

Emergence vs Novelty Production in Physics vs Biology¹

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Summary

Several notions of “emergence” have been proposed in physics. They mostly concern the emergence of new structures and forms (*morphogenesis*). From Turing and Thom’s analysis of morphogenesis to self-organization in far from equilibrium thermodynamics and Parisi’s networks, several types of emerging phenomena in complex systems will be recalled. Then the difference will be stressed with “novelty production” in biology, a very different notion that may be described in terms of “anti-entropy”, a different concept from negentropy. In Darwinian evolution, in particular, the conceptual (and possibly mathematical) frames require the construction of new perspectives, due to the nature of the intended observables and their historical specificity. The issue of “unification” with the many theories of inert matter involved in the understanding of biology will be hinted, by setting bridges and proposing conceptual dualities.

Part I, Physics

I.1 - Classical morphogenesis

Turing (1952) proposed an early mathematical model of *morphogenesis*: an action/reaction/diffusion system of chemical reactants, till now used to analyze some forms of inert matter produced by living systems (stripes on furs, shells...). Turing’s approach preceded the empirical observation by Belousov and Zhabotinsky (acknowledge only by 1961) of a class of reactions in non-equilibrium thermodynamics, resulting in a non-linear chemical oscillator, producing regular forms. Turing’s approach was enriched by the work by R. Thom and others - see (J. Petitot, 2017) for a survey and recent applications. In either case the phase space (the ensemble of pertinent observables and parameters) of emerging forms is mathematically pre-given. Yet, in Thom’s mathematics, the dynamics may change dramatically: his notion of “catastrophes” further specifies and enriches Turing’s notion of “breakings of symmetry”, due to “catastrophic instability”, in Turing’s words, that results “in the amplitude becoming infinite in a finite time” (Turing, 1952). In either case, unpredictable forms may then arise from a deterministic dynamics, yet the new observed forms are fully understood in the terms of the underlying dynamics.

These approaches derive from the 1892 Poincaré’s analysis of the Three Body Problem of unpredictable non-linear dynamics, pursued only by a few till Turing’s 1952 pioneering paper. However, not all non-linear dynamics yield “forms”². That is, two planets around the Sun (Poincaré’s problem), a double pendulum, or even rolling dice, may be described in terms of an

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unpredictable deterministic non-linear dynamics, possibly chaotic, a precise mathematical notion (Devaney, 1989; Laskar, 1994). Yet, they do not need to produce new forms, like Turing's stripes or Thom's singularities. Moreover, it may even happen that also linear dynamics may be unable to predict the physical phenomenon they are supposed to model. The "missing" parameters or the "effective number of degree of freedom" may matter more than the absence of non-linearity and the actual physical process and its equational determination may quickly differ or diverge, at least exponentially (Cecconi et al, 2012; Chibarro et al, 2015; see (Longo, 2016) for a review) – yet another kind of unpredictability with no unexpected, emerging forms, in general. In short, emergent phenomena in non-linear morphogenesis may be unpredictable, but many unpredictable dynamics, modeled by non-linear (and linear) mathematics, do not yield forms. In some cases, the emerging forms and structures are fully understood in the terms of the dynamics of the elementary components, the so called lower level of determination, by non-trivial theoretical frames; in other cases, to be discussed next, one needs even more radical theoretical inventions to deal with them.

I.2 - Asymptotic constructions

Boltzmann brought mathematical infinity into the game. The ergodic principle and the thermodynamic limit allow to derive *asymptotically* macroscopic properties (temperature, the second principle of Thermodynamics...), i.e. for numbers of particles tending to infinity. In this case, the emergence of these properties is understood, like in the equilibrium systems for morphogenesis above, in terms of the elementary and simple components of the dynamics – gas particles typically. The intelligibility of the emerging properties though requires an infinitary conceptual step.

Hurricanes, flames, Bernard cells ... are other examples of physical structures produced in non-equilibrium thermodynamic systems: they emerge spontaneously and, under certain conditions, they are a necessary result of the initial and contour conditions and of spontaneous symmetry breakings or small perturbations. They present emerging or *self-organized* observable forms, a result understood as dissipative structures in thermodynamics (Nicolis, Prigogine, 1977).

Both equilibrium and non-equilibrium systems may present critical phase transitions: Turing and Thom's shapes, snow flakes, flames, ferro-paramagnetic transition ... As summarized in (Bailly, Longo, 2006), for some values of the control parameters (e. g., temperature), these phenomena display a mathematical discontinuity or divergence of the evolution function or of its derivatives (phase transitions such as the freezing of liquids). This yields progressive transitions from ordered to disordered states (as in paramagnetism and ferromagnetism) and qualitative change in their dynamical regimes (such as bifurcations of phase-space trajectories or transitions from cyclic to chaotic behavior). Some of these examples are mathematically treated by renormalization methods first developed in Quantum Electrodynamics (Biney et al, 1992). These methods also deal with infinity, which is used, mathematically, when altering values of calculated quantities in order to compensate for effects of their self-interactions. The emerging structures are thus understood in terms of their components, possibly by using an asymptotic construction.

The hydrodynamics of incompressible fluids, in continua, still resists these, even infinitary, forms of reduction as emergence. No way, so far, to understand the theories dealing with incompressible fluids, water typically, by an analysis of their elementary components, molecules or atoms say (Chibarro et al., 2015): the phenomena dealt by hydrodynamics of these fluids, do not emerge from those analyzed by statistical physics or quantum mechanics. Partial bridges are proposed and the search for a new, unifying theory is the most promising direction. It is then

²Non-linearity, in mathematics, usually represents many bodies' interactions. In many case, like those studied by Poincaré (two planets and the Sun moving in interacting gravitational fields), almost never the linear approximation of the system of non-linear equations is possible - Poincaré's far from trivial "negative result" (Charpentier, 2006; Longo, 2018). Note that linearity represents mathematically that a (possibly complex) whole is the sum of simple components.

unsuitable to say, so far, that incompressibility in hydrodynamics “emerges” from molecular interactions, as we have no theory describing this emergence and only a suitable theory for incompressible fluids in continua can describe incompressible dynamics and the peculiar structure of its consequences (waves, currents...). That is, no theory describes the transition from particles to these hydrodynamical phenomena as “emergent” from their elementary and simple components, even not by infinitary tools. Thus the transition is *from one theory to another*, each at the pertinent scale. The latter may be mathematically given, typically, by Navier–Stokes equations for incompressible fluids.

I.3 - Search for unity

In all the cases mentioned above, except for the last one, that is the hydrodynamics of incompressible fluids, a peculiar form of reduction, as we said, allows intelligibility: a global dynamics, at a certain scale, is understood in terms of the elementary, possibly simple, components, as “emerging” (or “self-organizing”) from their lower scale. Yet, this reduction is far from obvious. From Turing and Thom’s analyses, to Boltzmann audacious asymptotic construction, a brand new theory, and its mathematics, has been invented in order to provide intelligibility. That is, some visible forms and the dynamics of their elementary components were understood jointly (unified) by proposing a new theory (Poincaré, Turing, Thom, Prigogine... renormalization theories etc). In a sense, in physics, “reduction”, if any, is the result of the invention of a new theory that allows to deal with both the “elementary” scale and the intended “larger” scale of emerging phenomena.

An even more explicit unification may be seen in the work by Newton, Maxwell and Einstein. For Galileo, falling apples and moving planets were totally unrelated phenomena. Newton unified them by a brand new theory and its mathematics. Maxwell unified optics, magnetism and electric phenomena by further mathematical inventions. We mentioned the asymptotic, very original, construction by Boltzmann – also in this case it is hard to say that he practiced a reductionist approach: besides inventing a modern atomistic theory of heat, he asymptotically unified, more than reducing, thermodynamics phenomena and molecular dynamics. Einstein unified gravitation and inertia, he did not “reduce” one to the other – or he did so at the price of re-inventing space-time. Nor physicists try to reduce the relativistic or classical fields to the quantum field: they search for a novel unifying theory – an open question since a century, also because these theories are not just different, but incompatible (Macías, Camacho, 2008). Yet, following (Bailly, Longo, 2006), one should mention the (pre-quantum) unification of electromagnetism (governed by the Lorentz-Poincaré group) and gravitation (governed by the group of diffeomorphisms of General Relativity). Non-commutative geometry (Connes, 1994) has been proposed in reference to the non-commutativity of quantum measurements: for the purposes a unification via mathematics, it is based on geometric structures removed from the ones directly suggested by the world of senses and from non-euclidean geometries. More recent theories introduce new symmetries (super-symmetries or symmetries of spacetime structure in a generalized sense, associated with the notion of super-space) allowing the articulation within a common framework of the external and internal spaces of quantum systems – for references and further work, see (Rovelli, 2004). From an epistemological standpoint, the unifying aspect of these theories is that they lead to the construction of unfamiliar spaces whose physical relevance is or should be corroborated by experimental investigation.

I.4 - More on physical emergence: networks

Emergence has been thus understood in physics in different and very rich theoretical frames, broadly described as “theories of complex systems”. Unification of different scales by new theories has been another methodological tool.

A recent approach refers to the peculiar complex nets of interactions known as “spin glasses” theories (Parisi et al., 1987; here is an image of a typical network “a la Parisi”). This approach analyzes the coupling between different spins that can be more or less intense - attractive or repulsive - depending on the material and the distance that separates them. They are modeled statistically as Ising spins (plus or minus one) coupled by random constants representing disorder. These constants evolve slowly as impurities diffuse and the spin glass changes in time - their couplings are then called frozen, or time-independent (quenched). The couplings force the behavior of each element or node in the network according to the state of the neighboring elements.



Parisi showed how these interactions may lead to self-organizing forms, in physics and, most surprisingly, that they may model some animals’ collective behavior. So, the peculiar dynamics of flocks of birds and school of fishes may be described in the mathematical terms of networks of spin glasses. These networks constitute then emergent collective behaviors and yield many possible dynamic equilibria. In short, the mathematical analysis is based on “rugged landscapes”, so that minor fluctuations of one or a few elementary components of the network may lead to very different global trajectories. Landscapes or the space of all possible landscapes are mathematically pre-given or pre-conceived.

A more classical approach to similar structures is *Graph Theory*, in particular random graphs (Janson, Rucinski, 2000). These have been extensively developed with relevant advances in recent years. The analyses are largely based on optimality techniques (optimized trade-off, maximal coupling...) and allow to describe critical transitions and other “emerging” structures in terms of scaling laws (van der Hofstad, 2016). The applications range from the analysis and administration of internet networks to recent AI applications that are based on statistical analyses and optimality methods on very large finite graphs (in Large Language Models, ChatGPT for example). Of course, the emergent phenomena have the usual physico-mathematical nature analyzed in this Part and follow “optimal” paths, enriched by some statistics (e.g. use the connection given by the highest probabilities), in huge and pre-given phase spaces. The paths and the results may be highly unpredictable, as most emerging phenomena in physics, from the ones hinted above to the forms of clouds or hurricanes and flames (the self-organizing far from equilibrium phenomena that we already mentioned). By the arguments below and in Part II we will stress the difference between the unpredictability in the many emergent phenomena described in the inert and the production of novelty in the living state of matter (and, indirectly, provide hints in cognition and in historical sciences).

I.5 - Pre-given phase or state spaces

More generally, in all the previous examples, once the level of emergent phenomena is identified, both the phase or state spaces of the elementary dynamics and that of the global level of the new forms or structures are mathematically pre-supposed or pre-given. From the possible forms in Turing and Thom, to Parisi’s rugged landscapes, the global dynamics take place in a pre-described

space of all possible trajectories – that is, the set of all possible emerging observables and the intended parameters are mathematically pre-given, in the most general sense. Thus, the unpredictability of the trajectory is given within a (possibly huge) space of possibilities. The infinity of all possible trajectories and of their spaces is not a problem, in mathematics - the point is to be able to describe it, a priori. The infinite phase space may even have an infinite number of dimensions, like some Hilbert spaces used for Schrödinger equation – this is not a problem, mathematically. It suffices that also the infinite and/or infinite dimensional space has enough symmetries, like the Hilbert spaces, to be definable, a priori, by a finite number of formal properties or axioms and definitions (a finite writing).

I.6 - Genericity and specificity

Before moving to biology, let's stress the fundamental common properties of *all* the very different forms of emergence or self-organization surveyed so far. On the one hand, the elementary components, whose dynamics underlies/justifies/causes... the emergent global forms and structures, are all *generic*, that is they are identical and interchangeable. This is fundamental symmetry property of all the systems mentioned above: molecules, atoms ... even birds and fishes in the last example, are or are considered in terms of this key symmetry – they are identical, interchangeable or “generic” as we say in (Bailly, Longo, 2006; Longo, Montévil, 2014). The novelty emerges at the intended higher scale of the observable form or structure. On the other hand, all the generalized surfaces, in one, two or three (or more) dimensions that appear in the mathematical modeling and in actual physical processes, from Turing to the landscapes and the structure of trajectories in Parisi's rugged landscapes, are “optimal” in the intended phase space. In various and different ways, extrema (minimal or maximal paths in the phase space) are mathematically searched in order to describe shapes of stripes, of hurricanes, clouds, flames... animals' flocks and schools forms. All these forms and surfaces are then *specific*, uniquely given as extremal (optimal) in the intended space, up to some probabilities, whenever statistical effects matter³.

“Downward causation”, whenever this is discussed, may modify the dynamics of some elementary and simple components, it does not modify their individual structure – at most changing spin, in spin glasses – and the elementary components remain “generic”. Even birds and fishes, for the purposes of the analysis above, are considered both all identical and “simple”, they are generic – their biology as complex organisms is irrelevant for the purposes of these analyses, a necessary simplification.

Part II, Biology

II.1 - From physics to biology

In the short survey above, we stressed that “emergent” phenomena in physics at a given scale have been made intelligible not on the grounds of existing theories of the lower scale, but by the invention of new theories and, possibly, their mathematics. These theories allowed to move between or unified different phenomenal levels or scales. Only in biology, some physicists, not all of them, and most molecular biologists think that organismal and evolutionary phenomena must be understood in terms of existing chemical-physical theories of molecules, against the entire history of modern physics, since Newton, and in spite of the fact that a cell, a tissue, an organism seem to

3 In the books by Bailly, Longo and Montévil, we observe that the objects analyzed in physics are *generic* and that their trajectories are *specific* (they are geodetics in suitable phase spaces, i.e. maximal or minimal in the intended partially ordered spaces). We stress instead the *specificity* (historicity/individuality) of the biological objects (organisms) and the *genericity* of their phylo-onto-genetic trajectories (one or a few out of are many possible ones). This is a fundamental duality of physics vs biology, see Part II. Our use of the term “generic” in physics was inspired both by the notion of generic element or state in this discipline as well as by its rigorous treatment in Type Theory, see the “Genericity Theorem” (Longo et al., 1993).

be rather peculiar observables, at their scales. As a matter of fact, the well deserved scientific hegemony of physics for four centuries is due both to its successes in the intelligibility of the inert matter and to the audacious invention of a brand new theory every few decades (and often of its new mathematics). An invention often and simply motivated by a change of scale (micro-physics vs classical and relativistic scales) and/or of observables (planets or falling apples, incompressible fluids, gas...). Each time a successful unification has been possible, it lead to a conceptual revolution, from Newton to Einstein. Yet, major conservation principles guarantee physics' fundamental unity, as "All a priori statements in physics have their origin in symmetry" writes H. Weyl, in reference to Noether's theorems and his own work, which allow to understand conservation principles (of energy, of momentum (inertia)...) in terms of symmetries (Kosman-Schwarback, 2010; Longo Montévil, 2014). But the theoretical unity must each time be reconquered, rarely or never is it obtained as a pure reduction to a presumed "lower" level. As a provocation, note that one of the difficulties for these never fully displayed theories of biological organisms as emerging from existing theories in chemical-physics is that... there is lot of water in a cell, an incompressible fluid. Perhaps, also in the general case, physics vs biology, we should better aim at a new unifying theory by an embedding of physics in theories of life, see (Longo, 2020) and below.

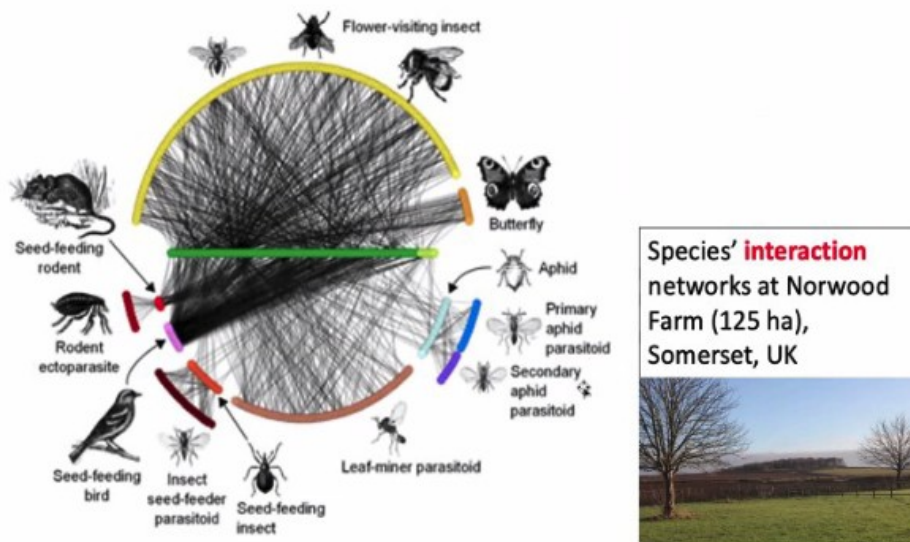
However, we must acknowledge that, in main stream molecular biology, physics is mostly replaced by ill defined theories of "information" and "genetic program" (Longo, 2019). Thus, non existing *exact* macromolecular interactions have been invented, acting like a "cartesian mechanisms... a boolean algebra" (Monod, 1970), whose perfect stereospecific interactions are "necessary" to transmit the genetic information and implement the genetic program. This was against evidence and against the statistical treatment of these interactions in chemical-physics since long (Paldi, 2020): macromolecules have huge enthalpic oscillations, interact in a brownian flow, their chemical affinities depend on the context and the stochasticity of their interactions is also enhanced by the peculiar physical state of water in small, highly compartmentalized cells (Bono et al., 2011).

II.2 - Biological networks of interactions

My theory [...] might lead to laws of change, which would then be main object of study, to guide our speculations with respect to past and future.

Charles Darwin (Barrett, 1960)

Let's consider a fundamental structure of interaction, in biology: an ecosystem. Ecosystemic networks are at the core of biological evolution, as evolutionary changes always take place in an ecosystem. Whether they are due to DNA mutations (the Neo-Darwinian thesis) or to ecosystemic interactions acting on developmental plasticity (West-Eberhard, 2003) or on epigenetic modifications (Jablonka, Lamb, 2008; Tal et al., 2010; Noble et al., 2014), in all cases, the ecosystem at least *negatively selects* (excludes) specific, changing offsprings ("hopeful monsters") or *enables* them (Longo et al., 2012), possibly leading to speciation. Evolution on Earth is a cascade of global and individual changes in more or less interacting, different ecosystems. In order to better spell out this perspective, consider the figure below (courtesy of A. Hilbeck). It represents the interaction schema of a real ecosystem, in a British farm, where 1,500 interactions of 560 taxas were closely analyzed (Pocock, 2012).



Our networks comprised **1501 quantified unique interactions between a total of 560 taxa**, comprising plants and 11 groups of animals...

Pocock et al. 2012. The robustness and restoration of a network of ecological network. *Science* 335: 973-977.

In this network, a key difference may be immediately noticed w.r.to the structure of morphogenesis, of self-organizing dynamics and of networks, mentioned in Part I. Those forms in physics emerge from the interaction of elementary and generic components. Instead, all the interacting components, the organisms in the species' interaction network, are:

- *specific*, as they are historically specified organisms, each deriving from different, though interacting evolutionary trajectories;
- their histories are possible ones, as they may be different in a different ecosystem (in this sense they are *generic*, e.g. rodents in Australia are different from rodents in Eurasia: they followed two possible, contingent evolutionary paths).

As a result, in the biological case, there are at least two types of changes, in time:

- the *emerging global forms* as *deformations* of the network (birds or pollinators may change feeding habits, say, i.e. some of the organisms with which they interact); these changes may vaguely resemble the genesis of forms in physical systems – in particular new connections may form, others may be dropped, waves of changes in the structure of connectivity may appear;
- evolutionary changes in the phylogenetic path of *individual organisms*.

This second type of changes, affecting individual evolutionary trajectories, is at the core of species' evolution. *Reproduction with variation* (and motility), the first principle in Darwin, mentioned in four out of the six first chapters of Darwin's "On the Origin of Species" (1859), introduces the fundamental cause of change in evolution: the permanent production of diversity. *Active motility* of organisms underlies Darwin's major attention to allopatric speciation - the formation of a new species due to displacement of a population to a new ecosystem. Notice that these are both "non-

conservation” principles, since, a priori for Darwin, phenotypes are not conserved and organisms actively move (they are not “inertial”) – some may have limited individual motility, by constraints. Thus, under all circumstances, species change. Even breeders, says he, cannot induce an identical reproduction in a race or strain they like, even by stabilizing at best its ecosystem⁴. The ecosystem may cause or, in any case, it canalizes, constrains and enables the changes due to reproduction and motility.

Of course, these changes of the historical specificity of individuals also induce modifications in the interactions, that is a dynamics of the network of relations, including the dynamics examined by the physics of complex systems in Part I. When, some 2 billions years ago, the endosymbiotic association of two prokaryotic cells formed a new organism, the eukaryotic cell (Margulis, 1996), or when deformations of the double jaw of some Gnathostomata gave rise to the early hears in vertebrates or when wings formed in feathered dinosaurs, the individual organisms as well as their ecosystemic interactions deeply changed. New viability niches emerged, the first by a symbiotic encounter of two different phylogenetic paths, the two others by ex-aptation or adaptation ex-post (Gould, 2002). The notion of function, for an organ, or even for a population in an ecosystem, is crucial - one may talk of “the function” of pollinators, say. In eukaryotes, the invaginated bacterium acquired a totally new function, as an organelle for energy production (mitochondria or chloroplasts), which deeply modified the existing metabolism. Bacteria remained, but a huge new niche of viability was produced – we are part of it. Note that, in biology, relevant forms are always associated to functions.

In summary, novelty production, in biology, follows from different principles and manifests itself differently from the various notions of emergence in physics: the changing historical specificity of *individual components* of a global (ecosystemic) network plays a key role, in addition to the modifications of the network itself – and one depends on the other. Since Darwin’s theory of evolution, but physiology also should be mentioned (Noble et al., 2014), suitable theories for the analysis of the emergence/production of new biological observables set the basis for implementing the methodology of physics along its history, mentioned above: invent a new theory for the intended phenomenal level - ecosystems, organisms, phenotypes... in addition to the diverse, scale dependent, theories in physics. Then try to unify, if possible. Unfortunately, we are far from a unified theory not only with any of the different or incompatible physical theories that may help to understand the physics of the cell⁵, but even within biology. Our effort (Soto et al., 2016) allowed to extend to ontogenesis part of Darwin’s approach to phylogenesis, but the internal strong functional coherence of an organism poses proper difficult challenges⁶.

II. 3 - The network of time

The ecosystemic networks above are organized in space and time. More or less implicitly, both in the examples of emergence in physics and in the discussion above on the production of novelty in biology, we have been thinking of emerging forms in space. Sometimes this forms are given in generalized spaces such as the many dimensional spaces of statistical physics, since Boltzmann, to

4 Darwin’s first principle is revolutionary at his time, since, for Lamarck, change is induced by the ecosystem. In Darwin, both causes of change are acknowledged.

5 Quantum and classical effects, in particular quantum and classical randomness, which mathematically differ (Calude, Longo, 2016), superpose in a cell, with phenotypic consequences (Buiatti, Longo, 2013). Examples of non reductionist work on physical properties that affect biological dynamics may be found in: (Bono et al., 2011), on the peculiar state of incompressible fluids in cells; in (Cortini et al., 2016), on the biological relevance of elasticity and other physical properties of DNA.

6 Our work on organisms has been also inspired by the etiology of cancer proposed in (Sonnenschein, Soto, 1999; see (Soto et al., 2016) and (Longo, 2018a) for more references). Typically, the notion of cancer, a tissular problem, hardly applies to an ecosystem, except by forcing a vague metaphor. Similarly, morphogenesis within an organism shares some features with evolutionary dynamics, such as reproduction with variation and the exploratory motility of cells, but the local and global (tissular, organismal) constraints are particularly relevant (Montévil et al., 2016).

Parisi's rugged landscapes. Similarly, one first views a biological interaction network as a spatial structure.

In the examples from physics in Part I, time may appear as irreversible in a linear dimension, the time of thermodynamics, possibly enriched by the fine analysis of relativistic and of perspectival time (Rovelli, 2019). In biology, time has a much more rich structure. As synthesized in (Longo, 2021):

The time of an ecosystem is a tissue of interacting rhythms and frequencies: when deforming these interactions or their tissue, rhythms, frequencies and their tuning change; conversely, a deformation of rhythms or frequencies and of their tuning modifies the tissue, the time of the ecosystem.

Let's spell out this view of biological time more closely. All organisms have their own rhythms. These begin with the least metabolic rhythm, as a chemical cycle; it goes to the complex circadian, cardiac and respiratory rhythms of many multicellular organisms. Here a distinction should be made. Physics imposes to life some fundamental frequencies: the day and night (circadian) frequency and the seasonal frequency, for example, are due to the rotation around and the inclination of the Earth's axis. These physical frequencies have the dimension of the inverse of time. Some of the biological rhythms are imposed by these frequencies, typically the circadian rhythms. Yet, the biological rhythms acquired, along evolution, a relative autonomy: when flying long-distance, East or West, our circadian rhythm must adjust, with pain (jet-lag), to the circadian frequency. In animals with cardiac and respiratory rhythms, these are relatively autonomous from physical frequencies – at most they slow down during sleep, also day sleep, or hibernation. Most plants instead seem to be fully subordinated to physical frequencies (day/night or seasonal light) and seasonal temperatures, but some plants may also have autonomous rhythms (Mas, Yanovsky, 2009; McLung, 2006).

Evolution produces a dynamic fine tuning of the many biological rhythms and frequencies in an ecosystem, a network of interacting clocks. Its changes contribute to evolutionary changes. For example, altered timing (heterochrony) in the expression of adaptive traits may contribute to speciation, like in the case of the 'limnetic' (shallow water) and the 'bentic' (deep water) form in the three-spined stickleback (*Gasterosteus aculeatus*), see (West-Eberhard, 2005). During the evolutionary interactions, pollinators insects (and birds) appeared while tuning their rhythms to the daily and seasonal flourishing of plants and viceversa, in a process of differentiation, adaptation and speciation both in plants and pollinators (Dilcher, 2000). This particular form of temporal coordination is dramatically highlighted by the current phenological disruption of the plant/pollinator fine tuning (Montévil, 2023), a disruption of the ecological tissue of rhythms and frequencies, allegedly due to the ongoing climate change.

Organisms use also accumulators to measure physical time. As recalled in (Longo, 2021), cicadas, which live 13 or 17 years underground before hatching, use an accumulator of the sugar absorbed from the roots of trees in order to emerge with that frequency set along evolution (Williams, Simon, 1995). In their dance, bees communicate to the others in the beehive the flying time to pollens. That time is measured by internal accumulators and rhythms, which are used also to estimate foraging time: even when the circadian frequency is experimentally disabled, foraging honeybees follow the correct interval timing, suggesting that the systems are independent, see (Foster, Kreitzman, 2004) for a broad survey and many examples.

In summary, most organisms, and all animals, have their own internal rhythms. Thus, they produce their own time, while coordinating their activities and time with the others, by reproduction with variation, motility and networks' enablement or negative selection (exclusion of the incompatible). In order to better describe these rhythms, we proposed a geometric representation of time by two dimensional schemata (Bailly et al, 2010): rhythms, in view of their autonomy, require a second mathematical time dimension and the schemata for rhythms are embedded as *spirals* in

three dimensions, for the purposes of their geometric modelling. Yet, we may need a proper third dimension for biological time, representing the historicity of life.

II.4 - The time of history

All the complex systems of thermodynamical nature mentioned in Part I are given in an irreversible time. Yet, hurricanes, flames... and all the other emerging physical forms and dynamics do not have a “history”: they are mathematically of the same type since always. Whenever possible, conservation principles allow to derive their shapes and dynamics, as optimal “surfaces” in the intended dimensions and in irreversible thermodynamical time, by the same technique and in the same mathematical phase space – that is, in principles, in the same set of observables and pertinent parameters⁷.

Life somehow changed since its early time on Earth. Radically new Darwinian observables were produced by evolution and new pertinent parameters are needed for their understanding. When audition popped-out (see the Gnathostomata above), with the corresponding organs as new observables, new parameters are needed for their observation. Ex-aptation (Gould, 2002) and overloading (Longo, 2017) are fundamental components of life’s evolution: an organ is adapted ex-post to a new function, but some may maintain their old function and be overloaded by a new one. Feathers still play the role of thermal protection, but they have an essential function as for flying: they are overloaded. Front podia of some dinosaurs were ex-apted as wings, but they do not help, in general, for walking – yet some birds use them for moving on earth as well. Our hands and brain are greatly overloaded. As F. Jacob observed, evolution proceeds by adapting a chassis of an old chair to make a radio-box. And we may add that one may conveniently sit on such a box, while listening to the radio – that’s how evolution goes.

What is highly unpredictable in these processes is the new function, not just the form. And the function, with the form, is the pertinent Darwinian observable. No combinatorial analysis of all possible forms, either in Turing’s or Thom’s or in thermodynamical dynamics may include all possible future functions. In the XVIII century, no one could insert in a space of all the possible observable functions of a chair, its possible future use as box of a radio – yet, they are both composed by a finite combinatorics of molecules, with minor changes, in this case. By his deep insight and intellectual honesty, Thom observes: “it is the lack of the definition [of the virtual possible] that affects - very seriously – the scientific nature of Darwin's Theory of Evolution.” in (Amsterdamski, 1990, p. 271). Of course, Darwin’s theory is scientific for us, yet a Darwinian analysis cannot use the same method of mathematical physics and posit a priori the phase space. We need to deal with historicity, as a dynamics of the space of the virtual possible, the phase space in our terminology. This has been suggested by many since (Longo, 2001; Kauffman, 2002; Longo et al., 2012)⁸. Today’s reading of the Einstein-Bergson 1921 debate (Longo, 2021) may show this fundamentally different perspective on time, which was part of their misunderstanding.

Beyond the differential calculus, born and used in mathematical physics since Newton, we must drop the Kantian assumption that the space (and time) of all possible trajectories, the phase space of contemporary physics, must be posited a priori by each specific theory. Typically, the current way of writing of equations in physics requires it – this motivates Thom’s remark on the non scientific nature of Darwin’s theory. In mathematical “heterogenesis” (Sarti et al., 2022), instead, an original operatorial approach allows to produce a new phase space by the encounter of diverse differential operators (“the production of diversity by diversity” as Sarti and co-authors write). This may

7 In statistical physics, the number of particles and dimensions may change, but they are both and all of the same “type”. Very High Energy physics, at temperatures higher than the Sun, seems to produce, in micro space and time, new observable particles and physical constants – a challenge close to the full understanding of the Big Bang, for contemporary physics. Perhaps, this is where a historical time is needed also in physics, with a proper dimension.

8 See (Longo, 2017; Montévil, 2022) for more recent reflections and (Sarti et al., 2022) for some new mathematics grounded on a new operatorial approach to differential calculus, where the time of history is explicitly given in a different dimension from the thermodynamical irreversible time.

provide a mathematical analogue or metaphor (the authors do not dare to say “model”) of the encounter of two prokaryotes, for example. This symbiosis produced the Eukaryotic Cell, and, thus, a totally new space of observables, parameters and possibilities: different evolutionary trajectories and their specific results merge to produce radically new observables – metabolism, biological functions Not only the global network of ecosystemic interactions deeply changed, but lots of specific organisms and their evolutionary trajectories were modified.

II. 5 - Non-optimality, resilience, non-conservative extensions

Physics is governed by mathematical optimality (extremal values in suitable phase spaces) or by statistics over generic elements. Since Hamilton, we know how to construct geodetics (optimal trajectories and structures) in pre-given phase spaces: falling apples and planets, all move along geodetics. All physical forms in Part I are optimal. Also Schrödinger’s equation, in quantum mechanics, may be derived as the trajectory of a law (an amplitude) of probability in (infinite dimensional) Hilbert spaces. Optimality makes sense in a given space with a partial ordering of its elements (“this is bigger than that”) and it may be derived from conservation principles. As already mentioned, infinity of the space, even of its dimension is not a problem in mathematics, provided that the space may be finitely described, a priori. In historical sciences, like biology, there is no way to describe a priori a non-existing phenotype. Before the evolutionary production of the ears’ structure, its form and *function* could not be pre-described, like the function as a radio box for the chassis of a chair in the XVIII century. As these structures are ex-apted from previous forms and functions, they are far from optimal: the historical constraints canalize and delimit the new forms and their functionality – like the box of a radio ex-apted from a chair, in Jacob’s example, and the “physically absurd” structure of the internal ear in large vertebrates⁹.

The absence of optimality in phenotypes and their constitutive trajectories is also due to the open nature of the changing space of the possible forms and functions: the partial ordered space where to compare and chose is not pre-given. Only breeders, Darwin’s reference example, can fix a goal and compare animals in the limited space of their farms – compare cows by their observed production of milk, say. In our perspective, we must add to Darwin’s first principle, reproduction with variation and motility, the notion of *enablement*, as the survival of what is viable and the *exclusion* of what is not viable (*negative selection* or not-enablement). In the close analysis of organs, say, physical optimality may sometimes provide a guideline for understanding, but no more than this. Consider the fractal structures of lungs and of the vascular system in large vertebrates (Bailly et al., 1989). Their fractal dimensions may be tentatively derived by maximizing the flow of a gas through a surface in a volume (lungs), or of a liquid through a volume in a volume (vascular system). This gives precise and optimal fractal dimensions, yet ... the lungs and the vascular system do not exactly implement them. The physical forces that justify the computation do not act on inert matter, fully shaped by these forces, but on cells that *first* reproduce with variation and move. Thus, their reproduction with variation, growth, shape and movement, the tissue they produce, are first the result of their activity, under the massive canalization of the physical forces, a constraint to the spatial organization of their reproduction and to motility. The result is that both systems *roughly* have the computed fractal dimension, but irregularity dominates on regularity and this is *functional*. The diversity of the fractal structure of lung’s alveoli, for example, is functional to resilience, both in an organism and in a population: changing atmospheric conditions would enable the survival of

9 An intelligent designer and programmer could do much better than the existing internal ears in large vertebrates, with an out-placed vestibular systems – in some invertebrates it is (more soundly?) related to the visual system (Bender, Frey, 2008) – but of course, this is just the contingency of a history and its constraints. As observed by Helmholtz, we should fire the designer of the vertebrates’ eyes: the nerve fibers route *before* the retina, blocking some light and creating a [blind spot](#) where the fibers pass through the retina. In cephalopod eyes, the nerve fibers route *behind* the retina, and do not block light nor disrupt the retina (https://en.wikipedia.org/wiki/Cephalopod_eye). The different phylogenetic origins and embryogenesis of eyes in relation to the brain make intelligible these different structures, far from “optimality”.

some variants, not others. And the ecosystem continually changes. If an organism had an optimal organ, in the rigorous sense of physics, and if the optimality of an organ in an organism were functional, that organism with a physically perfect organ would soon be dead, because of the ever changing ecosystemic conditions. Darwin's first principle is at the core of evolution and of *resilience* of life, as adaptation by changing. Developmental plasticity and various forms of heterogenesis, as permanent exploration of diverse, but possible, forms and functions, are a fundamental components of this process (West-Eberhard, 2005; Jablonka, Lamb, 2008).

In conclusion, a cell is not the emergence of order from molecular disorder, as in various forms of self-organizations observed in physics. These physical phenomena are grounded on symmetries and broken physical symmetries, are spontaneous and, thus, iterate their formation continually under our eyes. Instead, a cell is always from a cell. The problem of the origin of life is a red herring, when treated in terms of existing physical theory. We first need a sufficiently robust theory of organisms, then invent a new synthesis or unifying theory that would allow to relate or pass from the inert to the living state of matter. The obvious remark that inert matter preceded life and that no miracle happened, a remark I agree with, has no theoretical relevance. As for now, we can only move from a set of theories, in physics, to a different theorizing, in biology. Then try to unify, if possible.

In (Longo, 2020) the relation between existing theories of the inert and biological theorizing is conjectured to be that of a “non-conservative” extension¹⁰. That is, not only biology needs proper notions, principles and rules or laws (at least like hydrodynamics w.r.to theories of particles), but it may prove properties that may be stated in the language of one of the existing physical theories and that that theory is not be able to prove¹¹. By this, we were referring to the very complex physical-chemical processes that take place in a cell: the chemical cascades that go from DNA to RNA to proteins and the major macro-molecular networks in a cell can be described in a physical-chemical language, but no existing theory of physical type can derive nor justify them – they are perfectly absurd or with probability too close to 0 to exist. Yet, by using concepts and method from biology, they may become understandable. For some chemical processes in cells, this has been elegantly and concretely shown by (Sharma et al., 2023). By using Darwinian selection, that we articulated in enablement and exclusion of the incompatible (negative selection), Sharma and co-authors' approach opens the way to justify (and scientifically derive) the physical-chemical structure of the major macro-molecular structures and networks in a cell, by looking at their historicity as given inside evolving cells and organisms. In short, they hint to “a new physics that emerges in chemistry in which history and causal contingency through selection must start to play a prominent role in our descriptions of matter”. Sharma et al. consider their method a “unification” (“unifying key features of life with physics”), the wording we cherish since long in science, where biological historicity allows to understand how, in the chemistry of life, “interactions among existing objects and external factors lead to discovery of new objects, expanding the space of possible future objects”, in those authors words. There is no or little bottom-up emergence, but top-down canalization or constraints that make the structure and dynamics of inert matter within cells intelligible as a consequence of a historical phenomenon, biological evolution.

II. 6 - Anti-entropy production

In (Bailly, Longo, 2008; Longo, Montévil, 2012), we introduced a notion, *anti-entropy*, and a schematic measurement for *biological complexity*, originally based on counting number of tissues, dimensions in fractal structures, networks' sizes... in organisms. In these biological structures forms and functions are strictly related. Thus, anti-entropy is correlated with the formation of a multilevel,

10 In Mathematical Logic, an extension B of a theory A by proper notions and axioms (properties), is conservative when B proves *no new* theorems that may be stated in the language of A. Then B is non-conservative if it proves results that may be stated in the language of A, but unprovable in A (“new results”).

11 Gödel's incompleteness theorem may be equivalently stated by saying that Formal Number Theory, if consistent, possesses axiomatic non-conservative extensions (Longo, 2018).

integrated and regulated organization. However arbitrary and reductive its measurement may be, the approach helped to understand, by a mathematical analogy (we do not dare to call it a model), the increasing “complexity” of organisms along evolution, described in (Gould, 1996), as an asymmetric random diffusion from a left wall of “minimal” complexity (the bacteria, says Gould). The reproductive changes in individual organisms in an ecosystem may, a priori, both lead to a simplification (e.g. loosing or reducing podia when going back to the sea) or a complexification (increasing number of tissues, of fractal dimensions or size of networks, such as neural network). Yet, more complex organisms may have, in general, more chances to invent or co-constitute a new niche. We called “production of anti-entropy” these inventions. Anti-entropy differs dimensionally from negentropy, which is just entropy with a negative sign and that has been more or less abusively identified with “information” (Turing or Shannon’s notion, see (Longo, 2019)). Anti-entropy is a many dimensional-geometric notion, cf. its basic components above, while information on discrete data types is intrinsically one dimensional or its one dimensional encoding loses no information. In contrast to negentropy, it does not oppose to entropy, it actually “feeds” on entropy (Chollat-Namy, Longo, 2023), as many diffusion processes are essential to life, e.g. metabolism by diffusion in cells and organisms. Anti-entropy provides a (non-conservative) extension of physical notions, in the sense above, whose theoretical and philosophical meaning is discussed in (Miquel, 2011). In our recent work on anti-entropy, structure is more explicitly associated to biological function (and extended also to societal issues (Montévil et al. 2020)).

We can thus distinguish at least three forms of “emergence”, within three major theoretical frames. The many types of collective emergence in (mathematical) physics from large sets of generic and elementary components (from Turing’s chemicals to water particles in hurricanes and Parisi’s spin glasses...). The Theory of (molecular) Assemblies in cells proposed by (Sharma et al., 2023), a possible bridge between chemical-physics and biology. And, finally, anti-entropy production in biological processes. As for the dividing transition between the two last theories, observe that key component, actually a “segment”, of the evolutionary trajectories of multicellular organism is embryogenesis, since a phylogenetic path is the “sum” of a sequence of ontogenetic paths, including embryogenesis. Embryogenesis (re-)produces, with variation, anti-entropy not by an “assembly” of components. A child is not made by screwing in a leg, then putting fingers on top of it and eyes in holes – again, it is not an assembly of cells nor of tissues and organs. Embryogenesis begins with an organism, a unicellular zygote, a complex entity that engenders a multicellular organism by *differentiation*. At each cell reproduction, the organismal unity of the embryo is maintained while increasing the complexity of the whole. Embryogenetic differentiation radically differs both from physical emergence and from chemical assembly within evolving cells. Recall the developmental plasticity, which begins at embryogenesis, is at the core of evolution, in particular both by the individual and the global (connectivity) changes in an ecosystem – the space-time for life we started from in our analysis.

Yet another key component of biological phenomena should be recalled: inventing norms. By this, we mean the understanding of adaptivity of organisms as a non passive process that includes the deformations of the ecosystemic interactions: niches are co-constituted jointly to changes in individual phylogenetic paths and this also by the production of new rules – ranging from modes of macromolecular bindings, that depend on the context, to behavior in animals.

A comparative synthesis

In conclusion, we tried to distinguish between “emergence” in physics vs “novelty production” in biology, by a game of analogies and dualities.

Physics:

Emerging collective behaviors of generic elements, in theoretically pre-described phase spaces:

1. Many possible equilibria and/or far from equilibrium self-organizing forms and flows
2. (Spontaneous) symmetry breakings trigger emergence, in theoretical frames based on symmetry principles
3. Necessity (the emergence of unpredictable forms is qualitatively predictable, in probabilities – under certain atmospheric conditions, we expect a hurricane, even though we cannot predict exactly its forms and timing)
4. Optimality (geodesics, specific forms and dynamics)

Biology:

Anti-entropy production in phase spaces that result from evolution itself:

1. Production of new *individual* and *collective* structures in an ecosystem (changing phylogenetic trajectories of specific, historical organisms and their networks)
2. *Exploration* and *construction* of norms of interactions
3. *Coordinating* or *disrupting* spatial connectivity as well as bio-rhythms and physical time frequencies (the changing network of time in an ecosystem)
4. Not necessary (historical, contingent, highly unpredictable)
5. No optimality (genericity of the possible viable/enabled historical trajectories)

Assembly Theory (Sharma et al., 2023) may provide a bridge between these two theoretical areas, by using principles from the second in order to analyze some complex chemical-physical objects and networks of the first, when they are present in organisms. In reference to molecular structures and networks, (Sharma et al., 2023) write: “the assembly space is defined as the pathway by which a given object can be built from elementary building blocks”... its size “grows super-exponentially in the absence of any constraints”. We understand this notion of constraint in the biological sense of (Montévil, Mossio, 2015): constraints canalize, enable or exclude biological processes, while they are produced by these very processes, including the complex molecular flows and structures relevant to life. This is so, because, in a cell, molecules and their networks have a “biological function”, which depends on and affects cellular activities in a context (a tissue, an organ, an organism, an ecosystem...): thus, constraints act across all these levels, upwards and downwards, and canalize, enable or exclude also the macro-molecular dynamics.

The notion of *biological relativity* in (Noble et al., 2019) may frame this approach, when this is not understood in Galileo’s or Einstein’s sense (the invariance of laws under certain transformations of the reference system), but when it signifies the absence of a ground level (an absolute one - molecular typically) from which the others emerge and refers, instead, to the *causal relevance* of any level of organization in biological dynamics.

A side remark on cognition

The extensive use of immense data bases in recent applications of AI, such as the Large Language Models (LLM), in particular by techniques based on graphs or networks hinted in Sect. I.4, leads to highly unpredictable emergent structures. The nodes in these networks may be the result of human activities, e.g. meaningful sentences written by humans, in different contexts. In a way, then, these nodes are “specific” and “historical” in the sense above, yet the mathematics of the network

dynamics treats them as *generic* nodes, just labelled by different probabilities, thus the unpredictable “novelty” is actually an unpredictable emergent form in a graph, as in physical dynamics. Thus, “emergence” in LLM is of the same mathematical type as emergence in physics described in Part I: it uses variations of the same mathematical methods in immense networks of digital computers and data bases.

The confusion of optimization methods and probabilities in a connectivity structure (typically, based on the number of direct connections in a random graph) with “meaning”, in its human, historical, bodily... sense (Longo 2019), is a major conceptual mistake and may prevent the actual production of novelty in the potentially fantastic interaction humans/machines we may have today. The human “ex-aptation” or “overloading” of concepts or linguistic practices, their “metaphorical transfer” into new ones, or their radical invention, are theoretically remote from the new sentence added on the grounds of maximality or probabilistic criteria (the largest numbers of connections, the shortest paths to reach it in a graph... with some stochasticity added on top). These criteria force averages or emergence in conformity to mean fields (and “common sense”), the opposite of the human invention of “new points of view or new forms of sense”, of our “taking a risk” by inventing new meanings. In a sense, we do this every day or whenever facing a new situation in changing historical contexts and ecosystems. Let me just recall some major “productions of scientific novelty”, such as assuming the perspective of the Sun to analyze the Solar system (in no way this may be deduced from the “data”, see (Longo 2023)), writing radically new equations and their geometric (Newton) or algebraic (Leibniz) calculus that unify falling bodies and planets’ movement, assuming curving spaces to understand gravitation and inertia at once... just to mention a few theoretical inventions rich of history and sense and proposed against average thinking and common sense. These risky inventions were later followed by major changes also in the meaning of their linguistic expressions, by the invention, say, of Differential Geometry. The production of conceptual novelty, including new perspectives in organizing reality around us (such as space by new geometries, non-euclidean ones, say) is at the core of scientific inventions, often grounded on metaphysical or even religious commitments. For example, the invention of the “perspective” in early Renaissance painting, is a theologico-pictorial decision where the presence of the infinity of God in Annunciations is “metaphorically” suggested by the projective point (Arasse 1999); this invention is at the origin of the mathematical re-organization of space at the core of the scientific revolution and its mathematics (Longo, Longo 2020). In general, any new and relevant proof in Mathematics requires the invention of new concepts and structures, of new “perspectives”, strongly embedded in a historical context of meaning. As for more examples, infinitary or geometric judgements are at the core of the proofs of interesting statements of formal Number Theory that are formally unprovable – some difficult, recent “concrete incompleteness” results (Longo 2011). But even when considering formal proofs in the abstract frame of Type Theory, formally implementable in a computer, very basic Classical Logic yields practically non-mechanisable proofs for LLM: proofs “per absurdum” require connections in graphs by paths of a length and structure that goes beyond the limits of current (and possible?) programming methods in LLM (Oldenburg 2023). We, human mathematicians, bypass the problem by “establishing connections by new meanings”, not already present as paths in pre-given data bases, or by inventing new, non-existing symmetries, like young Gauss or proof-theorists in (Longo 2011), or new forms of the infinite in Mathematics, a concept to which theologians and painters gave a robust meaning by “showing” it to us in perspectival paintings, as a visible convergence or perspectival *point* (Longo, Longo 2020).

Let’s summarize the relations among unpredictability, emergence and production of novelty. The result of coin tossing is unpredictable, but it yields no emergence; the forms of hurricanes and clouds are unpredictable, *emergent* and optimal (they are geodetic surfaces in pre-given mathematical spaces), with no meaning, like LLM sequences of signs – yet we can interpret them: that cloud has the shape of an elephant, this sequence of signs statistically produced by ChatGPT is a nice poem... and thus arbitrarily attribute a function, a meaning to their forms. In biology, the

evolutionary emergence of a new organ, its form and function, has a meaning by its *functional* relation to the ecosystem and by the historical constraints that made it possible. Similarly, in cognition, the forms of the rocks and the clouds in a Deposition from the Cross or in other paintings by Andrea Mantegna (XV century, Italy), are painted in order to express the despair of the Universe for the death of Christ, they are creative and meaningful. They are the result of a historical formation of an artistic sense, of new observable forms of nature in paintings, an invention of Italian renaissance.

Formal, statistical and optimality methods are thus provably incomplete w.r.to biological and cognitive dynamics. Their abuse may also prevent human production of novelty, by imposing mean field criteria (follow the average, use the most probable) and even slow down more effective progresses in the applications of these fantastic discrete state machines produced by the inventive mathematics of the 1930s by Gödel, Church and Turing. Awareness of the limitations, beyond the usual technological arrogance, may help to improve also these technologies. In particular, by missing the differences between emergent phenomena in optimal or statistical dynamics in pre-given phase spaces, on the one side, and the historical formation of novelty and sense in changing spaces of possibilities, in biology and cognition, on the other, researchers in AI discourage the invention of new uses of digital networks to be constructed in collaborative, non-competitive interfaces between humans and machines (Lassègue, Longo 2024). Our aim is to go beyond the political ideology of *control* and *replacement* of biological and cognitive processes by statistically more probable or by “optimal” paths (geodetics with “no alternatives”) and by re-programming DNA (in spite of fifty years of failures), an ideology that still prevails. By developing an analysis that differentiates physical vs biological (and cognitive) theorizing, we aim instead to focus on the role of the scientific construction of knowledge and technologies by collaborating in the meaningful spaces of our communicating humanity, today greatly empowered by these digital devices and their networks, whose construction and use may be further empowered by the scientific awareness of their limits (Longo 2023).

References

- Amsterdamski et al. (eds) (1990) *La querelle du déterminisme*, Gallimard, Paris.
- Arasse, D. (1999) *L'Annonciation Italienne. Une Histoire de Perspective*. Paris: Hazan.
- Bailly, F., Longo, G. (2006). *Mathématiques et sciences de la nature. La singularité physique du vivant*. Hermann, Paris (in English, Imperial Coll. Press, 2011).
- Bailly, F., Longo, G. (2009). Biological Organization and Anti-Entropy. *J. Biological Systems*, Vol. 17, No. 1, pp. 63-96.
- Bailly F., Gaill F., Mosseri R. (1989) “La fractalité en biologie : ses relations avec les notions de fonction et d'organisation”, in : *Biologie théorique* (Y. Bouligand Ed.), Ed. CNRS.
- Bailly, F., Longo, G., & Montevil, M. (2010). A 2-dimensional geometry for biological time. *Progress in Biophysics and Molecular Biology*, 106(3), 474-484. <https://www.di.ens.fr/users/longo/files/CIM/2-dimTime.pdf>
- Barrett P-H. (1960), A transcription of Darwin's first notebook on "transmutation of species". *Bulletin of the Museum of Comparative Zoology* **122**, 247-94 (1960). doi.org/archive.org/details/biostor-839/page/n37
- Bender J., Frye M. (2009) Invertebrate solutions for sensing gravity, *Current Biology*, Vol 19 No 5.
- Binney J., Dowrick N.J., Fisher A.J., Newman M.E.J. (1992). *The Theory of Critical Phenomena: An Introduction to the Renormalization Group*. Oxford U. P.
- Bono I., Del Giudice E., Gamberale L., Henry M. (2011) Emergence of the coherent structure of liquid water. *Water Journal*, 2-1.
- Buiatti, M., & Longo, G. (2013). Randomness and multilevel interactions in biology. *Theory in Biosciences*, 132(3), 139-158.
- Calude, C. S., & Longo, G. (2016). Classical, quantum and biological randomness as relative unpredictability. *Natural Computing*, 15(2), 263-278.
- Cecconi F., Cencini M., Falcioni M., Vulpiani A. (2012) Predicting the future from the past: An old problem from a modern perspective, *Am. J. Phys.* 80 (11), November.
- Charpentier, E., Ghys, E., Lesne, A., & Laguës, M. (2006). *L'héritage scientifique de Poincaré*, Belin.
- Chibbaro S, Rondoni, L & Vulpiani, A. (2015) *Reductionism, Emergence and Levels of Reality: The Importance of Being Borderline*, Springer, Berlin.

- Chollat-Namy M., Longo G. (2023) Entropie, Neguentropie et Anti-entropie : le jeu des tensions pour penser le vivant, in *Entropies*, ISTE OpenScience, London.
- Connes, A. (1994). *Non-commutative Geometry*, New York: Academic Press.
- Cortini, R., Barbi, M., Caré, B. R., Lavelle, C., Lesne, A., Mozziconacci, J., & Victor, J.-M. (2016). The physics of epigenetics. *Reviews of Modern Physics*, 88(2), 25002.
- Devaney R. L. (1989) *An Introduction to chaotic dynamical systems*, Addison-Wesley.
- Dilcher D., (2000) Toward a new synthesis: Major evolutionary trends in the angiosperm fossil record. *PNAS*, June 20, 97 (13) 7030-7036 <https://doi.org/10.1073/pnas.97.13.7030>
- Foster R.-G., Kreitzman, L. (2004), *Rhythms of life. The Biological Clocks that Control the Daily Lives of Every Living Thing*, Profile Books: London
- Gibb, Sophie; Hendry, Robin Findlay; Lancaster, Tom (eds.) (2019) *The Routledge Handbook of Emergence*. Routledge Handbooks in Philosophy. Abingdon: Routledge.
- Gould, S.-J. (1996) *Full House*. Three Rivers Press, New York.
- Gould S.-J. (2002) *The Structure of Evolutionary Theory*, Harvard U. Press. Hebb, D.O.
- van der Hofstad R. (2016) *Random Graphs and Complex Networks*, Cambridge U.P.
- Kosman-Schwarback, Y. (2010). *The Noether theorems : Invariance and conservation laws in the twentieth century*, Springer.
- Kauffman S. (2002), *Investigations*, Oxford, U. P.
- Jablonka E, Lamb MJ. (2008), *Evolution in Four Dimensions*, MIT Press.
- Jacob, F. (1965). *Génétique cellulaire: Leçon inaugurale prononcée le vendredi 7 mai 1965* Collège de France.
- Janson R.-T., Rucinski, A. (2000) *Random graphs*. Wiley-Interscience Series in Discrete Mathematics and Optimization, New York.
- Laskar J. "Large scale chaos in the Solar System", *Astron. Astrophys.*, 287, L9 L12, 1994.
- Lassègue J., Longo G. (2024) *L'alphabet de l'esprit. Critique de la raison numérique*, to appear.
- Longo, G. (2001) Space and Time in the Foundations of Mathematics, or some challenges in the interactions with other sciences. Invited lecture, *First AMS/SMF meeting*, Lyon, July. <https://www.di.ens.fr/users/longo/files/PhilosophyAndCognition/space-time.pdf>
- Longo, G. (2011). Reflections on Concrete Incompleteness. *Philosophia Mathematica*, 19(3), 255-280. <https://www.di.ens.fr/users/longo/files/PhilosophyAndCognition/Incompl-PhiloMath.pdf>
- Longo, G. (2016) A review-essay on reductionism: some reasons for reading "*Reductionism, Emergence and Levels of Reality. The Importance of Being Borderline*", a 2015 book by S. Chibbaro, L. Rondoni, A. Vulpiani. **Urbanomic**, London, May 8 (<https://www.urbanomic.com/document/on-the-borderline/>).
- Longo, G. (2017). How Future Depends on Past Histories and Rare Events in Systems of Life, *Foundations of Science*, pp. 1-32. <https://www.di.ens.fr/users/longo/files/biolog-observ-history-future.pdf>
- Longo G. (2018) Interfaces of Incompleteness. In Minati, G, Abram, M & Pessa, E (Eds.), *Systemics of Incompleteness*, Springer, New York, NY. <https://www.di.ens.fr/users/longo/files/PhilosophyAndCognition/Incompleteness.pdf>
- Longo, G. (2018a). Information and Causality: Mathematical Reflections on Cancer Biology. In *Organisms. Journal of Biological Sciences*, vol 2, n.1. <https://www.di.ens.fr/users/longo/files/BiologicalConseq-ofCompute.pdf>
- Longo G. (2019) Information at the Threshold of Interpretation, Science as Human Construction of Sense. In Bertolaso, M., Sterpetti, F. (Eds.) *A Critical Reflection on Automated Science*, pp. 67-100, Springer, Dordrecht. <https://www.di.ens.fr/users/longo/files/Information-Interpretation.pdf>
- Longo G. (2020) Naturalizing Physics. Or, embedding physics in the historicity and materiality of the living. In *Deleuziana*, n. 11, special issue on "Differential Heterogenesis: Deleuze, Mathematics And The Creation Of Forms" (Sarti et a. eds), April (<https://www.di.ens.fr/users/longo/files/NaturPhysics.pdf>)
- 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. <https://www.di.ens.fr/users/longo/files/TwinsVSclocks.pdf>
- Longo G. (2023), *Le cauchemar de Prométhée. Les sciences et leurs limites*, Paris, PUF.
- 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
- Longo G., Milsted K., Soloviev S. (1993)The Genericity Theorem and effective Parametricity in Polymorphic lambda-calculus. *Theoretical Computer Science*, 121:323--344 (<https://www.di.ens.fr/users/longo/files/genericity-theorem.pdf>)
- Longo, G., Montévil, M. (2012) "Randomness Increases Order in Biological Evolution." In *Computation, Physics and Beyond*, edited by Michael J. Dinneen, Bakhadyr Khossainov, and André Nies, 7160:289–308. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer. <https://www.di.ens.fr/users/longo/files/CIM/anti-entrNZ.pdf>
- Longo, G., Montévil M. (2014). *Perspectives on Organisms: Biological Time, Symmetries and Singularities*. Dordrecht: Springer.

- Longo, G., Montévil, M., & Kauffman, S. (2012). No entailing laws, but enablement in the evolution of the biosphere. *GECCO'12 – Proc. of the 14th Intern. Conf. on Genetic and Evolutionary Computation*, 1379-1391.
<https://www.di.ens.fr/users/longo/files/CIM/noentail.pdf>
- Macías M., Camacho A. (2008) On the incompatibility between quantum theory and general relativity, *Physics Letters B* 663, 99–102
- 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.
- Mas, P. and Yanovsky, M.J.,(2009) Time for circadian rhythms: plants get synchronized. *Current opinion in plant biology*, 12(5), pp.574-579.
- McClung, C.R., (2006) Plant circadian rhythms. *The Plant Cell*, 18(4), pp.792-803.
- Miquel P-A. (2011) Extended physics as theoretical framework for system biology? *Progress in Biophysics and Molecular Biology*, Elsevier, 106 (2), pp. 348-352.
- Monod, J. (1970). Le Hasard et la Nécessité. In *Le Seuil Coll. Points* (in English, 1972).
- Montévil, M. (2022) Historicity at the hearth of biology. *Theory in Biosciences*, 141, 165-173.
<https://doi.org/10.1007/s12064-020-00320-8>
- Montévil, M. (2023) Disruption of biological processes in the anthropocene: The case of phenological mismatch, *submitted*
- Montévil M., Sonnenschein C., Soto A. (2016) *Theoretical approach of ductal morphogenesis*, *J. Theoretical and Applied Vascular Research* 1 (1): 45–49.
- Montévil M., Stiegler B., Longo G., Soto A., Sonnenschein C. (2020) Anthropocène, Exosomatisation et Néguentropie, dans B. Stiegler (curat.) *"Bifurquer, Eléments de réponses à Antonio Guterres et Greta Thunberg"*, Paris.
- Nicolis G., Prigogine I. (1977). *Self-organization in non-equilibrium systems*. New York, Wiley.
- Noble D., Jablonka E., Joyner M-J., Muller J., Omholt S. (2014) Evolution evolves: physiology returns to centre stage, *The Journal of Physiology*, 592.
- Noble R., Tasaki K., Noble P., Noble D. (2019) Biological Relativity requires circular causality but not symmetry of causation: so, where, what and when are the boundaries? *Frontiers in Physiology* 10: 827.
- Oldenburg R. (2023) Limitations of and Lessons from the Learning of Large Language Models, *Qeios*, Dec 28, ID: 9FH6AD, doi: <https://doi.org/10.32388/9FH6AD>
- Paldi A. (2020) Stochastic or Deterministic? That is the Question. *Organisms. J. Bio Sci.*, vol. 4, N.1.
- Parisi G., Mézard M., Virasoro M.-A. (1987) *Spin glass theory and beyond*, Singapore, World Scientific.
- Petitot J. (2017) *Elements of Neurogeometry: Functional architectures of vision*", Springer.
- Pocock et al. (2002) The robustness and restoration of a network of ecological network, *Science* 335, pp. 973 -977.
- Rovelli C. (2004). *Quantum Gravity*. Cambridge Monographs on Mathematical Physics.
- Rovelli C. (2019) *The order of Time*, Penguin Books, NY.
- Tal O., Kisdi E., Jablonka E. (2010), Epigenetic Contribution to Covariance Between Relatives, *Genetics* 184: 1037–1050, April.
- Sarti, A., Citti, G., Piotrowski, D. (2022) Differential Heterogenesis. *Lecture Notes in Morphogenesis*. Springer, Cham.
https://doi.org/10.1007/978-3-030-97797-9_4
- Schrödinger, E. (1944). *What is life ? The physical aspect of the living cell* (Cambridge).
- Sharma A. et al., (2023) Assembly theory explains and quantifies selection and evolution, *Nature*, Vol 622, October 12, 321 <https://www.nature.com/articles/s41586-023-06600-9>
- Sonnenschein C., Soto A. (1999). *The Society of Cells: Cancer and Control of Cell Proliferation*. Springer Verlag.
- 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.
- West-Eberhard M-J. (2003) *Developmental Plasticity and evolution*. Oxford U. Press, New York.
- West-Eberhard, M-J. (2005), “Developmental plasticity and the origin of species differences”, in: *PNAS*, 102 (1), 6543–6549.
- Williams K.-S., Simon C. (1995), “The Ecology, Behavior, and evolution of Periodical Cicadas”, in: *Annual Review of Entomology*, 40, 269-295.