, synthetically⁵⁷.

In sum, we make symbolic inventions anchored on natural practices, in actions on the world, which are conditions of its possibility, do not determine them, and which may diverge in the accumulation of historical paths. Some go so far as to propose principled caesuras with nature. These become most serious if they come to assume the role of monochromatic political government, which seeks to (and succeeds in) preventing debate. Authoritarianism is the current political counterpart of this programmed and re-programmable view of nature, which thus obeys orders. Scientism, of which Grothendieck explicitly accuses the theoretical foundations of geno-centric biology⁵⁸, is its technical counterpart. The rupture with nature, and its slaughter due to a governance without intelligibility, follows. Alternative proposals primarily seek a unity between an organism's development and its ecosystem, its evolution. On the one hand, evolution is the result of the plasticity of development (West-Eberhard, Jablonka, cited); on the other hand, the analysis of development (ontogeny) can be based on the same principles that make evolution (phylogeny) intelligible.⁵⁹

The analysis of culture then also requires other tools, those that make different human symbolic and technical cultures intelligible: the tools of history, economics.... These tools have in common with the analyses of the living the appreciation of the historicity of processes: the living and culture permanently construct new observables and objects of knowledge, this is at the heart of their historicity, far from the

⁵⁵ For example, some toposes (“étales”) are spatial manifolds that represent both algebraic and topological properties, linking discrete structures (Galois theory, number theory) with geometric properties in the continuum, Artin M., A. Grothendieck and J. L. Verdier, (1972) *Théorie des topos et cohomologie étale des schémas* - (SGA 4), Séminaire de Géométrie Algébrique du Bois-Marie, année 1963–64; second edition published as Lecture Notes in Math., vols 269, 270 and 305, Springer-Verlag.

⁵⁶ Caramello O. (2025) The “unifying notion” of Topos. In M. Panza et al. (eds.), *The Mathematical and Philosophical Legacy of Alexander Grothendieck*, Chapman Mathematical Notes, Springer.

⁵⁷ Zalamea F. (2012), *Synthetic Philosophy of Contemporary Mathematics*, Urbanomic (UK) and Sequence Press (USA) (review in Longo G. (2015), *Conceptual Analyses from a Grothendieckian Perspective*, in *Speculations*, December).

⁵⁸ With surprising lucidity, in Grothendieck A. (1971) La nouvelle Eglise universelle, *Survivre... et vivre* n°9 Août-Septembre, Monod's 1970 book, quoted above, is described as a form of “scientism,” in the sense, in my view, that having captured a fragment of the real (genetic expression and its control by genes themselves-an interesting phenomenon, but one that led to later building epicycles upon epicycles of “control” in order to avoid epigenetics, i.e., organismic and ecosystemic inheritance and control of gene expression), Monod claims that he can understand everything with this knowledge, that DNA contains a *complete description* of the organism and its development.

⁵⁹ Soto A., Longo G., Noble D. (eds.) (2016) *From the century of the genome to the century of the organism: New theoretical approaches*, a Special issue of *Progress in Biophysics and Mol. Biology*, Vol. 122, 1, Elsevier.

stability of the "space of phases" (observables and relevant parameters) proper to existing theories of the inert⁶⁰. The analysis of the natural rootedness and, then, constitutive autonomy of the notions of the mathematical continuous and discrete, of their possible "genesis," as well as of their internal dialectic and, then, with nature, is the attempt made here.⁶¹

Extended criticality, anti-entropy and heterogenesis

Is the inertial continuum of physics, the first and fundamental principle of conservation (Galileo), a continuous symmetry⁶² in space, adequate to say anything about the living? Almost nothing, except that a dog falls with the same acceleration as a stone - without disallowing the role of gravitation in morphogenetic processes, a constraint on their unfolding. But the "primary cause" of the generation of biological forms, morphogenesis, is the "reproduction with variation and motility" of cells. Of course, under massive "constraints". Primarily, one internal to the cells themselves, DNA, which provides the "pattern" of macromolecules, in largely stochastic interactions⁶³. Thus, the many fractal structures⁶⁴ (lungs, vascular system...) do not have the crystalline regularity of a physical structure, only shaped by the forces that impose its fractality, but are irregular, diverse. And this is functional: the diversity of lungs, for example, within an individual, among individuals in a population, contributes to the resilience of the individual, of the population, in the face of environmental changes. And every cell reproduction is a "critical transition": a bifurcation that re-organizes the overall structure (the tissue), into a new coherence structure, in which even the two daughter cells are different from each other and from the mother cell. We called this criticality "extended"⁶⁵: transitions occur in cascades, are "dense," that is, present in every relevant time interval-metabolic cycles, heartbeats, respirations. Instability is channeled, first by DNA, an internal constraint, a very important chemical-physical trace of evolution, then by all external conditions, from pre-existing tissue structure, to hormonal system, great regulator of cell reproduction in an organism, to eco-systemic conditions (from gravitation and air pressure, to temperature... to other organisms). The "smooth" (differentiable) continuity of classical physical processes is continuously broken, in the living, by non-differentiable transitions, the cascading, critical transitions: the continuum is not discretized, but "punctuated" by structural changes in local organization (the two new cells, the re-organized tissue...).

Instability, stabilized by constraints, both of which are always changing, are the engine of novelty production, in biology, which we have called anti-entropy⁶⁶. This, does not oppose, with a negative sign

⁶⁰ Longo, G. (2017). How Future Depends on Past Histories and Rare Events in Systems of Life, *Foundations of Science*, pp. 1-32.

⁶¹ "The powerful dogma of the fundamental break between *epistemological clarification* and *historical explanation*, as well as the psychological explicitation in the frame of sciences of mind, the dogma of the break between *epistemological origin* and *genetic origin*, this dogma, as long as the concepts of "history," of "historical analysis" and of "genesis" are not limited in an inadmissible way, as they usually are, this dogma must be reversed from top to bottom" [Husserl E., *The Origin of Geometry*, 1933].

⁶² And differentiable: possesses not only the first derivative, but all the other, continuous ones, which are themselves differentiable.

⁶³ Elowitz, M. B. et al. (2002). Stochastic Gene Expression in a Single Cell. *Science*, 297(5584), 1183-1186.

⁶⁴ Brown J.H. et al. (2002) The fractal nature of nature: power laws, *Phil. Trans. R. Soc. Lond., B*, 357:619-626.

⁶⁵ Bailly, F., Longo, G. (2008). Extended critical situation: the physical singularity of life phenomena. *Journal of Biological Systems*, 16(02), 309-336; Longo G., Montévil M. (2011) From physics to biology by extending criticality and symmetry breakings. *Progress in Biophysics and Molecular Biology*, 106(2), 340-7.

⁶⁶ Bailly, F., Longo, G. (2009). Biological Organization and Anti-Entropy. *J. Biological Systems*, Vol. 17, No. 1, pp. 63-96; Longo, G., Montévil, M. (2012) Randomness Increases Order in Biological Evolution. In *Computation, Physics and Beyond*, edited by Michael J. Dinneen, Bakhadyr Khoussainov, and André Nies, 7160:289-308.

to entropy (negentropy), but has its own dimension - it coexists with the production of entropy in an organism, indeed it feeds on it: the processes of chemical diffusion, in a cell, in an organism, are entropic and are essential to life⁶⁷. Anti-entropy is the permanent production of biological novelty, of new organization therefore: to forms it associates functions. So energy is certainly globally conserved, but an organism absorbs and transforms energy, using it to produce and rebuild organization (anti-entropy), always different, also using entropic processes.

All this breaks the fundamental continuous symmetry of all existing physical theories: the conservation of phase space. The primary task of the theoretical physicist, when faced with an original problem or experience, is to invent a good space of observables and relevant parameters (a "phase space"), even an entirely new one, in which, possibly, to treat the problem mathematically. But this space then remains fixed for the theory, at most it can change the number of parameters. In historical theories, on the other hand, what changes, it was said, is first and foremost the space of the possible, which is not pre-given⁶⁸. The evolution of the living produces new phenotypes, which combine new forms with new *functions*. As the space of phases (of the possible) changes, the laws change. Consider when, as a result of the invagination of a bacterium into an archea, mitochondria, as organelles of the eukaryotic cell, are formed⁶⁹: everything changes. Metabolism, its laws, change profoundly. The DNA of the cell and its organelles changes. Macro-molecular interaction networks are built whose existence is made possible only by the cell with its new biological structure, impossible to *derive* from fundamental chemical properties. Of course, those molecular interaction networks are compatible with existing chemical theories, but, I insist, not derivable: only evolution and the new ecosystem of the complex eukaryotic cell make the *chemistry* of the cell intelligible⁷⁰. Biology is not reducible to chemistry, not least because one needs biological, evolutionary historicity to understand the chemistry of the cell itself.

Thus, new functions are historical, unnecessary novelties, like those of all the organs of multicellulars that will follow in the course of evolution; they are not already given in a list of all possible functions. This changing of the laws themselves, in space and time, is now mathematically treated as "heterogenesis"⁷¹: in short, they change the "laws," the equations, the differential constraints, from point to point. A culture of change makes the historical nature of biological and human processes better intelligible, enriching classical determination, but also quantum indeterminacy, with a new, more radical, form of unpredictability: that of the very space of the possible, in the analysis of life and of culture, both the result of a history. Indeed of histories, intertwining, mutually shaping each other.

⁶⁷ Chollat-Namy M., Longo G. (2023) Entropie, Neguentropie et Anti-entropie : le jeu des tensions pour penser le vivant, in *Entropies*, ISTE OpenScience, London.

⁶⁸ Longo, G. (2017). How Future Depends on Past Histories and Rare Events in Systems of Life, *Foundations of Science*, pp. 1-32. This feature of historicity has been proposed since the early 2000s by this author, by Kauffman S. (2002), *Investigations*, Oxford, U. P., and taken up in other historical theories: Koppl, R. G., Kauffman, S. A., Felin, T., & Longo, G. (2014). Economics for a creative world. *Journal of Institut. Economics*, 11, 1-31.

⁶⁹ Margulis, L. (1996). Archaeal-eubacterial mergers in the origin of Eukarya: phylogenetic classification of life. *Proceedings of the National Academy of Sciences of USA*. 93 (3): 1071-1076.

⁷⁰ Sharma A. et al., (2023) Assembly theory explains and quantifies selection and evolution, *Nature*, Vol 622, October 12, 321. The phenomenon is analogous to the enunciation in Number Theory, but indemonstrability within it, of some arithmetic assertions: Longo, G. (2011). Reflections on Concrete Incompleteness. *Philosophia Mathematica*, 19(3), 255-280. Technically, biology is a nonconservative extension of chemistry (and, a fortiori, of physics).

⁷¹ Sarti, A., Citti, G., Piotrowski, D. (2022). Differential Heterogenesis. *Lecture Notes in Morphogenesis*. Springer, Cham.