Why do we need theories?

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Abstract

Theories organize knowledge and construct objectivity by framing observations and experiments. The elaboration of theoretical principles is examined in the light of the rich interactions between physics and mathematics. These two disciplines share common principles of construction of concepts and of the proper objects of inquiry. Theory construction in physics relies on mathematical symmetries that preserve the key invariants observed and proposed by such theory; these invariants buttress the idea that the objects of physics are generic and thus interchangeable and they move along specific trajectories which are uniquely determined, in classical and relativistic physics.

In contrast to physics, biology is a historical science that centers on the changes that organisms experience while undergoing ontogenesis and phylogenesis. Biological objects, namely organisms, are not generic but specific; they are individuals. The incessant changes they undergo represent the breaking of symmetries, and thus the opposite of symmetry conservation, a central component of physical theories. This instability corresponds to the changes of the environment and the phenotypes.

Inspired by Galileo's principle of inertia, the "default state" of inert matter, we propose a "default state" for biological dynamics following Darwin's first principle, "descent with modification" that we transform into "proliferation with variation and motility" as a property that spans life, including cells in an organism. These dissimilarities between theories of the inert and of biology also apply to causality: biological causality is to be understood in relation to the distinctive role that constraints assume in this discipline. Consequently, the notion of cause will be reframed in a context where constraints to activity are seen as the core component of biological analyses. Finally, we assert that the radical materiality of life rules out distinctions such as "software vs. hardware."

Keywords: default state, mathematical symmetries, phase space, biological organization

> Nothing is more practical than a good theory
>
> Attributed to Ludwig Boltzmann.

1. Introduction

Broadly speaking, the aim of science is to improve our understanding of nature. Scientists seek this knowledge for its own sake and also for guiding us to act responsibly when using this knowledge. Given that the scientist does not have direct access to the world outside her and because the consequences of action are far from obvious, these are not easy tasks. Centuries ago the founders of mechanics were strongly committed to Christian faith, and thus circumvented this problem by believing and asserting that the infinite goodness and perfection of God justified the agreement between their theoretical reasoning, and the phenomena observed by them (Cottingham 2013). In other words, since God does not intend to deceive us, we, as Her creatures, can trust our own senses and rationality. Moreover, God could be viewed as a legislator both of nature and of human activities; thus, the notion of "law" could be extended from divine will and human societies, to the dynamics of nature. In the last 150 years scientists stopped relying on religion as a means to determine objectivity. Darwin's book "The origin of species" was a main contributor to this profound change in philosophical stance in science. From our perspective, this modern viewpoint implies that scientific objectivity should be conceived of as constructed by a human activity.

In spite of Descartes' Meditations, both physicists of yore and todays' practitioners put forward ideas and methods that are counterintuitive and usually contrary to common sense (Bachelard 2002; Wolpert 1994). The frame of reference we use as scientists is thus different than the one we all use in everyday situations, for example when we talk about "sunrise" and "sunset". Remarkably, com-

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mon sense notions are useful in our everyday lives; this is probably why we still talk about the sunrise today, half a millennium after Copernicus proposed the notion of a heliocentric planetary system, a notion we are exposed to from childhood. This example also illustrates why the naïve perception that facts exist independent of any reference frame is incorrect. There is no observation devoid of theoretical content; sunrise and sunset refer to the sun rotating around the earth as in Ptolemy's theory. As put by the philosopher DC Dennett: "There is no such thing as philosophy-free science; there is only science whose philosophical baggage is taken on board without examination" (Dennett 1995).

Scientists purposely suspend the common sense world view used by all in our everyday life when constructing theories and contrasting them with experiments. Scientific theories provide organizing principles and construct objectivity by framing observations and experiments. Even research performed within the frame of one "wrong" theory sooner or later will result in the demise of such a theory, thus advancing our knowledge. This goes with one caveat, that the theory in question has to have clear enunciates that allow their demise by both theoretical and experimental considerations.

Physics provides the best example of why theory is central to the success of a scientific discipline. It also provides examples of how "wrong" theories such as the "luminiferous ether theory" which was conceived to explain the propagation of light, was useful in framing observations. A comment by H. Poincaré, published before the dismissal of the ether theory illustrates the role of theories: "Whether the ether exists or not matters little - let us leave that to the metaphysicians; what is essential for us is, that everything happens as if it existed, and that this hypothesis is found to be suitable for the explanation of phenomena. After all, have we any other reason for believing in the existence of material objects? That, too, is only a convenient hypothesis; only, it will never cease to be so, while some day, no doubt, the ether will be thrown aside as useless,"(Poincaré 1905). Indeed, the "luminiferous ether theory" ceased to be useful at the beginning of the 20$^{\text{th}}$ century. Light was found to have both wave and particle properties; particles do not need a medium to travel. Moreover, the speed of light was supposed to be set with respect to the ether, but instead it was shown to be always the same in the 'vacuum', whatever the viewpoint of the observer is. This finding paved the way to special relativity.

2. Principles of conceptual construction and principles of proof in Mathematics, Physics and Biology

A brief excursion into Mathematics may help to clarify some general ideas about the foundation of natural sciences. Euclid's work is a permanent blend between constructions and proofs: Euclid traces lines, constructs plane figures and, by means of rotations and translations, gives proofs. Logic is also crucial to proof, as exemplified by proofs "per absurdum". Euclid proposes mathematical structures, of which the main one is the line with no thickness. Then, he builds on these structures by tracing, intersecting, rotating and translating. By means of these transformations, composite mathematical structures are obtained.

For more than two millennia from Euclid to Grothendieck, the proposal of new concepts and structures as well as the singling out of *"principles"* for these constructions, was at the core of mathematical activity. The construction of concepts and structures is followed by the development of suitable *principles of proofs* by means of logic. The job of these principles is to preserve the "meaning" of structures along proofs. For example, deriving by "modus ponens" (if A, and "A implies B", then B) preserves the "sense" (or truth) of the assumptions being examined. In a sense, principles of proof are formal transformations that preserve the mathematical meaning as an invariant of the proof[1].

The transfer of mathematical tools to another discipline should always take into consideration the origin and the constitutive dynamics of these tools. Specifically, these mathematical tools are far from neutral because they carry with them a specific organization of phenomena and a specific way of reasoning that cannot be separated (dissociated?) from them. Similarly, experimental tools such as sequencing techniques tend to force the search for answers to all kinds of biological questions in terms of sequences. Furthermore, animal models are far from neutral; S Gilbert discussed how the adoption of animal models that reproduce all year long in carefully controlled laboratory conditions obliterated the effects of the environment on the construction of the phenotype (Gilbert 2005). This omission resulted on the adoption of the idea of a developmental "program" totally contained in the genome. "Modern" biologists became oblivious to the previously entrenched notion that the environment plays a major role on the determination of phenotypes. In fact, polyphenism (one genome, multiple phenotypes) was discovered well before genetics entered the biological scene (Weismann 1875).

2.1. Principles of construction and proof in Mathematics and Physics

The deep link between Mathematics and Physics is due to their shared principles of construction. The concepts of Mathematics are used to single out physical concepts and objects. In Physics, the notions of speed and acceleration became scientific when forced into a mathematical construction by applying differential calculus and limit concepts to them (derivation and integration). It is the mathematical writing of equations that produces the stability of the physical concepts of energy or momentum. These

[1] The differences between principles of construction and of proof as well as those between generic and specific objects are discussed in detail elsewhere (Bailly and Longo 2011; Longo and Montévil 2014).

concepts may be characterized as invariants in the equations of movement under time or space transformations, respectively [Noether's Theorems, 1918, see (Bailly and Longo 2011; Longo and Montévil 2014)]. In other words, the concepts of Physics acquire stability when they are treated by the same methods and the same principles of construction used for mathematical concepts. Moreover, the objects of Mathematics, namely, the defined concepts, are "generic", exactly like the objects of Physics. That is, they are invariant of experiences and theory under suitable transformations: a line or a Hilbert space in geometry, a stone or an electron in Galileo's or Bohr's experiences are all invariant or symmetric with respect to replacement by another mathematical or physical object of the same type.

Some objects of Physics are "first" mathematical ones: an electron is a solution of Dirac's equation. Anti-matter is the negative solution, which originally had no physical meaning. Sacharov and Feynman dared to interpret this purely mathematical solution by some peculiar empirical evidence: the disappearing of a particle and the production of twice its energy as gamma-ray and called the "invisible" interacting particle a positron, and this gave the concept of anti-matter. This is a paradigmatic case of the intertwining of Mathematics and Physics. However, the transfer of such an extraordinary methodology into another discipline, like Biology, may either not make sense at all, or result in a surprising meaning that should be examined closely. In summary, exact mathematical invariances and the transformations that are mostly defined by means of equations play an identical constructive role in Mathematics and Physics: they propose or single out objects and show the sense in which they are "generic". This is all grounded on the fact that these two disciplines share similar "principles of conceptual construction".

While Mathematics and Physics share principles of construction they differ regarding the "principles of proof". On the one hand, in Mathematics, these "principles of proof" are of logical-formal nature and they make it possible to preserve meaning (or truth) in deductions. In Physics, as a natural science, on the other, proofs are grounded on experiences, in the broad sense of observations and experiments.

2.2. Principles of construction and proof in Biology

Physics and Biology share the principles of empirical proof, but they radically depart from the physico-mathematical practice regarding the principles of construction. Objects and concepts do not share the same "perfect" stability and interchangeability of those in Mathematics and Physics, a stability and a genericity which is defined by the mathematical invariance with respect to intended transformations. For instance, the *states* (speed, energy level) of an electron may change over time, but the invariances and the transformations that define its *properties* are stable (mass, for example). Physico-mathematical objects and concepts have no intrinsic or objective history[2].

The historical (phylogenetic, ontogenetic) formation of a biological object is instead crucial: each organism originates from a pre-existing one. The understanding of the evolutionary and ontogenetic path of a given organism is crucial to its scientific description as a biological object. Moreover, history produces the "specificity" of an organism and the organs within it. That is, each biological object is the result of an historical development which makes it specific and, in a sense, unique. This uniqueness poses problems for scientists, because all scientific analyses require some level of generality. The inherent specificity makes it necessary to determine the best level of general description of a biological object. In conclusion, while Mathematics and Physics share the same construction principles and deal with generic objects, with no history, Biology can neither rely on the same construction principles nor on the genericity of the objects; yet, like in Physics the proof principles are empirical.

2.3. The role of mathematical symmetries and invariants

When discussing construction principles we mentioned the stability of physical objects which depends on the preservation of invariants under transformations. For example, all circles are similar, and the ratio of the circumference to the diameter, π, is invariant.

In modern Physics, "symmetries" are transformations preserving the key invariants observed and proposed by the intended theory. In short, the conservation of these quantities is grounded on the idea that the "laws" of Physics are the same at different positions and times. The types of symmetries usually referred to in Biology are a subset of those in Mathematics; for example, symmetry with respect to an axis on a plane. Those symmetries represent specific cases of transformation such as a space rotation preserving the properties of the geometric structure under examination.

In Physics, changes of symmetry may force a change in theory; as an example, in classical mechanics time is reversible, while in thermodynamics time is oriented (Table 1). In other instances, a theory can accommodate a single change of symmetries, like the theory of critical phase transitions. This is exemplified by the passage from water vapor to snowflake, namely, the appearance of a new observable, snow. This phenomenon is called a phase transition and occurs at a point named the critical point. Since ontogenesis and phylogenesis are characterized by

[2]Cosmology is an exception to this, with the Big Bang as a limit case. Yet, this is exactly where the encounter of non-unified theories (quantum and relativistic fields) poses major problems to any attempt to consistently give historicity to physical objects: major physical constants are claimed to change in the first few nanoseconds after the Big Bang, but the physical constants remain stable afterwards. This is very far from biological histories, such as phylogenesis and ontogenesis: changing objects, functions, and observables is their permanent state of affairs.

	Physical world			Biological world
	Linear / equilibrium physics	*Classical thermodynamics*	*Far from-equilibrium / self-organization physics*	
Time	No arrow of time	Arrow of time	Arrow of time	Arrow of time (adds a biological level of irreversibility)
Conservation	Conservation principles (energy, momentum, etc)	Conservation and introduction of a non-conservation principle (production of entropy)	Conservation and a basic non-conservation principle associated to randomness in the self- organization process	Non-conservation principle, new possibilities
Description space	Stable	Microscopic: stable Macroscopic: shrinks over time	Microscopic: stable. Macroscopic: increases over time (emergence, yet causally reducible)	Not stable over time (emergence) *
Mathematical symmetries	Stable symmetries	The system gets more symmetric over time (measured by entropy increase)	Simple symmetry breaking (the system becomes less symmetric on the basis of former symmetries)	Ubiquitous symmetry changes.
Framing principle	Conservation of energy	Increase of entropy	Identical iterations (at the statistical level)	Non identical iteration.
Historicity	No (past and future are equivalent)	No (peculiar features from the past are destroyed by the dynamics)	No (a few features are akin to historicity but the framework is ahistorical and the objects are spontaneous)	Fully historical systems (objects are historical and not spontaneous)
Default state	Uniform rectilinear movement	Stationary state with maximal entropy (equilibrium)	Stationary state under constant flows (non-equilibrium)	Proliferation with variation and motility

Table 1: *From physics to biology: A comparison of fundamental principles for theory construction* [adapted from (Longo et al. 2015)].

the formation of new objects and symmetries, the theory of critical phase transitions is relevant to theory building in Biology. However, unlike in Physics, where the new object appears at and beyond the critical point, in Biology changes occur relentlessly.

2.4. Phase Spaces

The invention of phase spaces in Physics, that is, of the spaces of pertinent observables and parameters, has a rich history. There is neither space, nor mathematized plane in Greek geometry; this is a geometry of figures and of lines, manipulated by translations and rotations. Infinity is implicit, like in the notion of "line with no thickness" or it is *potential*, like in the "prime number theorem" in which an algorithm is given that, for any collection of prime numbers, constructs a larger one.

A different notion of infinity was generated in paintings in Italy at the end of the Middle Ages. It originated from a theological debate which specified the positive content of God's *actual* infinity instead of just potential infinity as the only conceptually possible one (Zellini 2005). This newly established concept of infinity moved into paintings under the form of *perspective*: in Annunciation paintings in the 14th century, the projective point is a symbolic form of the presence of the infinity of God (Figure 1), (Arasse 1999; Longo 2011; Longo 2010). In the 15th century, Piero della Francesca, Ghiberti, Alberti and others, invented a general technique from this pictorial construction, a "practical" version of projective geometry. In turn, in the 17th century, Desargues turned it into the full glory of a mathematical theory.

To continue this short history of infinity, as Kant beautifully philosophized, the infinite spaces of Descartes and Desargues provided the very "conditions of possibility" for doing Physics. In other words, the *a priori* awareness (or the "positing") of space (and time) were the necessary preliminaries for framing Newton's equations. Yet, 19th century Physics went further. The complete determination of a physical process may only be given by also specifying the pertinent observables. So, Hamilton, Poincaré, Gibbs and others explicitly referred to the choice of "what needs to be measured", possibly an invariant quantity of the intended process. In this way, two major invariants were added in the specification of space (or time): namely, momentum (in conjunction to space) and energy (as conjugated to time). Then, momentum *and* space or energy *and* time provided the fundamental phase spaces for physical analyses. This boosted the modern splendor of equational descriptions in Physics: once given the appropriate phase space, equations or functions describe the dynamics.

Figure 1: Lorenzetti, Ambrogio, *L'Annonciation,* 1344. Pinacoteca Nazionale, - Wikipedia.org, CC-PD-Art. A column, solid near the ground is attenuated towards the top where it overlaps and hides the vanishing axis of perspective at infinity, an explicit reference to God. In 1344, this was an extraordinary innovation: a rigorously drawn projective space. And then, by the effect of the geometry of this floor that goes from man to God, a new space is deployed: God is present in the story being told, albeit hidden, far away at infinity. The Madonna has a new human dimension: her solid, three-dimensional body accompanies the expression of a nascent humanism. Perspective introduces God as the actual limit,at infinity, therefore as the limit of a space which encompasses everything, including the human spaces which are renewed. All of the first paintings with "prospettiva" will be annunciations, this unique locus of the meeting between infinitude and finitude according to Catholic theology (From (Longo 2011)).

The phase space is the space of all possible states of a physical system. The procedure which requires that the phase space be a "condition of possibility" and thus a priori for constructing physical knowledge is still at the core of all forms of mathematization in Physics. That is, theoretical Physics is advanced by first positing the phase space of the possible dynamics, a task that may be rather abstract. We may compare this task with that of the painters mentioned above: before placing objects, the pictorial space was organized by means of perspective, the practical application of projective geometry. In classical mechanics, the phase space contains all possible positions of all the objects in the system and their momenta in order to determine the future behavior of that system.

Often, the hard part for the theoretical physicist is to invent the right phase space. In quantum Physics, for instance, the choice of Hilbert's spaces allowed Schrödinger to give an equational description of quantum dynamics, as the dynamics of an amplitude of probability. Another example is the choice of the frame of Connes' non-commutative geometry with the purpose of unification of quantum mechanics with relativistic theories. We stress again that the key point in this very powerful approach to physical dynamics is the pre-definition of the pertinent phase space.

The *a priori* choosing the phase space applies also in relativity theory. Energy and matter modify the metrics and thus the curvature of space, but neither the topology nor the dimension of the intended Riemannian spaces where Relativity Theory is analyzed. The resulting phase space, with the key observables, energy and momentum, does not change. This powerful procedure may be viewed as a strong form of separation of space and time from physical matter; admittedly, this represents a convenient dualism. Again, like in Italian renaissance paintings, the space is drawn before objects and humans are placed in it (de Risi 2012)[3].

The previous narrative generates a basic question in the quest to gain an understanding of biological phenomena. Namely, is there a way to construct *a priori* a phase space for organisms as is done in Physics? Here we arrive at one of the many challenges biological objects pose to scientists. During ontogenesis the appearance of an animal changes radically. Change is even greater through phylogenesis; this change encompasses the phenotypic diversity of the living world from unicellular organisms to butterflies, whales and humans. Is it wise to imagine a "phase space" that would contain all possible phylogenetic trajectories? This query brings to memory SJ Gould's idea of whether in replaying the "tape of life" we would end up with the same "tree-of-life" that we know and of which we are a part of. From the very contingency of life, his answer was a resounding "no" (Gould 1990).

We know from ecological developmental Biology that living beings are co-determined by their ancestry and their macro- and micro-environment. Reciprocally, organisms shape their environment. In short, evolution is about change along a hereditary history, and these changes represent a change of observables and changes of symmetries. All these factors make it apparent that there is no predetermined phase space (Longo et al. 2012). That is, the conditions of possibility for the emergence of new objects are generated along the way. Among the many examples of this type of event, the appearance of the ossicles of the inner ear in mammals which originated from jaw bones in reptilians is a rather dramatic one.

3. Causality: Theoretical versus differential causes

In classical mechanics, which deals with phenomena at an intermediate scale like objects of our everyday life (balls, bridges, trucks), it is relatively straight-forward to identify a theoretical cause. According to the principle of

[3] The separation of space from the objects inhabiting it is a sort of dualism that is also central to theories of information and computer sciences. Information or software is strictly separated from the hardware in all current theories of Information: in Biology, the use of information metaphors would make the material structure of organisms irrelevant to evolution (Gouyon et al. 2002).

inertia, if no force[4] modifies the state and properties of an object, the object conserves its state and properties. A ***theoretical cause*** would then be a force that modifies the state and properties of the object in question[5].

In contrast to the inert, biological entities are able to generate action (agentivity); they move and reproduce. This inherent ability of biological entities poses challenges to the classical notion of theoretical cause. In Chapter 5, we address this issue and propose the notion of a "default state" which represents the equivalent of inertia in mechanics. Put simply, the biological default state is what cells do when placed in an environment appropriate for maintaining flows of matter and energy. In these conditions, they move, proliferate and generate variation. Under these circumstances, we assert that the default state is a ***theoretical cause.*** Anything that affects the default state is a ***constraint***.

Constraint is a term that has been used in evolutionary Biology to indicate factors that limit the production of phenotypic variants. In our view of the organism, a constraint is a factor that will change the range of "possibles". A negative constraint will narrow down the range of possibles. For example, during rodent perinatal development, estrogens masculinize the hypothalamus, thus narrowing the repertoire of possibles to just the negative feedback, while in the absence of estrogens the hypothalamus expresses both positive and negative feedback. A constraint could also hinder one possible while enabling another. For example, the bottom of a tissue culture flask blocks the displacement of the cells below this surface but allows the cells to "crawl" along this surface.

When a perturbation is introduced into a biological system, for example, when one group of animals is treated with a hormone and another group of comparable animals with the vehicle alone, a difference in the behavior of the system is observed. We call this perturbation a ***differential cause.*** The difference in treatment provoked the modification in the system's behavior in a contextual manner, whereas a theoretical cause represents an invariant with respect to all pertinent contexts. In order to learn about the theoretical cause underlying the differential cause we need to find out how the latter affects the constraints on the system; for this to be achieved, we need to rely on a suitable theoretical frame.

4. Rooting biological knowledge in the specificity and materiality of life

Can the practice of postulating the phase space be transferred from Physics to Biology? It all depends on the preferred observables. If one considers phenotypes and organisms as pertinent objects of analysis, there is no way to consider them as time or space invariants. Indeed, in Biology we follow Darwin's approach, which is based on a non-conservation principle for phenotypes: that is, "descent with modification". Thus, in our view, there is no way to pre-define the phase space. Kant was right: there is no way to follow Newton's path to turn the analysis of organisms into a science. We need, instead, brand new principles and ideas. The strong form of dualism ingrained in Physics seems unsuitable for Biology and to the absolute materiality of life. Life is based on the *actual* materials living objects are made from, which includes a particular DNA, particular RNAs, proteins and membranes, just to mention some of the cell's components. There is no way to dissociate the actual materials from which living organisms are made from the functions these organisms fulfill[6]. When dealing with computers, however, the "software" is independent of the hardware. This radical difference between the inert and the living makes the transplantation from the mathematical and physical sciencesBiology unsuitable due to the fact that they do not contemplate the fundamental materiality of living entities.

Another important difference between Physics and Biology was alluded to above, namely, that in the latter the pertinent observables, phenotypes and organisms, are specific while in the former, objects are generic. Additionally, these biological observables continually change as a consequence of their material internal dynamics and of the interaction of organisms in contingent ecosystems. Yet, "organization" remains. Once we postulate organization as the invariant structure common to all organisms, an obvious question comes to mind: would it ever be possible to mathematically formalize this postulated "invariant"?

While searching for a way to deal with this postulate, we acknowledge that the best empirical solution to the challenge posed by the specificity of biological objects subject to continual changes is to adopt an extension of common practices in experimental Biology. These practices aim at decreasing variation as much as possible among the objects being studied to render them more "generic". For example, cloning of cells and developing animal strains by sister-brother pairing renders these biological objects more alike, comparable to monozygotic twins. However, the theoretical relevance of this common practice has not been made explicit by the practitioners. We propose the construction of a suitable experimental context where the best level of generality is obtained. In view of its resemblance to required transformations to preserve invariance when inventing a new concept or structure in Mathematics, Maël Montévil called these procedures "symmetrization." Empirical symmetrization in the context of proper

[4] In physics, a force is any interaction that, when unopposed, will change the motion of an object.

[5] However, in the small-scale world of quantum mechanics inert matter poses new challenges to causality, like quantum entanglement.

[6] In the last half of the 20th century we witnessed the replacement of certain *organ* functions by engineered devices that are useful in the short run, for example, dialysis machines and mechanical hearts. However, they do not substitute for the actual biological organ. In the long run, organ transplants are the best solution to overcome organ failure. Paradoxically, while organs can be replaced with mechanical devices, cells cannot.

theoretical principles may be an effective way to advance Biology while waiting for the development of appropriate mathematical tools to formalize the theoretical concepts we intend to develop.

5. From "Physics" to "nature" and toward an autonomous Biology

The Greek word from which the scientific discipline we call "Physics" originated from what today we call nature, including live objects such as plants and animals. In fact, Aristotle's Physics comprised both the inanimate and the living. "Nature", the latin word, originally meant "birth" as well as "beget", notions that evoke life. Although it was also synonymous with Physics, in ancient times the shift in meaning reveals a change of scope of the science. The mathematization of the world view and the origin of mechanics excluded out of the realm of "hard" science, for the most part the biological as well as the most distinct human characteristic, the mind.

Scientists interested in what we now call Biology (the term was introduced independently by Lamarck, Treviranus and others in the early 19th century) tended to polarize themselves into two main currents: vitalism and physicalism. The vitalists proclaimed the independence of Biology from Physics while the physicalists expected to reduce Biology to Physics.

We mentioned above that the dualism inherent in physical disciplines from Descartes to Information Theory is inimical to the constitutive "materialism" of the living, and we have succinctly explained why theories from one discipline cannot be automatically applied to another discipline. We also explored the main differences between Physics and Biology; this analysis was not meant to provoke a feeling of "Physics-envy", but to the contrary, it made us feel re-invigorated by the challenge posed by Biology. Philosophers, particularly those from the "Continental" tradition have long observed the differences between these two disciplines, and the radical difference between alive and inert (Kant 2000; Canguilhem 2008; Bergson 2007). That is, the agency and normativity of the living and the process of individuation (which will be addressed in this issue by Paul-Antoine Miquel and Su-Young Hwang). We biologists need to address the relentless change of the living objects and their individuality, their incessant change of symmetries, and their creativity. The Mathematics to formalize such an enterprise are yet to be developed. The challenge of tackling biological problems before such mathematization is truly invigorating, and history tells us that it has already begun. Biologists have already gone a long way guided by evolutionary theory, a theory of relentless change which is itself being reconstructed.[7]

[7] Darwin's theory of evolution underwent changes, a major one as the "modern synthesis" in the 20th century and it is now undergoing major critical reconstruction (Noble et al. 2014).

The task now before us is to build a theory of organisms comprising the entire life cycle. From our perspective, such theory-building task requires a multidisciplinary perspective, encompassing philosophy, Mathematics, Physics and Biology. This PBMB issue is a preliminary attempt through our own multidisciplinary effort towards a theory of organisms.

6. Conclusions

Altogether, we propose that the articulation between organisms and Mathematics is not equivalent to that of inert objects and Physics. This is mostly due to the historicity, variability and contextuality of organisms and cells. These are summarized by a very relevant conceptual duality: the genericity of physical objects and the specificity of their trajectories, in contrast to the specificity of biological objects and the genericity of their possible trajectories. The basic principles that we thus propose for Biology are different in nature but compatible with relevant physical principles. Mathematical models which are necessary to understand complex, non-linear interactions need to be grounded on robust biological principles. Finally, a theory of organisms eventually should be able to lead us towards this most human characteristic, the mind, which was excluded from the scientific realm at the dawn of the scientific revolution.

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