LA DELEUZIANA – ONLINE JOURNAL OF PHILOSOPHY – ISSN 2421-3098
N. 11/2020 – DIFFERENTIAL HETEROGENESIS

Naturalizing Physics. Or, embedding physics in the historicity and materiality of the living

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Abstract

The rich blend of theories and experiences that made the history of physics possible still now enlightens the scientific method. We stress the need to learn from this method the force of making its principles explicit, while developing a rich diversity of theories, which are often incompatible. Unity is preserved by common founding principles and their mathematical form, such as the understanding of conservation properties (energy, momentum etc.) in terms of symmetries. When moving from the inert to the living state of matter, new challenges are posed, beginning with biological "heterogenesis", as "genesis *of* and *from* diversity" in a changing space of pertinent observables and parameters: the Darwinian ecosystem. The question that is posed is how we may consistently embed the theories of the inert into biology. By naturalization we mean an analysis of physics as part of the sciences of nature, not as the science governing them all. In particular, the founding symmetry principles of physical theories, often used to "naturalize" (but, actually, to "physicalize") other sciences, will instead be framed in more general dynamics which deal with fundamental changes of symmetries, as they apply, in our views, in all historical sciences, beginning with biology. This paper will accordingly explore the notion of (non-)conservative extension of theories in a precise mathematical sense. We stress a perspectival epistemology that promotes a dialogue of theories, in search for bridges or even unity, inspired by the method of "unification" at the core of major theoretical inventions in physics. Our main motivation is the need to go beyond the strong dualistic separation of space (or of the more general "phase space") as a pre-given container of the dynamics of matter, that biased physics from Aristotle to Newton and, in a technically different way, even Einstein.

1. Physics as part of the natural sciences, an introduction

Physics has been leading the scientific revolution, and for centuries has represented the richest revolutionary thinking of nature, constituting a paradigm for all sciences. This well deserved role has its origin in a complex blend of naturalism and metaphysics, including the naturalistic metaphysics and theology of 15th century science (Cassirer 1906). Then, by a marriage with mathematical idealities, physical theorizing led to the invention of fantastic conceptual tools of investigation of both geometric and analytic nature. Invariance and conservation principles, beginning with Galileo's inertia, thus symmetries, geodetics, and ergodicity … provided the unifying principles for a rich diversity of theories. However, Quantum Physics, Relativity Theory, and Hydrodynamics, … are far from being technically unified; the first two are actually incompatible (their fields, entanglement phenomena … are jointly inconsistent), the third belongs to the different physico-mathematical world of the analysis of incompressible fluids in continua, (Chibbaro et al. 2015), though we all know that water is composed of quanta. Yet, common symmetry principles ground theories that differ just by working at different scales or with different observables. Note that the existing theoretical unifications required new theories, new mathematics, and each time a true revolution: Newton – unifying planets and falling bodies, Maxwell, Boltzmann … Einstein – the equivalence of gravitation and inertia, within the same theory. A key aspect of inter-theoretical unifications is the invention of a common phase space (the mathematical space of pertinent observables and parameters).

These fantastic achievements often lead to some philosophical arrogance, in particular in relation to the very productive role of mathematics. Too well-known papers by top researchers on the "The Unreasonable Effectiveness of Mathematics *in the Natural Sciences*", mostly quoted only by the captivating title, deal only with the interactions of mathematics with physics - as if biology were not a science of nature[1]. Moreover, it is often forgotten that the different theories in physics are the result of original work at the appropriate scale or phenomenal level: when changing either of them, physicists dared to invent a new theory, often a new mathematics … in which case the problem of unification is soundly posed. Biology instead seems to deserve only to be flatly and progressively occupied by existing physico-mathematical tools, as if the *living state of matter* were not a rather original observable. In rejecting this physicalization of biology, often presented as a naturalization, we will therefore present instead an integration of physical homogeneous dynamics into a heterogenesis, more adequate to historical sciences, such as biology. This is in continuation of the work with F. Bailly and M. Montévil, see references, and in Soto & Longo (2016), and has found now its mathematical counterpart in the original approach proposed in Sarti et al. (2019), which allows a dialogue at the cross-road of independent scientific itineraries.

In an attempt to correlate the science of the inert with the science of the living, we will first stress some metaphysical commitments that biased, in a constructive way, physics' historical construction. It is often said: "life must obey the laws of physics!". What does this mean? That a cat must fall with the same acceleration of a stone or that one can *derive* the cat's biological properties from "physics"? Or, more weakly, that the description of biological phenomena must be *compatible* with physics? When facing such a confusion, one should first ask: from which of the incompatible theories in physics should one derive biology? And

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[1] Also a major book by H. Weyl on the philosophy of mathematics and of natural sciences, in his 1927 edition, refers only to physics as a natural science, except for one key issue: "The idea of the gestaltiste and the gestaltichen type plays an important role in biology, although here it is mostly associated with the teleological concept of organ function." (pointed out by G. Heinzmann). However, in the 1949 English edition, Weyl added several interesting remarks on biology and chemistry (Weyl 1949).

observe, at least, that there is a lot of water in an organism, with a peculiar blend of hydrodynamic, classical and quantum effects (Del Giudice et al. 1983; Arani et al. 1995; Lesne 2006; see Buiatti & Longo 2013 for a discussion). We will thus raise the problem of the "compatibility" of biological theorizing with regard to fundamental physical principles (it should not violate/contradict them), an issue which is often confused with the "derivability" of biological properties from those principles, where symmetries play a major role.

A major challenge in the passage from theories of the inert to historical sciences, in general, and of life in particular, is that the phase space should be extended to biology's pertinent observables. Then one of the main forms of dualism of modern science should be dropped, a major conceptual discontinuity: in section 3, we will discuss the theological origin of the separation of "spaces" from inert matter inhabiting them. More generally, the analyses of the relations between theories should also refer to methodological as well as empirical issues bridging physics and biology, in part addressed by the logico-mathematical notion of "conservative extension" mentioned below and by its application to "heterogenesis". In particular, dualities, such as the genericity of physical objects (under stable border conditions, one falling stone or an electron is worth all) *vs.* the specificity of their trajectories (they are geodetics, unique-optimal paths), are reversed in biology, in our perspective: objects are specific (historical) while their phylo-ontogenetic trajectories are generic, they are possible ones (Bailly & Longo 2011), (Longo & Montévil 2014). This yields the challenge of "generalization" of experiments in biology: as all experimentalists know too well, observations and experiments on an individual organism cannot be generalized just by an analysis of the border conditions, in view of the historical specificity of organisms, (Montévil 2019; 2020). On these grounds, the peculiar nature of both *diachronic* and *synchronic* measurements in biology will be recalled, following (Longo 2017; Montévil 2019), yet another challenge when broadening the analyses from the inert to the living state of matter.

2. Dualism and the expressiveness of physics

Different forms of dualism found the effectiveness of western science, driven by physics and by the construction of machines (Rossi 1962). Assessing the biases or limits that these sciences and techniques (implicitly) pose may help in further scientific work. Following an early and major human invention, the distinction soul/body, we also separated, during the Scientific revolution, space (and time) from the bodies inhabiting it. As hinted in section 4, this was a key step, of religious origin, that allowed the framing of equations in *pre-given* Cartesian spaces**.** This split, whether ontological (space and time exist per se) or epistemic (they are Kantian "conditions of possibility" for knowledge construction), allow us to "write equations, solve equations" (Newton) by fixing the physically pertinent parameters in pre-given spaces. In the 19th century, by positing a priori "phase spaces" (pertinent observables and parameters), physicists extended this separation by new observables: momentum or energy where added to space or time, an *extension* of the a priori of Newtonian physics. And time was definitely formalized as a parameter ranging on a pre-given Cantorian line. More generally, each new theory (Hamilton's mechanics, thermodynamics, electrodynamics …) was given in a pertinent, a priori, phase space. The great organization of knowledge (or of the world) proposed by Aristotle then found its modern version: "the actual is already 'in potentia'" in the (phase) space of all possible trajectories. In this historical context, Relativity Theory definitely "spatialized" time: following different interpretations and developments, time is subject to (about) the same transformations as the space parameters and/or it even loses its role as a mathematical parameter (Rovelli 2008; Bouton & Huneman 2018). Even though the relativistic geometry (the *metrics*) is strictly correlated to energy and matter (or even depending on them), the global space-time structure, as Riemannian manifold with a given dimension and topology, remains separated from or ontologically precedes matter, as argued in sect. 4.

When confronted with life phenomena, a new epistemological perspective seems to be needed. So, in order to enrich the traditional physical observables, many theories further reinforced this dualism and its correlated metaphysics, by proposing even more radical forms of soul/body separation. By the references, beyond physics, to the notions of "information" and (genetic) "program", the distinctions syntax/semantics and software/hardware extensively affected biological research. Most often, these references were disguised under the form of even more dangerous "metaphors" that guided intuition and experiences with no request for rigor, thus without explicit principles to confront, develop, or negate.[2] The very effective dualism of classical physics, such as space vs. matter, was thus further extended by these linguistic inventions of ours, which were also very powerful for constructing machines, such as modern computers, but far away from the radical (non-dualistic) materiality of life phenomena.

The materiality and the historicity of life forbid the stability and independence of any form of "software" as much as of any pre-given space of all biological possibilities: it is a specific matter that is inherited, such as DNA, RNA, proteome, membranes with their chemistry and no other, no software independent from "hardware". Some of this organized and inherited matter locally changes and, jointly with changing phenotypes, it reduces the symmetries or invariance in biological dynamics, by the inexistence of an invariant software, of a stable phase space and by the specificity of rare events. Historicity, under the form of changing phase spaces and rare events are discussed in Longo (2017), also in comparison with various forms of "path dependence" and "large deviations" in physics (Vulpiani et al. 2014), which also depend on the past or are rare, but remain within the frame of a processual time in pre-given phase spaces (see below). Historicity is further specified by the new mathematical

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[2] See Longo & Mossio 2020 or the papers in Soto & Longo 2016 for a few out of many recent critiques and an alternative proposal.

ideas in (Sarti et al. 2019): it also depends on changing "differential constraints" which produce new spaces and dynamics, as further analyzed below.

The problem may concern whether physics too, in view of the historicity of cosmology, is undergoing a similar change in perspective, at least when studying the evolution of the Universe. In Cosmology, rare events matter and there are "novelties", such as the early "emergence" of fundamental constants or of new observables and parameters, including space and time themselves. These are some of the major challenges for this science, which is "physical", as it only deals with inert matter, but historical as well. In this case, concepts coming from biology could inspire physics, an unusual occurrence. Yet, we can note such an influence in a major physicist, Boltzmann (1844 – 1906), who, while discussing randomness in physics, was also inspired by Darwin (Broda 1982). Indeed, Darwin had a very modern view as for the unpredictable (random) variability of the living and the production of diversity, that he expressed in terms of the "extreme sensitivity" (!) of organisms to changes of internal and external (environmental) "conditions" (Darwin 1859: chap. 5).

A fully theorized historicity of cosmology could perhaps help in better framing also the analysis of the "emergence" of a peculiar new observable in the Universe: living organisms. Following Darwin and Darwinism, we put aside the problem of the origin of life in an inert Universe, too difficult or an impossible problem in absence of a good theory of "what an organism is", and focus first on some theoretical and epistemological relations between physics and biology. For example, hydrodynamic properties (of incompressible fluids in continua) do not emerge "*theoretically*" from quantum properties, but "historically". That is, we have two robust theories at different scales, with different observables and for good empirical reasons, Hydrodynamics and Quantum Mechanics: the problem is posed soundly when working at bridges and/or looking for a unification of theories (Chibbaro et al. 2015). Then Cosmology may help to understand the formation of the new hydrodynamic observables (the early water in the universe, say) and set, by this, a historical time. The two problems of course interact, yet the understanding of the theoretical dependence and the historical order should not be confused, but reciprocally enriched – it is unlikely that the second would help in deriving Navier-Stokes' equations from Schrödinger's, at the core of the two theories.[3]

Similarly as for theories of life. For example, the approach in Bailly & Longo (2009; see also Longo & Montévil 2014: ch.9), provides a tentative explanation of the increasing "phenotypic complexity" of organisms in evolution, by an asymmetric diffusion equation. Thus, a form of entropy growth (a diffusion) *models* time increasing organization. We called "anti-

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[3] As explained in Chibbaro et al. (2015), hydrodynamic equations are not sensitive to the details of microscopic dynamics. Moreover, the individual behavior of particles, as described by the one-body distribution function, depends on the global or macroscopic hydrodynamic field, which is thus assumed, not derived from (possibly asymptotic) particle dynamics. Thus, there is no junction of two different theories, but the macroscopic case is used as a 'bootstrap' for constructing the microscopic/macroscopic bridge. Also the derivation of Navier-Stokes equation for *incompressible fluids* from Boltzmann's equation seems unlikely, in spite of remarkable progress of approximations under strong assumptions (Briant 2015).

entropy" this abstract and purely quantitative measure of biological complexity, which may thus grow with entropy. Yet, this analysis does not allow to *deduce* the principles of biological evolution, that is Darwin's "reproduction with variation" and "selection" in changing (heterogeneous) phase spaces, nor other robust theories in biology, such as "cell theory", away from spontaneous generation, and physiology, that are better framed in evolutionary and organismal approaches (such as Gould 2002; West-Eberhard 2003; Mossio & Montévil 2015; Soto & Longo 2016).

3. The singularity of physics in the sciences of nature

In the title of Bailly & Longo (2011), we mentioned the "physical singularity" of life phenomena. This idea is not thematized in the book, except in the informal sense of the specificity or historicity of organisms as also hinted here. Shouldn't we better reverse that evocative wording and see, conversely and more precisely, inert matter as a "singularity" of an ambitious global theoretical frame? When restricting the focus from living to inert matter, we drastically reduce the number and nature of pertinent observables: typically, the Darwinian organisms and phenotypes "go to 0". By a wild analogy, note that Euclidean geometry is Riemannian geometry at curvature 0, it is thus a "singularity" of the general Riemannian frame (one point-value, 0, in the range of all possible curvatures).

In other words, since physics and its theories are strongly needed in biology, they must be part of it. Thus, biology should be seen as an *extension* of physical theories, as it deals with more observables: biological functions, phenotypes, organisms … which do not belong to the language of physics. Can then the logico-mathematical notion of "conservative extension"[4] help to consistently *embed* physical theorizing into the biological?

A mathematical guideline may be provided by the work in Sarti et al. (2019). The invention of mathematical physics, in pre-given phase spaces, is based on differential analysis (Newton) under homogeneous constraints (fixed dynamical equations in pre-given spaces). Mathematically, the extension to historical dynamics may be described by moving to heterogeneous differential constraints, that is to changing differential constraints and, thus, changing dynamical equations. In short, interacting differential operators, in Sarti et al's

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[4] An extension T' of a theory T by new notions and axioms (properties), is *conservative* when T' proves no new theorem that may be stated in the language of T. In Mathematical Logic, this is not a minor issue: Gödel's incompleteness theorem, a milestone of the century, can be restated by observing that Set Theory, with an axiom of infinity, is a non-conservative extension of Arithmetics; that is, Set Theory proves extra theorems of *Arithmetics*, such as Gödel's undecidable statement (Longo 2018i), and a lot more by adding more infinities or extra principles (Longo 2011). Also without being infected by "Gödelitis", a common disease abusing of that fantastic result, these notions may informally apply to non axiomatized theories, with some extra-logical sanity (see Kreisel 1984). That is, they may provide a guideline for theoretical thinking, with no need for the exact rigor of Logic and axiomatized theories. In Miquel (2011), biology as an extended physics is also considered, along the lines of the notion of "extended criticality" (in Bailly & Longo 2008; Longo & Montévil 2014).

calculus, engender new differential constraints and phase spaces. The extension conserves the role of the differential analysis; does it conserve the latter also in the technical sense of "not proving more theorems" for the homogeneous case? It is likely to be so: the alternative answer (proving more theorems) would be, though, an amazing result, an analogue, in the much more explored field, as for provability, of the "concrete incompleteness" theorems for Arithmetic (Longo 2011). That is, the heterogeneous case would allow to prove so far unprovable new theorems of classical Analysis …. By continuing our wild (and provocative) analogy, if one adds infinite sets or curving spaces, then one moves from Arithmetic to Set Theory or from Euclidean to Riemannian manifolds. In these cases though, it is known exactly which new observables and properties to add; when canceled, one goes back to the singularity of Arithmetic (Set Theory with no infinite sets) and of Euclid's geometry (Riemann's geometry with no curving spaces). The conservativity of these extensions can be soundly analyzed, by a non obvious negative answer (Gödel as for Arithmetic, see footnote) and a positive one (Geometry). Either result would be very interesting as for heterogenesis vs. known physical dynamics in fixed phase spaces.

Note that we just posit the theoretical problem of the (non-)conservativity of compatible extensions of physics, as the actual difficulties lie first within physics itself. The lack of unity of quantum and classical/relativistic fields or the ongoing, but far from accomplished, work in unifying hydrodynamics or even chemistry with quantum physics (Chibbaro et al. 2015), has not (yet) allowed for the development of unified approaches (see Longo 2016) for a review. That is, of which theory in physics, precisely, should biology be an extension dealing with biological functions, Darwinian phenotypes and organisms? In a cell, there are plenty of quantum, and classical effects, as well as effects proper to water, including of quantum origin (Del Giudice et al. 1983; Cortini et al. 2016); they superpose and have consequences on phenotypes (Buiatti & Longo 2013). Their analysis, though needed, is essentially incomplete with regard to the theory of onto-philogenesis of organisms we work at, see (Montévil & Mossio 2015; Soto & Longo 2016; Longo 2017). We will go back to the mathematical proposal in Sarti et al. (2019), after discussing the theological commitments that ground the invention of pre-given universes of all possible dynamics.

In summary, several theories in physics contribute to the understanding of life. Instead, there is no need, in principle, to talk of cells, organs, organisms and functions in order to investigate interacting physical particles, falling bodies, and stars.[5] So, if we will ever get to a "unified theory" or "theory of everything", physics should be seen as a singularity of that

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[5] Quantum Physics though may pose a challenge here. Its objects or observable values are co-constructed at measurement. If this is viewed as an act of a living observer, the embedding of theories would no longer be conservative: properties of life would contribute to establish properties of the inert. What matters though is the interaction of a classical measurement instrument with the quantum process: they jointly produce the "measured quantum properties". Are proper biological observables truly concerned with this interaction? Can the quantum/classical interface be objectivized independently from the measuring living agent? The debate is very lively on this matter and goes beyond our purposes.

general frame, that is as the absence of living matter. The very analysis of this embedding and of its conservative/non-conservative alternative, in relating physics to other sciences of nature, is part of what we dare to call a "naturalization" of physics.

4. A priori spaces

Greek philosophers extensively discussed about potential vs. actual infinity. The first was and is meant to be a never ending succession of numbers or an indefinite extension of lines (an "a-peiron", with no boundary or limit), the second is the *actual* limit of counting or of infinite lines, e.g. the projective point. During the (late) Middle Ages (Zellini 2005), actual infinity was accepted as a legitimate concept, actually an ontology, only in reference to the infinity of God. Then, it received its first symbolic representation in the early Annonciations of Italian renaissance (XIV century). The projective/limit point of the so called "linear perspective" was not only a "symbolic form" for the organization of the pictorial space (Panofsky 1927), but also and primarily a geometric representation of the infinite presence of God when meeting with the finiteness of the Madonna (Damisch 1987; Arasse 1999; Longo S. 2013, 2014). Theological considerations explicitly motivated the early painters, often priests and theologians, such as Ambrogio Lorenzetti (see his 1344 (!) Annonciation, below), and their commentators of the time (Arasse 1999): the actual infinity of God, preceding the existence of the Universe of matter, was *made visible* in the painting by the convergence at infinity, the "costruzione legittima" (the linear perspective).

And there was (mathematical) space. The result of a profound debate on infinity, in theological circles, made actual infinity visible by a geometric construction, which provided at once the tridimensional space for framing and allowing the new humanism of Italian Renaissance, in paintings and general knowledge. As later theorized: "since the 'locus' exists before the bodies placed in that loci, it must necessarily be placed graphically first" (Gauricus, *De sculptura*, 1504, quoted in De Risi 2012). Thus, the a priori role of the mathematical space, as preceding and framing the very existence of matter, to be later placed in it – by God, the painter or the scientist.

Since Descartes, Desargues and Newton, modern physics mathematized and made a fundamental use of this approach – even though not everybody agreed.[6] Of course, there is nothing wrong in the theological origin of a scientific concept, the point is to be aware of this and not to consider a historical construction as an absolute – as this would be actual mysticism. At these regards, H. Weyl observes that we have lost, in science, the productive marriage with religion of Greek times. He could not be aware though of H. Damisch and D. Arasse's stress on the mathematical power of theology (it is clear that A. Lorenzetti was also a very creative geometer) that contributed to the birth of the modern science of space (Longo 2019).

Many consider Einstein's relativity as a break with this dualistic approach, the separation of the container from the contained. However, Koyré (1925) observes:

> the theory of relativity does not destroy the idea of unique time and space: on the contrary, it presupposes them at every step and cannot be thought and understood otherwise. The theory of relativity [...] is a profoundly absolutist theory, it is the completion and direct heir to the Cartesian doctrine of the absolute value of spatial measurements. (quoted in Ruffin-Bayardin 2019)

This remark can be made more precise in the light of Einstein's 1935 work. The presence of matter shapes relativistic spaces, in the precise sense that the energy-momentum tensor is strictly correlated to (it gives) the space curvature, thus to the metric of space (by Gauss-Riemann "theorema egregium"). So, it is not exact to say that *spatial measurements* in Relativity are an absolute or are independent of the inhabiting matter, since the metric relations depend on the distribution of matter or, equivalently, of energy and momentum, and ground spatial measurements. Yet, Einstein's approach consistently refers to a priori (or underlying or absolute) Riemannian manifolds as for its dimensions and *topology.* In particular, the proof of the "inconsistency or incompleteness" of quantum mechanics, given in (Einstein et al 1935), the well-known EPR argument, is based on the (implicit) assumption of the

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[6] For Leibniz, space and time are the order of possible existences, in space simultaneously, in time successively. That is, space and time are derived entities whose relational foundation is ontologically subordinated to things and their states (Anfray 2007).

absolute *topological* separability[7] of any pair of different events in the quantum phase space, (Longo 2018i). So, the metrics is relativistic and depends on the presence of matter or energy, yet the (separated) space and phase space topology of quantum observables is independent from the material dynamics. Since, in a sufficiently separated topology, the dimension is a topological invariant (Alexandroff & Hopf 1972), then the Riemannian manifold and the intended extension to a phase space, both for their dimensions and topology, are considered an a priori of knowledge construction (or an absolute, if one assumes an ontological perspective) also in General Relativity Theory.[8]

It should be clear that the invention of infinite mathematical spaces, since early Renaissance paintings, is one of the major achievements of western science. Its effectiveness as for organizing knowledge by rigorous a priori constructions of a phase space makes no doubt: just consider the fantastic use (actually, invention) of Hilbert spaces in order to make mathematically intelligible quantum dynamics as trajectories of probability amplitudes (Schrödinger equation in Hilbert spaces, Sobrino 1996). We are just stressing the powerful cognitive tracks as well as the bias this approach has been positing for science. Note that, since the proof of the irrationality of $\sqrt{2}$, singling out the limits of knowledge constructions has been a way to better specify existing knowledge and/or invent new science. As summarized in (Longo 2018i), this was the case for Poincaré's geometry of dynamical systems, invented on the grounds of his "negative result" in classical mechanics, and the incomplete-ness of formal systems, by Gödel, Church, and Turing in the '30s, that started Computability, Proof Theory and Programming Theory. These results radically departed from mechanistic-linear and formal views of physics and mathematics as step-wise construction of the actual on pre-given potentialities. Yet, we have to go further and analyze the very formation of the space of possibilities.

An analysis of the a priori in existing theories may help to transfer to other sciences, such as biology, the creative physico-mathematical methods, more than the theories. Indeed, a focus on the bias due to pre-given phase spaces already opened the way to new tools for investigation, such as the work on differential heterogenesis in Sarti et al. (2019). Sarti et al.'s interacting differential operators dynamically construct the phase space and are, at last, a truly new mathematical idea inspired by historical sciences, such as biology and semiotics. Moving back and forwards with regards to existing physical theories, by restricting, when

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[7] A "separated (Hausdorff) space" is a topological space where for any two distinct points there exists a neighborhood of each that is disjoint from the neighborhood of the other. Of course, different metrics may yield the same topology.

[8] Poincaré (1902) dared to break also with these a priori, but did not turn his remarks into mathematics: "Beings that would experience our normal sensations in an abnormal order, would create a different geometry from ours" - a divination, if one thinks to Non-commutative Geometry (Connes 1994). He also claims that, in order to evaluate the distance of a body, we imagine the movement necessary to reach it. More importantly for us as it goes beyond the metrics, he suggested that an immobile being could take the movements of other bodies for changes of state. That is, with no reference to a metrics, a sufficiently separated topology allows to distinguish different points, either as movement or, claims Poincaré, as different states. In our words, the mathematical construction of space follows from and depends on action.

needed, heterogeneity to homogeneity, a singularity of heterogeneity as hinted below, may help in naturalizing them - and deal, perhaps, even with the changing phase spaces of Cosmology.

5. Randomness and time

> *The further we go from physics to the worlds of biology, psychology, linguistics, economics, ... the more we lose symmetry – the use of classical probabilistic concepts in heterogeneous environments becomes problematic.*
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> M. Gromov, Bernoully Lecture, March 27, 2018.

Randomness is a matter of time or, better, it can be defined only in time. Randomness is unpredictability with regard to the intended theory (Calude & Longo 2016), where being able to predict or not implies a judgment in time.[9] It differs in classical vs. quantum frames, as mathematics and experiments consistently prove (the violation of Bell probabilistic inequalities, empirically corroborated in the presence of "entanglement", Aspect et al. 1982). Since Poincaré, the classical unpredictability of non-linear systems is fully understood: it is due to the classical limits of measurement, always an interval, and the non-linearity of the intended dynamics. Then, a fluctuation below the best possible measurement may be non-linearly amplified, in time, by a bifurcation or along a homoclinic trajectory (at the intersection of stable and unstable manifolds), by positive Lyapunov exponents, etc. (Devaney 1989). Then "we have a random phenomenon" (Poincaré 1902). Quantum randomness instead begins at measurement (Heisenberg indetermination); it is elegantly treated by Schrödinger's equation, a dynamics of a law (an amplitude) of probability; it pops out at entanglement, since distant measurements show non-classical probability correlations.

Yet, physics shows again its principial unity by a tight correspondence, in all theories, of random events and local irreversibility of time. These phenomena co-exist and imply a symmetry breaking, as one may show by closely looking at existing theoretical frames (Longo & Montévil 2017). Moreover, the pre-given phase space, as a space of all possibilities, allows a probability measure to be given to randomness, by Lebesgue measure for example, even in infinite dimensional Hilbert spaces. Thus, from Laplace (1820) to Kolmogorov (1932), randomness is "what is measured by probabilities". Random means then unpredictable, but "not too much" (Mugur-Schachter & Longo 2014): all future events are part of Aristotle's

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[9] Algorithmic Information Theory allows to compare and unify asymptotically (for infinite sequences) the various forms of randomness in physical theories (see Calude & Longo 2016). Incompressibility for finite strings of numbers, a very important practical notion in times of immense data bases, does not define randomness, since any sufficiently long finite string is compressible (Calude & Longo 2017).

potentialities and their "becoming actual" may be given in probabilities. Heterogeneous dynamics thus pose a problem, since an unpredictable novelty, in biological evolution for example, may break yet another fundamental symmetry: the conservation of the phase space (see Longo 2017 for a theoretical reflection in these terms, and Gould 2002; West-Eberhard 2003 for examples). Thus, no probability measure is possible in the phase space of evolution. As Gromov stresses (in exergue), this applies to all historical sciences, including economics (Koppl et al. 2015).

R. Thom, in two papers in Amsterdamski (1990), beautifully summarizes the traditional view in physics, enriched by an explicit Platonist philosophy of mathematics: the mathematical phase space pre-exists the randomness ("noise") affecting the system (Thom 1990: 270), thus "the bifurcation pre-exists the fluctuation" (see above as for this notion due to Poincaré). In Biological Evolution, as for Darwin's observables, we should dare to say instead:*"the fluctuation co-constitutes the bifurcation"*. Or, more specifically, the ecosystem is constructed by co-evolving species and their niches, by motility and reproduction with variation; it yields or *enables* (Longo et al. 2012) interactions and changes, at all and among all levels of organization.

A distinction can then be made between processual time and historical time (Longo 2017). Far from equilibrium dynamical processes, such as hurricanes, flames, micelles… , have an irreversible time, but they have been the same type for the last 4 billion years and they may be treated by exactly the same mathematics. In particular, the path and the deformations of a hurricane may be given in probabilities. Meanwhile, over the same duration, life somewhat changed and different tools of analysis are required: bacteria are not a good biological "model" for the mathematics nor for a laboratory working on morphogenesis in mammals, say. Probabilities are of little help in predicting future phenotypes. Again, this may help to distinguish also the (thermodynamical) time of the processes of formation of a star or a planet (they are restricted to of a few possible types) and cosmological time, where novelties continually pop out. These two forms of time may be represented in two different dimensions by the approach proposed in Sarti et al. (2019). Moreover, physical frequencies, in the dimension of thermodynamical time, should not be confused with biological *rhythms* – internal ones, such as heart beats and respiration (Günther & Morgado 2005), and ecosystemic correlated rhythms and frequencies (Longo 2020). Thus, we have added a further dimension for the representation of biological rhythms (Bailly et al. 2011; Longo & Montévil 2014: ch. 3), inspired by the Kaluza-Klein method in physics for unifying gravitation and electromagnetism. Altogether, by adding Sarti et al's approach and our, one thus obtains a three-dimensional "geometric schema" for biological time, in the Kantian sense hinted in Longo & Perret (2017). A collapse of two of these three dimensions brings us back to physical (thermodynamical) time, an (oriented) line, thus a singularity of the tridimensional time manifold of biology.

As for the notion of "collapse" and the relevance of increasing symmetries, when moving from biology to physics, there is a remarkable convergence between the mathematical approach in Sarti et al. (2019) and the analysis of empirical measurement in biology, developed in Montévil (2019). On the mathematical side, a classical differential dynamics is the fully "symmetrized collapse" of a differential heterogenesis, in Sarti's words. That is, the former works in stable (invariant, symmetric) phase spaces as well as under space-time homogeneous differential constraints. Similarly, the challenge of preparation of experiments and measurement on phenotypes and organisms is due to the difficulty of "symmetrizing", in Montévil's words, the experimental conditions (same phylogenesis, stable environmental conditions, no undesired, nor spontaneous variations …). This requires an analysis of the phylo-ontogenetic history of the intended organism or phenotype and then imposing constraints, as homogeneous as possible.[10] Thus, measurement in physics may be described as the fully symmetrized collapse of this empirical praxis in biology, as experimental conditions in physics are, or may easily be, stabilized (symmetrized), once a good theoretical framework is found: no individual conditions nor ontogenetic and historical times, in principle, and constraints are identified with contour conditions – otherwise the physicist may learn from the biologist, one of our goals here (in Cosmology, as for history?). In other words, the artificial conditions that are needed in a laboratory, in order to control and make the experiments reproducible, are based on a sound but imposed symmetrization, which is a way to depart from the "natural" conditions – once more, in biology, physicalize or symmetrize may mean "moving away from nature". In conclusion, the analyses in Sarti et al. (2019) and Montévil (2019; 2020) provide a mathematical and an empirical frame, respectively, for dealing with the onto- and philo-genetic historicity and novelty production of life. Of course, the symmetrized collapse is the inverse of the (non-)conservative embedding problem, mentioned in section 3. An analysis of the two directions constitute our way to frame the theories of the inert in a broader natural context.

6. Temporalize (phase) spaces, by way of conclusion

In the move from physics to biology, one should first exclude considering the preferred *Relativistic* or Quantum Theories of time as … an *absolute*, as it is too often done: theories of time are instead relative to specific scales or phenomenal levels. Their transfer beyond the intended phenomena does help not in setting bridges towards other (historical) sciences of nature, as we tried in Longo (2020) in reference to the (sequels of) Bergson-Einstein debate on time. Note that physics has been successfully parametrizing dynamics in time, a major

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[10] For example, "The basal metabolic rate (BMR) considers organisms at rest, that is to say, undisturbed, non-sleeping organisms in a thermoneutral environment and in a post-absorptive state" (Montévil 2019). A forced "symmetrization" which allows comparisons of measurements and repeatability of experiments; field and maximum metabolic rates are also definable, but relevantly differ from BMR as for values and stabilized experimental conditions.

idea in Galileo's analysis of movement. Then, from Newton to Einstein and Schrödinger, the time parameter has been treated by the same tools as space, in particular as a Cantorian continuum, a line "seen" in space. In Minkowski's relativistic spaces (1908), but in current views of time as well, the time line is "there", in the mind of a mathematician or physicist, like a line in space. This is the reason for the discontent beautifully expressed by Weyl, a major mathematician of Relativity and Quantum Theories, in Das Kontinuum (1918): the point-wise, continuous and spatialized line representation of time is conceptually remote from phenomenal time.

More recent distortions are due to the very useful computational tools used in physics both for modeling and simulated "experiments". The impossibility or cost of actual experiments too often encourages research programs to replace "nature" by computer screens. Once I had the occasion to appreciate the extraordinary simulation of a turbulence implemented by a young physicist. The most wild non-linear dynamics were unfolding under our eyes as in no other way they could ever be experienced. I then asked to the modeler: push the restart button. At his surprise, the chaotic dynamic iterated identically, a physical nonsense. The discrete, pixel by pixel, nature of the data base allowed this miracle, iteratable at leisure. Space and time were replaced by pixels and by the clock of the computer, even in the imagination of the scientist.

As for time, in two books and in several (downloadable) papers with Bailly and Montévil, we developed a theory of biological time, summarized in Longo (2020), well distinguished from both the "time of physicists" and the "time of philosophers", the latter mostly an analysis of psychological time. These two forms of time are at the core of the debate that issued from the revolutionary views of time in Relativity Theory, since McTaggart (1908). The time of phylogenesis requires a third form of analysis, that is an independent, autonomous representation, marked by changing phase spaces and rare events, as hinted above. Similarly, in ontogenesis, biological rhythms differ from physical frequencies. If we generalize space to phase space, it is then the phase space that is temporalized, in our approach. That is, the biologically pertinent phase spaces (organisms, phenotypes, ecosystems ... with their organization in and of space) are the result of a historical (and material) evolution. Of course, when dropping history and rhythms, one goes back to an invariant, pre-given phase space, with all its symmetries and only a processual time parameter.[11]

Yet, the collapse from the living to the inert state of matter is far from obvious, as it may also require complex dualities, as already hinted in relation to the inversion "generic" vs. "specific", that may constructively relate the two forms of theorizing (see end of sect. 1). In Bailly & Longo (2009; see also Longo & Montévil 2014: ch. 9), the time of evolution is technically described as an operator, while energy (or mass) is a parameter, in accordance with

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[11] If observable quantities are conserved, Noether's theorems force the symmetries of the observables, thus of the phase space. Then, symmetries as conservation properties, allow to derive the dynamics (by the Hamil-tonian, typically) and classical morphogenesis in particular. But if the pertinent observables are not conserved (changing phenotypes, say), one has a more general case, a differential heterogenesis (Sarti et al. 2019).

the allometric equations (the possibility to parametrize several biological properties, for example on the individual mass; Günther & Morgado 2005). This may suggest a fruitful duality, to be explored, possibly in collaboration with a quantum physicist: a well-known theorem, due to Pauli, roughly states that, if energy is an operator, bounded from below (as it is the case in physics), then time cannot be an operator and is, instead, a parameter. In biology, both ontogenetic and phylogenetic time are bounded from below, as organisms, species and life have an origin. Then their operatorial representation may fit with or, perhaps, even entail the understanding of energy or mass as a parameter in biology.

The sound embedding in the more general biological/historical heterogenesis, of these and other notions invented by the powerful mathematics and physics of homogeneous frames, based on strong metaphysical claims such as static theological universes, is part of what we dare to call a naturalization of physics.

Acknowledgment. The collaborations and exchanges with Maël Montévil, Alessandro Sarti and the "Organisms" team constructed the conceptual phase space and the conditions of possibility for this work.

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