An alphabet of scientific categories

Un alfabeto de categorías científicas

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Abstract

The paper discusses the possibility of understanding the entire system of scientific knowledge from a simple alphabet of fundamental categories, which by condensing degrees of complexity between levels of analysis are capable of recapitulating an immense variety of data and principles. Our focus, however, will be placed on physics and chemistry (and, to a lesser extent, biology), leaving for further publications the study of neuroscience and the human sciences.

Keywords: System, universality, alphabet, category, condensation of complexity

Resumen

El artículo analiza la posibilidad de comprender todo el sistema de conocimiento científico a partir de un simple alfabeto de categorías fundamentales, que al condensar grados de complejidad entre niveles de análisis pueden recapitular una inmensa variedad de datos y principios. Sin embargo, nuestro enfoque se centrará en la física y la química (y, en menor medida, en la biología), dejando para futuras publicaciones del estudio de la neurociencia y las ciencias humanas.

Palabras clave: Sistema, universalidad, alfabeto, categoría, condensación de complejidad

1. Conceptual atoms and the "factorization" of complexity

The human mind shows an extraordinary ability to discern patterns in nature. The development of science has led us to capture them and elucidate their connections.

If one embraces the idea of an ontological continuity between all objects of reality, it must be possible to formalize the structure and function of consolidated sciences (physics, chemistry, biology…) through matrices composed of categories. As it shall be shown, these symbols, integrated into a conceptual

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architecture, are meant to synthesize both the fundamental ideas of these disciplines and the operating rules that relate those primary notions. Thus, they may contribute to some of the ongoing discussions in philosophy of science concerning the nature and scope of the connections between the different fields of knowledge, and the ontological assumptions behind the different models about the relationship between the sciences.

This exploration of the generative power of certain categories can actually reinvigorate explanatory reductionism in the theory of science, through the study of the basic semantic elements provided by the different sciences. Furthermore, this attempt may shed light on the deeper question about the viability of ontological reductionism. This conceptual reductionism (or, rather, this search of conceptual simplicity in the formalization of the system of human knowledge) may help to overcome traditional criticism of reductionism in general, especially regarding the necessity of differentiating between levels of complexity and explanatory orders from one science to another.

Indeed, it is fascinating to realize that the mind possesses a truly outstanding capacity to explain a vast and heterogeneous number of phenomena by using a relatively small number of ideas. The generative power of certain systems of thought thus resembles an alphabet of concepts, a catalogue of ideas and a map of logical categories that is often simple but unequally deep and fundamental, in which simplicity stands as the preeminent way for examining complexity. In the 17th century, Leibniz envisioned this project in one of his earliest essays, *Dissertatio de arte combinatoria*,[1] inspired by the work of authors like Ramón Llull and René Descartes. Also, over the last decades, proposals of the so-called "general systems theories" have insisted on the necessity of looking for systematic theoretical constructs capable of transcending barriers between disciplines and fields of research.[2]

For example, physics –classical and relativistic- is based upon a set of fundamental categories: matter, energy, space and time. We know that matter and energy are ultimately expressions of the same underlying reality, as contained in Einstein's famous equation . Likewise, the theory of relativity has shown that space and time cannot be treated as separate entities. However, in purely practical terms, it is very difficult for our imagination to find a more "fundamental" category in which matter and energy become perfectly unified, even if the development of theoretical physics has unlocked their intimate connection.

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[1] Leibniz, G. W., "Dissertation on the Art of Combinations", in Loemker, L. E. (Ed.), *Philosophical Papers and Letters*, vol. 2, Dordrecht, Holland: Springer Netherlands, 1989, pp. 73-84.

[2] For an overview, see Boulding, K. E., General systems theory—the skeleton of science, *Management science*, vol. 2, núm. 3, 1956, pp. 197-208; Von Bertalanffy, L., *General system theory*, New York, núm. 41973, 1968, p. 40.

Therefore, it is didactic to keep the traditional distinction between them. It may be the case, of course, that these supposedly fundamental categories actually stem from a single and more basic principle (a "supra-category"), but for our purposes it suffices to state that ulterior concepts, like velocity and momentum, can be reduced to more essential notions. Yet, in addition to these fundamental categories physics needs a series of operating rules. They can be regarded as equivalent to the idea of "fundamental forces of nature," which impose their respective laws upon the objects that fall under their domains.

An analogy can be drawn between this idea of "*conceptual atoms*" of reality and the fundamental theorem of arithmetic. According to the latter, every integer greater than 1 either is a prime number itself or can be represented as the product of prime numbers. It is at least surprising to realize that this theorem, which encompasses such a profound truth about those intriguing and subjugating entities called prime numbers, was already proved by Euclid of Alexandria between the 4^{th} and 3th centuries B.C. (and later by Gauss using modular arithmetic). Indeed, the theorem establishes a fascinating property of integers greater than 1: that of their unique factorization in terms of 1 and prime numbers. Primer numbers, together with the unity, stand as the true bricks of the set of integer numbers, as if the entire architecture of basic arithmetic could be expressed in terms of these pillars. Of course, the problem lies in the existence of an infinite number of prime numbers –as it follows from an argument of logical necessity–, such that the set of integers needs, in terms of cardinality, as many fundamental factors as members. Likewise, in our model reality can be regarded as the result of a unique *factorization*, in which every element susceptible to being distinguished from another up to a significant degree (and it maybe that the subjective part implied in the expression "significant degree" cannot be excluded for the sake of complete objectivity) is represented in terms of basic factors. There is a difference, however, since in our view the number of basic factors cannot reach infinity, given the finitude of elementary constituents of matter.

Of course, the atomic hypothesis points in this direction. In any case, this unique factorization of the elements of reality in terms of *primitive* ("prime") *notions*, of fundamental concepts whose combination yields that particular structural and functional disposition in space-time, adds an important element of variability: while in arithmetic the sequential arrangement of prime numbers does not alter the value of the product (10=1x2x5=1x5x2=2x1x5=2x5 x1=5x1x2=5x2x1), in reality the order of the elements matters; the analysis of cardinality must therefore be adequately integrated with that of ordinality, the analysis of "matter" with that of its "formal" disposition.

Categories usually respond to agreed definitions on elements considered as relevant, given their explanatory potential to understand a phenomenon.

Laws or operating rules have to be discovered. Therefore, if laws are combined with a set of categories, they can add new information, whose content contributes to expanding our knowledge of a system. Of course, the border between that which is defined, or invented (and, in a certain way, tautological) by our logical creativity, and that which is truly synthetic or "revealed" by our research on the world, is not easy to elucidate. Furthermore, definitions are improved through theoretical and experimental developments. It may even be necessary to incorporate new definitions in order to cover previously unknown or poorly understood domains of reality, as it happened with the concept of entropy.[3] It is also inevitable that a science such as physics combine aprioristic definitions, evaluated according to their explanatory utility and their importance when it comes to providing our model with logical consistency, and operative definitions, designed to illustrate how a certain magnitude can be measured.

2. Models, systems and the principle of selection

In a certain sense, a model of a system can be regarded as a representation of its possible states. This notion coincides, essentially, with that of "phase space" in the physical sciences. Such a space of possibilities is susceptible to adopting different rules of transformation, which can be conceived as laws of evolution that enable the observer to make inferences about the relationships between one state and another as a function of time. A state can then be interpreted as a potential configuration of the system, and a system as a set of potential configurations connected through a series of rules. So, it may be understood as a specification of a system, which allows the observer to distinguish it sufficiently from another state. This elementary representation is capable of manifesting the similarity between a logical and a natural system, both of which consist of states bound by rules.

Classical mechanics, for instance, is deterministic in the sense that the laws governing the evolution of the different states of a system can specify com-

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[3] In any case, and although entropy stands as a notion of fundamental importance for understanding irreversible processes, it may be debatable whether or not it can be decomposed into more basic categories. According to dimensional analysis, entropy can be understood in terms of energy (and therefore of mass, length and time) and temperature (dependent on the average speed of the particles that compose a system). However, its conceptual importance is so high that it is theoretically plausible to grant it a certain degree of autonomy, perhaps not so much as an utterly new and irreducible category but as a new law of nature (the second law of thermodynamics) which, despite being founded upon more fundamental notions, incorporates an operating rule that needs to be recognized on its own.

pletely its future outcomes. Complete knowledge of a certain state of the pair "position/momentum" (in classical mechanics, a state can be understood as a point in the phase space)[4] offers a complete determination of the evolution of the system, such that it is possible to unveil a set of determinations through which one can understand the behavior (seen as dimensional evolution) of the system. This deterministic character is also projected onto the past: from a given state it is possible to know where the system was backwards in time, provided that a clear distinction between past and future has been established by setting an axis that divides both directions in the flow of time. Thus, the laws of classical physics must be reversible, and in consequence they must be unaffected by the direction in which time flows. Indeed, among the set of imaginable laws, only some of them are allowed within a system. There can be reasons of internal (compatibility between laws) and external (compatibility with physical reality, which is assumed to behave independently of the observer) consistency. So, in deterministic systems like those with which classical mechanics deals it is not possible to find laws that violate the property of reversibility; hence, the system must show uniqueness into the past and uniqueness into the future.

Therefore, an important question concerns the *principle of selection* that allows us, from a logical multiplicity, to choose only a certain set of laws. This "meta-law" (or "meta-laws", which should in principle be reducible to an even higher law, if a mind could ever achieve such a "logical monotheism," in which no degree of freedom were permitted and everything were completely determined by an absolutely universal and fundamental law) constitutes some sort of "law of law", through which a set of potential behaviors for a system can be selected, thereby determining a family of possibilities. The general laws of conservation, based upon principles of symmetry, can be contemplated as instantiations of these "meta-laws," given that they constrain the possible outcomes within the set of rules of transformations that can govern a physical system.

Indeed, *laws* may appear as models inspired by the irreducible fact that the universe manifests one structure instead of other, one function instead of other, but they can also be seen as concomitant operative rules: as the reasoning that runs in parallel to the facts, as the code by which information is transferred in the universe. A law is therefore the determination of the spatiotemporal structure of a domain of physical reality. To determine means to select an itinerary among a set of possibilities. Given the impossibility of knowing, with complete certainty, if the remaining conceivable possibilities

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[4] In quantum mechanics, a set of states is represented by a vector space over the complex numbers.

are actually realistic and consistent with other principles of nature, a law can therefore be regarded as the crystallization of a piece of evidence, of a *datum*: namely, how reality is organized, spatially and temporally, under specified conditions. Leonardo da Vinci masterfully recapitulated this idea when he wrote that "Nature does not break her law; nature is constrained by the logical necessity of her law which is inherent in her."[5]

Some authors have adopted an anti-realist view, arguing against the concept of "law," both in its metaphysical meaning (as universal and necessary rules) and its scientific understanding (in terms of symmetry, transformation and invariance).[6] However, one can always conceive of the laws of nature as idealizations of the mind, as mental models about certain domains of reality in which we seek to unveil invariant magnitudes that allow us to acquire a deeper understanding of the mechanisms involved in material processes. As it happens with any mental representation, in formulating a law of nature it is impossible to construct a 1:1 scale map between the theoretical statement and its counterpart in nature. Laws can thus be regarded as sufficient abstractions inside a set of well-defined boundary conditions; they only take into account the most relevant factors in the patterns of behavior shown by the natural processes which we aim to elucidate. Here, "relevant" simply points to the structures and properties that we need to consider for understanding the fundamental mechanisms of interaction through a series of spatial and temporal stages.

For example, let us analyze an ideal gas. Since Boyle, Mariotte, Charles, Gay-Lussac and Avogadro, we know that there is a fixed relation between the pressure P of a gas, its temperature T, its volume V and the number of moles n, according to the famous expression $PV=nRT$, where R stands for the universal constant of gases (equivalent to 8'31 J/$molK$ in the International System of Units). In this equation of state, a function $f(P,V,T)=0$ is defined in terms of three state variables, which provide a sufficient description of the most relevant factors that explain how an ideal gas behaves under thermodynamic equilibrium. This formula is the result of applying a very rigid set of presuppositions, like the absence of interactions between the gas molecules and the possibility of neglecting the individual volumes of the atoms which compose it. But if we adopt a more realistic point of view and we accept that the molecules cannot be represented as infinitesimal points free of attraction or repulsion, we need to elaborate more complex mathematical expressions. Thus, Van der Waal's equation establishes a correction for the ideal case by introducing the interactions between the molecules and their respective in-

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[5] *The notebooks of Leonardo da Vinci*, OUP, 1952, 7.

[6] Cf. Van Fraassen, B. C., *Laws and Symmetry*, Clarendon Press, 1989.

dividual volumes, introducing terms that depend on the nature of the particular gas. These terms grant us the possibility of adjusting the equation of state for the ideal gas to the observed experimental behavior, by distancing ourselves from the ideal conditions that had been imposed for the sake of simplicity in our examination of the subject.

Laws are therefore to be contemplated as limiting cases. Because we focus our analysis on certain variables while disregarding others, they can never constitute a complete description of reality, but only a sufficient summary of the fundamental factors that allow us to grasp the mechanisms of a particular domain of reality. This evidence implies, of course, that ultimately all laws of nature point to the conservation of some magnitudes in the context of the different processes accessible to the human intellect. Thus, a law always represents an ideal situation. For it is clear that no single body endowed with mass can ever be free of forces affecting it; indeed, gravitational attraction is omnipresent between massive entities, even if the result may be imperceptible or the combined effects may cancel out (so that in practice the body can be regarded as behaving in an inertial way). So, Newton’s first law, according to which in the absence of forces a body moves with a strictly constant velocity and in a uniform, rectilinear manner, can never be satisfied by a massive entity (which compose a vast majority of particles that are relevant for understanding physical structures). A law may then be interpreted as an imposition that selects possible itineraries, excluding other behaviors. Without Newton’s first law of motion, a body subject to centrifugal forces would not tend to leave the orbit through the tangent line and in a rectilinear trajectory, as a consequence of the inertia that it has acquired. Before our eyes, these discarded, or even counterfactual patterns may seem contingent, but we cannot know whether they are actually impossible, that is, incompatible with other laws of nature (such that they are not “co-possible”).

Thus, a law can be said to explicate the action of nature whenever certain conditions are fulfilled. It is therefore the characterization of a domain of objects and processes, or the subset of a range of possible behaviors, seen as variables of a function. From a deeper ontological point of view, the problem of determinism is still haunting, because, again, it is impossible to know whether this entire range of variables was actually feasible at a certain spatiotemporal point. Mathematically, a variable can adopt an arbitrary number of values, and it is thus encapsulated within a function; but physically, or even metaphysically, it is unclear whether the universe was determined to adopt this value of this variable at this spatiotemporal location. Nevertheless, for our present analysis it may be sufficient to leave this severe and far-reaching problem aside.

From the perspective that has just been exposed, a law can be interpreted as a determination of possible behaviors under certain boundary conditions. Then, all laws must be ultimately compatible with each other, and they must be consequently overlapped if we contemplate the universe as a single system, or a set of subsets, because they all refer to the same underlying physical reality. Hence, a law can be taken as essentially equivalent to a principle, at least as it is commonly used. More precisely, a principle, in any case, seems to denote the beginning of a logical process. Thus, it would stand as a premise sustained upon evidence, but selected to initiate a chain of reasoning, as it happens with Einstein's equivalence principle about the identity of gravitational and inertial masses (such that the acceleration imparted to a body by a gravitational field be independent of the nature of the body), which unleashed a remarkable intellectual quest that led to the geometric conception of gravity and enhanced our understanding of the relation between inertia and gravitation.

In summary, a scientific law –the formalization of a natural law within a theoretical model- can be visualized as a statement that, at a specific level of analysis, cannot be reduced to a more fundamental principle.[7] Of course, a law is always referred to a given set of ideal conditions that demarcate its range of application. For example, if I argue that, on the surface of the Earth, any object thrown by imparting upon it an initial velocity on the x-axis will describe a parabolic trajectory, it is clear that in the case of a feather I will have to take into account the effect of the friction exerted by the air, which will deviate this object from the ideal geometrical shape that it should follow. Because the human mind has been incapable of identifying a single law of nature, but only a set of laws with different although occasionally entangled domains of application, it is impossible to find a law of absolutely universal application (that is to say, a law embracing all known physical situations).

There is, of course, a certain degree of arbitrariness in this conception, knowing that the frontier between one level and another is often ambiguous. However, if reality can be rationally described as a coherent formal system built upon a minimized number of premises, all laws referring to upper levels of complexity should be ultimately founded upon more basic laws, perhaps upon the *most fundamental law*, both structurally (as the law from which

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[7] When these laws are traced back to the atomic level, some of them are found to be statistical in nature, but this fact does not invalidate their character as laws, because the aggregate of statistical phenomena can be condensed into a deterministic process, at least macroscopically.

the less universal laws are built) and chronologically (as the first law from which, in the history of the universe, the remaining laws were born).[8]

Indeed, one may pose the following questions: Why is nature normative? Why these laws instead of others? What is the fundamental law, the *Urgesetz*, if it exists, from which the other laws emerge? Will the human mind reduce the vast set of phenomena and laws to a single operative rule, or the multiplicity of laws is consubstantial to the universe, for without it no degrees of freedom would emerge and nothing new would arise in cosmos?

To return to our initial considerations about the factorization of complexity and the possibility of elucidating a set of basic categories in each science, it is always controversial to determine what these fundamental concepts would be. Nevertheless, dimensional analysis can help us to unravel some of these categories, by teaching us that all physical magnitudes are expressed in irreducible fundamental units, such as mass, length, time or electric current in classical physics (hence, the thermodynamic temperature might not be fundamental, since in kinetic theory it is represented as the result of the aggregate movement of countless molecules and, therefore, it is contemplated in terms of its average speeds). The development of a theory of measurement may contribute to achieving a profounder degree of reduction of these notions, by showing how certain magnitudes can only be measured in terms of spatial and temporal registers, which would stand as the truly "operatively irreducible notions".

In any case, a deeper examination will highlight the close relationship that exists between the fundamental categories and the physical framework adopted. The elucidation of the basic categories of a science like physics will depend on the model that one employs, thereby assuming different conceptual shapes if one starts with classical physics (whose most basic notions are mass, length, time, electric current ...) or the theory of relativity (where, among other peculiarities, space and time are intertwined, observations are local in nature and the speed of light in the vacuum stands out as a universal norm of nature).

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[8] Likewise, it is important to notice that when we explore the deeper levels of matter -especially in the sphere of elementary particles-, "reality" becomes a rather undefined concept. While in the macroscopic realm it is relatively simple to distinguish a wave from a particle, our understanding of the more fundamental strata of nature has shown that matter cannot be divided into waves and particles, if we want to be faithful to experimental data and committed to theoretical consistency. In its ultimate foundation (at least as it is presently known) material reality consists of both waves and particles; without fear of losing generality and completeness, it can be said that *it is both* a wave and a particle.

3. The condensation of complexity and the fundamental categories of physics and chemistry

To a first approximation, physics is the study of material processes. In order to refine this definition we need a better understanding of the term "matter", and therefore a sharper elucidation of the basic notions employed by the fundamental theories of physics is required. A theory will be deeper in accordance with the number and the nature of the connections between magnitudes (or "categories") that it is capable of discovering.

The theory of relativity investigates the invariant forms in the universe, that is, the transformations that allow us to identify structural invariants in the universe, which should be measured by all observers in the same way, regardless of their state of motion. The most fundamental principle that supports its reasoning is that of general covariance: the idea that the form of the laws of nature must be independent of the frame of reference used to express them. From this universal requirement physics emerges as the study of the laws of nature, their relations and their observation, conceived as general functions of the universe that must be common for all frames of reference. Therefore, it addresses the forms that underlie any process of measurement (in quantum mechanics, from practically irreducible notions such as those of state and observable it is possible to elaborate a mathematical formalism that models the evolution of an object -understood, in a certain way, as a concentration of energy in spatial cells-).[9]

These considerations suggest an understanding of physics as the rational and empirical study of the activity of an individual object and the interactions between individual objects, by unveiling the underlying properties. We come, therefore, to the conclusion that physical science is founded on the possibility of referencing objects -as entities arbitrarily susceptible to delimitation- in a communicable framework. Thus, the legitimacy of differentiating one object from another in our spatial and temporal registers is implicitly assumed. Observing can then be interpreted as the act of assigning space-time properties that are communicable from a frame of reference to an object or group of objects. Each potential observer will record its own local measurements, but it should always be possible to find transformation rules that allow to commen-

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[9] In quantum mechanics it is well known that the categories of "state" and "observable" play an essential role. However, for the sake of simplicity, and given the complexity of the extant debates on quantum mechanics, which inevitably demand a more detailed examination, our analysis of the fundamental categories of physics will gravitate, essentially, around classical and relativistic mechanics, and the discussion of quantum mechanics will be left for further publications.

surate the respective observations based on a fundamental invariant of nature, which is the speed of light in a vacuum, whose value has to be measured unanimously. Hence, within the framework of special relativity, the Poincaré group represents the Minkowski group of space-time isometries (the Lorentz transformations constitute a subgroup within the Poincaré group), thanks to which the interval between any two events remains invariant.

If one still adheres to a definition of physics as the study of material processes, in the light of the preceding reflections it seems reasonable to conceive matter, in the most parsimonious and generic way, as a dimensioned activity, that is, as an activity (or spatiotemporal unfolding) referenced in a framework whose information can be shared by different observers by virtue of the universality of the laws of nature. This understanding of matter would of course incorporate ordinary matter, antimatter, radiation and dark matter (a type of non-baryonic matter -essentially, matter other than protons and neutrons, which compose the atomic nucleon- that plays an essential role in the formation of large-scale cosmic structures and their ulterior development), as well as dark energy: thus, the totality of the real, or nature in its entirety as it is knowable for physics; in other words, all the structures and properties of the universe that are potentially accessible to the human mind.

One needs at least two initial degrees of freedom in order to generate meaningful propositions, susceptible to empirical contrast.[10] One of them corresponds to a fundamental category, while the other is related to the fundamental law or operating rule. It is possible that thermodynamics and quantum mechanics may incorporate additional categories and operating rules, but, again, this hypothesis does not significantly affect the primary in-

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[10] An interesting analogy to this philosophical statement can be drawn from the theory of numbers. Indeed, it is at least conceivable to describe an entire universe of objects from a single element, namely unity. All integers can be expressed in terms of unity; even zero can be written as (1-1), and from the binary system we know that 0 and 1 suffice to characterize natural numbers. Then, if 0 is defined as 1-1, it seems possible to express all integers in terms of 1. However, in addition to the element -1- we always need a set of operations (that can be interpreted as "rules of inference"), ultimately summation (+) and subtraction (-). Ideally, all integers could be reduced to a counting in terms of 1. Regarding complex numbers, and given that the imaginary number *i* does not exist in the domain of real numbers, it is clear that we need to define an additional element, which cannot be deduced from 1 (except if we consider it as the result of applying some operators, upon it). Furthermore, there is a profound semantic difference between unity and nullity. Syntactically, both notions can be regarded as instances of a specific set of numbers (real numbers), and they exhibit no deeper difference than the one that exists between 1 and 2, or between 2 and 3. But from a semantic point of view, they diverge. 1 house is not equal to 1 tree, yet 0 houses is equal to 0 trees. Thus, syntactically any unity is equal to any other unity: 1=1, though semantically it is clear that the units used to define the elements are important, because 1 kilogram is not equal to 1 meter. Yet, in the case of nullity, units seem to vanish, as if a universal nullity might be applied, even if a universal unity cannot be defined regardless of the frame of reference employed.

tention of illustrating and analyzing how each science, in charge of studying every level of complexity that can be reasonably distinguished on structural and functional grounds, assumes all the complexity examined by the more fundamental disciplines.

A "scientifically meaningful proposition" can be understood as the result of applying the scientific method to the study of a physical phenomenon, in which we are designing a proposition that reflects, as faithfully as possible, a given situation. Such a proposition is based on fundamental explanatory factors that in most cases are simply taken for granted, without the need to elucidate the entire demonstrative itinerary that, from logical and ontological precursors, has led to them. Thus, the elaboration of a scientific statement can be interpreted as the creation of a function that satisfies the conditions imposed by the domain of reality that we wish to apprehend. And in every function it is necessary to distinguish at least two elements: the object on which it is applied and the operative rules that it entails. For example, if we apply Newton's second law of motion to understand how the frictional force affects the displacement of a block of stone along an inclined plane what we are doing is to construct a function, whose argument is given by that physical body in particular, under a set of boundary conditions that constrain the range of the problem. The function applied will give us the operational rules governing that phenomenon. Therefore, and in more fundamental terms, the function can be equated with the laws of nature (the *form* of the universe), while the argument converges on the specific object of nature that we intend to study (its *matter*).

Thus, in every attempt at unraveling a mechanism we are trying to apply a function on an object in the context of a certain group of boundary conditions. The result of this operation is a set of data defined with respect to a reference system (for example, a quantitative value that is measured in a given system of units). So, if we return to the previous example, Newton's law about the relation between force, inertial mass and acceleration can be seen as the function that we apply on an object -the block of stone- situated under certain boundary conditions. By learning to elucidate a phenomenon from a scientific point of view, we have managed to explicate the information implicitly contained in that scenario. After all, no new information is added to the data implicit in our knowledge of the operative rules and the object in question. Therefore, it is in the discovery of new laws and new objects where true progress in the natural sciences lies. Identifying a new law (that is, a new operative principle) or a new object (that is, a new element of reality) expands the radius of our scientific knowledge. On many occasions, science merely applies known laws on known objects under changing boundary conditions, such that it does not ultimately generate new substantial information about the process; rather, it simply extends what is already known to cover scenarios whose explanatory variables do not differ significantly from previously explored situations.

Schematically, the conceptual architecture that has been outlined in the previous lines obeys the following model:

$$\begin{bmatrix} \textit{matter...} \\ \textit{energy...} \\ \textit{space...} \\ \textit{time...} \end{bmatrix} \text{ X } (\textit{fundamental laws of nature...}) = \textit{physically meaningful propositions}$$

In this conceptual structure, the notation "…" is introduced after every fundamental category and law of nature because it is clear that each of them implies a series of concomitant propositions, both *ad intra* (concerning the relationship between one category and the other) and *ad extra* (regarding the relationship between categories and operating rules).[11] Thus, it is possible to establish a narrow analogy between this conceptual system and that of a mathematical ring, understood as a fundamental algebraic structure consisting of a set that is equipped with two binary operations, satisfying certain axioms and capable of generalizing the basic arithmetic operations of addition and multiplication.

For example, and in a simple and idealized situation, we can think of a system composed by two electrons at a certain distance experiencing, according to Coulomb's law, electrostatic attraction. The previous representation would therefore yield the following physically meaningful proposition (in this case, about the evolution of the system):

$$\begin{bmatrix} \textit{electric charges} \\ \textit{distance} \end{bmatrix} \text{ X } (\textit{Coulomb's law}) = \textit{electrostatic force}$$

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[11] In essence, and although drawn from a different starting point, this model is closely related with Batterman's interesting notion of "asymptotic reasoning" (see BATTERMAN, R. W., *The devil in the details: Asymptotic reasoning in explanation, reduction, and emergence*, Oxford University Press, 2001), our focus, however, is not so much on the elimination of details as on the identification of the fundamental explanatory categories in the different sciences.

Or, in a system constituted by an ideal gas,[12]

$$\begin{bmatrix} \textit{pressure} \\ \textit{temperature} \\ \textit{volume} \end{bmatrix} \; \text{X} \; (\textit{Boyle's law}) = \textit{state of the system}$$

Also, and in accordance with the main equation of Newtonian mechanics,[13]

$$\begin{bmatrix} \textit{mass} \\ \textit{aceleration} \end{bmatrix} \; \text{X} \; (\textit{Second law of motion}) = \textit{evolution of system}$$

The transition from physics to chemistry involves "condensing" the degree of complexity that underlies the sometimes problematic division between both disciplines:

$$(\textit{categories of physics}) \; \text{X} \; (\textit{operating rules of physics}) \xrightarrow{\textit{condenser of complexity}} (\textit{categories of chemistry}) \; \text{X} \; (\textit{operating rules of chemistry})$$

To bring an example, we can use Proust's law of definite proportions (according to which a chemical compound always contains the same elements combined together in the same proportion by mass), a principle that lies at the basis of stoichiometry, to examine a chemical reaction leading to the formation of a compound:

$$\begin{bmatrix} \textit{Hydrogen atoms} \\ \textit{oxygen atoms} \end{bmatrix} \; \text{X} \; (\textit{Law of definite proportions}) = \begin{matrix} \textit{ratio of oxygen to hydrogen} \\ \textit{in water molecules} \end{matrix}$$

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[12] The constants of proportionality present in the equations of certain laws, like Coulomb's law of electrostatic attraction, can be considered as parts of the operating rules of that system, and therefore as elements of the expression of the laws themselves.

[13] Of course, the category of acceleration could in turn be decomposed into its constituent elements, in terms of spatiotemporal relations.

Proust's law can certainly be explained in terms of physical principles, although its statement condenses a vast amount of intermediate complexity between the level of elementary particles and that of chemical elements.

A *condenser of complexity* can therefore be regarded as a representation of the conceptual transition from a more fundamental to a higher-order level, between which it is reasonable, in the light of our present scientific knowledge, to draw a distinction with respect to their conceptual or semantic fields (that is, the group of categories and operational rules that suffice to understand their structure and potential activity, or their possible states and rules of behavior). Thus, this condensation of complexity involves transferring the explanatory properties from the more fundamental to the more complex levels, thereby endorsing a version of semantic reductionism through the quest for conceptual simplicity. This condenser of complexity is certainly an essential component of the model that has just been presented, given that it highlights the importance of reducing on the basis of those explanatory elements that suffice to understand the state and evolution of a system. Hence, by elucidating the fundamental explanatory elements it aims to unfold a common underlying pattern to different systems that can be grouped in accordance with their explanatory requirements, or their fundamental conceptual structure. This semantic unit would actually stand as the general sufficient condition, instantiated in a vast array of particular cases.

Indeed, the place of chemistry in the universe of scientific knowledge has generated interesting debates, whose implications for philosophy of science and, moreover, ontology (referred to the study of the specific nature of chemical objects and their reducibility to physical entities), have been emphasized by different authors.[14] Certainly, one of the great questions that need to be posed concerns the possibility of reducing the entire body of chemical knowledge to the underlying physical laws and properties, and whether success in applying quantum mechanics to chemistry actually justifies the complete theoretical reduction of chemistry into physics. Of course, this problem is intimately connected with the validity of assuming ontological continuity between all levels of reality.

As the complexity of the object of a particular science increases (such that its analytic decomposition turns out to be more difficult), the discipline in question is compelled to create new categories that become its core concepts, be-

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[14] For a detailed analysis of this problem, see Van Brakel, J., "On the neglect of the philosophy of chemistry", *Foundations of Chemistry*, vol. 1, núm. 2, 1999, pp. 111-174; Primas, H., *Chemistry, quantum mechanics and reductionism: perspectives in theoretical chemistry*, Springer Science & Business Media, vol. 24, 2013; Hettema, H. (Ed.), *The Union of Chemistry and Physics. Linkages, Reduction, Theory, Nets and Ontology*, Cham: Springer, 2017.

cause new structures and properties appear in accordance with the scale of our analysis. In Philip Anderson's words, "at each level of complexity entirely new properties appear […]. At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous ones."[15] Apart from the categories and laws borrowed from physics, chemistry works with its own categories and explanatory principles, capable of encapsulating the leap in complexity that it needs to take in order to examine the chemical properties of the different substances and the ways in which they react.

These condensers of complexity show an interesting analogy with the mathematical process of passage to the limit. In both of them the overwhelming complexity that mediates between levels is subsumed by generating a set of innovative categories and rules, which absorb the pseudo-infinite scale of summations (an analogy of the model used to describe large systems). Indeed, a quintessential idea, from which mathematicians have greatly profited since at least the 17th century, is that of limit. It allows us to conceive points not as real infinitesimals but as arbitrarily small limits. Thus, the concept of limit is capable of overcoming the contradiction between the Scylla of non-being (an infinitesimal and non-extensive real point, dimensionless in nature) and the Charybdis of being (a compact and extensive structure, but which *a priori* seems susceptible to division by the power of imagination). In this way, in order to measure the speed with which a function varies at a point it is not necessary to invoke the idea of infinity (even if it is in terms of the infinitely small) but that of a limit of differential quotients, which represents the approximation of the secant lines until they converge on the tangent at that point. Therefore, the conceptual basis of differential calculus lies in the notions of limit and difference. It is from them that a thorough understanding of this extraordinary mathematical tool arises, whose fecundity in virtually all domains of human knowledge is simply incommensurable.

It is not, therefore, illusory to claim that in the fundamental equations of quantum mechanics the whole of chemical science is contained. For these purposes, it is necessary to distinguish between the *general form* and the *particular provisions* within the different systems, each of which presents its own boundary conditions. For example, it can be said that the entire system of classical mechanics is summarized in the three laws of motion formulated by Newton. In fact, in the expression *Force* = *mass* × *acceleration* an unimaginable amount of information is condensed, from which almost all relevant data for the analysis of the problems addressed by Newtonian mechanics actually emanate. Indeed, there is a beautiful intellectual symmetry in Newton's laws

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[15] "More is different", in *Science*, vol. 177, núm. 4047, 1972, p. 393.

of motion. In fact, they keep a close analogical connection with Kant's three categories of relation: inherence and subsistence; causality and dependence; community or reciprocity: the first law deals with the subsistence of motion, as an inherent reality to any material entity through the notion of inertia; the second law points to the cause behind the change in motion –the application of a force-; the third law refers to the reciprocity between action and reactions, such that for every action there must be an equal and opposite reaction. The three of them seem to constitute a complete system of thought, in which all imaginable cases regarding motion are taken into consideration and all conceptual possibilities are subsumed into this triad of principles. Of course, such an outstanding degree of completeness may not necessarily appear in our formulation of all laws of nature, but it is difficult to deny that its degree of intellectual plenitude represents a praiseworthy ideal, the fruit of an intriguing harmony between form and content.

Nevertheless, the general form of classical mechanics needs to address a vast array of specific problems, where the boundary conditions may be more important than the theoretical foundation on which their study is based. Anyone who has dealt with problems of increasing complexity in this area will soon notice how naïve it is to believe that the knowledge of Newton's second law suffices to solve any hypothetical difficulty arising in the regimes on which classical mechanics is applied. It is possible to introduce so many details, such a heterogeneity of situations, such a diversity of agents involved in that system...; so many boundary conditions, after all, that although on a purely theoretical level everything is reduced to using the fundamental equation of mechanics wisely, in practical terms it is useless to attribute all our knowledge of the system to that compact formula.

Likewise, in chemistry we are exploring a set of phenomena that, despite deriving from the fundamental laws of physics, demand an adequate conceptual and practical treatment. The chemical systems incorporate new information, which in its fundamental aspects neither contradicts nor significantly extends the information that has already been contemplated by physics, but which in specific situations has to be combined with factors to which physics does not always pay sufficient attention. Although the Periodic Table can be explained from quantum mechanics, whose principles are capable of elucidating the composition of the atoms and the properties of the valence electrons (which play a fundamental role in differentiating the various elements of matter), in examining those systems with which chemistry is concerned it is essential to operate not only with the categories imported from physics but also with the convenient analytical tools that fully capture the defining details of those situations.

Thus, it can be said that the less fundamental systems, such as those studied by chemistry, do not add significant information that cannot be inferred from the basic laws of matter as examined by physics; however, they possess a level of complexity of their own, a specific configuration. As Martin Rees has written, "every lump of material, whether living or inanimate, is governed by Schrödinger's equation- the basic equation of quantum theory that describes all atoms and assemblages of atoms. In practice, though, we can't solve this equation for anything more complicated than a single molecule. The complexity of the solution depends on how many atoms are involved, and also on the intricacy of their internal structure (for instance, a living cell is vastly more complex than a regular crystal made of the same number of atoms). Moreover, even if we had a hypercomputer that could solve Schrödinger's equation for a complex macroscopic system and reproduce that system's behavior, the computer output would not yield any real insight. The insights that scientists seek require different concepts."[16]

For this reason, the investigation of the particular dispositions of the agents has to be combined with the appropriate knowledge of the interactions that govern these systems, which basically point to the fundamental forces of physics. The central categories of chemistry remain physical in nature, but the complexity of the system has its own characteristics, a uniqueness stemming from the particular configurations that determine it and from the interest of the scientist, who prioritizes the unraveling of some properties over others.

For example, to understand chemical reactions one needs to grasp how the exchange of electrons between the compounds occurs, and consequently the nature of the chemical bond. To elucidate these reaction mechanisms one must use concepts which, like that of electronegativity, refer to fundamental laws of physics, but only have a relevant role in chemical phenomena. Indeed, electronegativity (a measure of the tendency of an atom to attract a shared pair of electrons towards itself) represents a valuable example of a category at the interface between physics and chemistry. Although essentially physical in nature, given that it can be understood through fundamental quantum and electromagnetic principles amenable to a physical explanation, its true potential only shines in the study of chemical reactions and the chemical properties of the different elements. Thus, electronegativity pictures, in a vivid manner, the continuity between physics and chemistry, while at the same time highlighting the specificity of the domain covered by a strictly chemical inquiry. For it is only in chemical processes that this notion reveals its full explanatory utility. Along these lines, electronegativity can

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[16] Rees, M., *Our cosmic habitat*, Princeton University Press, 2017, p. 153.

be regarded as a condenser of complexity, capable of providing a profound link between the physical and chemical analyses of material processes. A vast quantitative and qualitative range of physical complexity is integrated into this category, which by means of the operational rules of chemistry helps us understand a specific family of material properties and processes (namely, chemical properties and reactions).

A chemist must become familiar with the nature and properties of matter, illuminated by our knowledge of the underlying physics, because the chemical properties of substances (that is, the properties that are related to the participation of a substance in a chemical reaction) cannot be clarified without understanding their physical properties. But in addition to the composition, structure and properties of matter, chemistry studies its transformations in the course of the reactions that certain substances can experience. The first part characterizes the physical dimension of chemistry, while the second part condenses its specific character, the level of complexity that it adds to the purely physical treatment of a system. Therefore, chemistry benefits immeasurably from the physical discoveries about the atomic and molecular structure of matter. Without understanding the properties of electrons, atomic nuclei and photons, for example, it would be impossible for the chemist to comprehend, at its deepest level, the nature of the elements and the compounds they are capable of generating. Indeed, some rather sophisticated methods for determining molecular structures are highly abstract and quantum in nature, like Mulliken's theory of molecular orbitals (in which electrons, instead of being assigned to individual bonds, are treated as if they were moving under the influence of the nuclei that compose the molecule in question, describing molecular orbitals that can be expressed as linear combinations of atomic orbitals), inspired by progress in our understanding of quantum mechanics and its potential applications in chemistry.

In theory, chemistry could make significant progress in the absence of much of the fundamental physical knowledge borrowed from quantum mechanics. In fact, in the eighteenth and nineteenth centuries important developments in organic and inorganic chemistry took place. However, only with the creation of the fundamental model of matter offered by quantum mechanics it became possible to identify the real pillars on which the constitution of atoms and molecules was based, entities that represent, so to speak, the quintessential alphabet chemistry. This penetration into the deeper dimensions of the material realm not only expanded our physical knowledge but also had a positive impact on chemistry, and opened new and valuable horizons of research. Thus, the study of the chemical bond has allowed us to discern a framework of formidable explanatory power to justify how most reactions in which atoms and molecules participate actually occur. This elucidation of the mechanisms that underlie chemical reactions would have been unattainable without progress in our understanding of matter in its most fundamental aspects. Furthermore, the essential concepts around which the study of chemical reactions gravitates invoke a set of thermodynamic principles that were elucidated by physics through the study of energy transformations. Notions such as equilibrium constant, reaction rate, phase rule and chemical equilibrium encapsulate important applications of the great discoveries within the field of energy physics, many of which were made in the 19th century. And, of course, when one contemplates the Periodic Table and the way in which the different elements are grouped according to their properties, it is possible to observe a particular display of physical properties, determined to a large extent by the arrangement of electrons in the atom.

Thus, Linus Pauling, one of the greatest chemists of the 20th century, renders the following definition of chemistry: “the universe is composed of matter and radiant energy. Matter (from the Latin *material*, meaning wood or other material) may be defined as any kind of mass-energy (…) that moves with velocities less than the velocity of light, and radiant energy as any kind of mass-energy that moves with the velocity of light. The different kinds of matter are called *substances*. Chemistry is the science of substances –their structure, their properties, and the reactions that change them into other substances. This definition of chemistry is both too narrow and too broad. It is too narrow because the chemist in his study of substances must also study radiant energy, in its interaction with substances. He may be interested in the color of substances, which is produced by the absorption of light. Or he may be interested in the atomic structure of substances, as determined by the diffraction of X-rays (…) or by the absorption or emission of radiowaves by the substances. On the other hand, the definition is too broad, in that almost all of science could be included within it. The astrophysicist is interested in the substances that are present in stars and other celestial bodies, or that are distributed, in very low concentration, through interstellar space. The nuclear physicist studies the substances that constitute the nuclei of atoms. The biologist is interested in the substances that are present in living organisms. The geologist is interested in the substances, called minerals, that make up the earth. It is hard to draw a line between chemistry and other sciences.”[17]

The reason behind the difficulty outlined by Pauling may reside in the fact that chemistry stands at the epicenter of the natural sciences, halfway between physics (which provides its foundations) and the biological sciences (which apply the results of chemistry for understanding the structure and properties of biological entities). Therefore, it can be regarded as the upper

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[17] Pauling, Linus, *General chemistry,* Courier Corporation, 1988, pp. 1-2.

layer of physics and the ground of biology, connecting matter in general with the particularities exhibited by the specific structures adopted by matter throughout cosmic evolution. This privileged position at the crossroad of the natural sciences has been crucial for increasing our knowledge of the material world, discovering fundamental applications of this understanding that have shaped our civilization and, moreover (a consequence of incontrovertible transcendence for the development of the human mind), broadening our awareness of the intimate connection between the different realms of reality, in particular between the physical and the biological spheres.

4. The whole, the parts and the possibility of reduction

We are not proposing, in short, that the whole be greater than the sum of the parts, or that the complexity of the chemical systems implies the emergence, *ex novo*, of information that is not contained in the fundamental laws of physics. The whole is reduced to the sum of the parts *plus* the interactions that they establish, but in the determination of the parts and their particular interactions, the more general principles of physics only act as basic guidelines, as global functions that must be applied on specific situations, mediated by a set of boundary conditions and inexcusable internal regulations.

Physical and chemical properties coexist, and they are manifested depending on our level of analysis and the kind of phenomena studied. Indeed, it can be argued that these classes of properties are actually the result of the same fundamental laws acting on different situations (that is, on different states and processes defined by a set of boundary conditions). Sometimes the complexity of the system is so substantial that it is almost impossible to find the exact solution to the equations stemming from the application of these fundamental laws. Fortunately, scientists and mathematicians have developed successful theoretical tools for addressing the problem of computing physical variables in highly complex systems, where an exact solution is virtually unattainable. They all tend to start from relatively simple and reasonable assumptions that help simplify the complexity, by focusing on certain relevant and far-reaching factors and "pruning" other, less influential (and frequently negligible) aspects. One of them is the virial theorem, which allows us to calculate the average kinetic energy of a system consisting of a large number of particles in terms of the total potential energy. This result has proven extremely useful in the field of statistical mechanics. Also, and to bring an example from condensed-matter physics, quantum chemistry and materials science, the so-called "density functional theory" offers the possibility of modelling the electronic structure of many-body systems, like atoms, molecules and condensed phases.

Thus, it is clear that despite the extreme complexities exhibited by certain physical and chemical systems, by employing certain computational methods and stressing some relevant factors it is often feasible to deal with equations that in principle seem not soluble in an analytic sense, given the number of elements involved. Again, extreme quantitative complexity, as is the case in the study of many-electron systems, does not need to imply the presence of new laws and principles essentially different from the underlying conceptual structure formalized through quantum mechanics. Even if we do not understand how to interpret them in a precise and consistent manner (as the controversies surrounding the meaning of quantum mechanics indicate), we have nonetheless acquired a fair knowledge of how these laws relate to each other and shape the structure and functionality of a significant amount of physical systems. Hence, it is not necessary, at least in principle, to invoke qualitatively different laws other than those depicted by quantum mechanics in order to treat more complex material assemblies, for it is a matter of developing the adequate mathematical methods to find the approximate solutions to the applications of these laws.

Of course, our view is far from assuming that the gap between levels cannot be surmounted. Rather, it admits as premise that "*natura non facit saltus*." Only the poverty of our knowledge of the detailed microscopic transitions and the extreme complexity of the different systems impedes us from sketching a strictly gradual transition.

In any case, the difficulty of explicating the detailed mechanical itineraries between levels acquires an almost dramatic character in the transition between chemistry and biology.

For example, natural selection can be explained by physical and chemical principles, but it covers such a vast and complex realm of entities that it is virtually impossible to reduce this notion to its more basic components. Indeed, natural selection can be regarded as a universal mechanism of efficiency. Such a rule guarantees the survival of those forms that have achieved a higher degree of adaptation to their environment. Unveiling how the force of natural selection operates allows us to compute the probability of survival of a biological entity in a given set of boundary conditions. However, absolute certainty (meaning "full predictability") is impossible, due to the presence of uncontrolled contingencies. To use a legitimate analogy, natural selection "quantizes" the potential organic forms that can be adopted by a biological entity in order to survive in a certain environment. Out of the virtually countless range of organic forms that are feasible both structurally and functionally, only some of them fulfil the criteria needed to subsist in a specific ecological unit; thus, they can be regarded as the *eigenvalues* of the operator.[18] But the prediction of the exact organic form that will finally survive is an almost utopian dream, although it may be plausible to elucidate some general rules describing the probabilities of transition from one biological state to another (as in quantum mechanics), by indicating which states are compatible with that ecological unit.

Indeed, the extreme difficulty of offering biological predictions points to the insufficiency of an understanding of science in terms of its power to anticipate future outcomes of a process. It seems, in fact, more reasonable to characterize science as the intellectual discourse that tries to elucidate the structure and mechanisms of natural objects and processes, by explaining how the parts are connected in a systematic way. The unveiling of a mechanism may not lead to the possibility of making successful predictions, at least "hard predictions," like those amenable to physics and chemistry. For not only physics, but also chemistry, exhibits an outstanding predictive power in many of its domains of research. Thus, Mendeleev could predict the existence of unknown chemical elements by understanding the way and order in which atomic properties appear in the Periodic Table, or more recently Rudolph Marcus could present a theory of electron transfer reactions in chemical systems that produced outstandingly accurate kinetic and thermodynamic predictions.

In biology it is however possible to propose "soft" predictions about the generic type of effect that may probably arise out of a certain process, but hard, strict predictions susceptible to precise quantification are almost impossible, due to the relevant role played by the boundary conditions around biological systems, their continuous interaction with the environment (that grants an almost unique character to biological entities, beyond the shared principles and structural patterns), their internal complexity and the omnipresence of randomness and uncontrollable contingencies. The overall effect of these and other factors generates a richness of possibilities, a vastness of

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[18] Indeed, this thesis is by no means new. As it was noted by Woese and Fox, "the organizational differences between prokaryote and eukaryote and the composite nature of the latter indicate an important property of the evolutionary process: Evolution seems to progress in a "quantized" fashion. One level or domain of organization gives rise ultimately to a higher (more complex) one. What "prokaryote" and "eukaryote" actually represent are two such domains. Thus, although it is useful to define phylogenetic patterns within each domain, it is not meaningful to construct phylogenetic classifications between domains: Prokaryotic kingdoms are not comparable to eukaryotic ones. This should be recognized by an appropriate terminology. The highest phylogenetic unit in the prokaryotic domain we think should be called an "urkingdom" —or perhaps "primary kingdom". This would recognize the qualitative distinction between prokaryotic and eukaryotic kingdoms and emphasize that the former have primary evolutionary status". Woese, C. R. & Fox, G. E., "Phylogenetic structure of the prokaryotic domain: the primary kingdoms", *Proceedings of the National Academy of Sciences*, vol. 74, núm. 11, 1977, pp. 5088-5090.

potential configurations, an "openness" of the system (beyond the general laws and structures that constitute its bases) that offers a valuable conceptual bridge between the field of study of the natural sciences and that of the social and human sciences, for this dual character, halfway between universality and particularity, or between generality and individuality, represents an important root of variability and behavioral exuberance.[19]

At this point it is pertinent to clarify to a larger extent a concept of great relevance for our discussion, which has been latent in the previous paragraphs. In effect, our considerations inevitably evoke the idea of "*reduction*" and "*reductionism*" as a legitimate scientific method. But what should, in our view, "reduction" mean in the theory of science?[20]

By reduction we understand the process of unveiling the foundations of a certain proposition from more basic principles. Hence, reduction should not mean for us the elimination of heterogeneous information but the attempt at founding the comprehension of more complex entities upon the simpler strata on which they are sustained, ultimately upon the set of fundamental laws that rule the universe (thus, from this perspective an ultimate convergence between conceptual and ontological reductionism should be viable). Concerning human consciousness (a topic which exceeds the scope of the present paper), we believe that instead of eliminating the apparently subjec-

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[19] The reasons behind the shadow of indeterminacy in biology are lucidly summarized by Ernst Mayr in the following way: "Without claiming to exhaust all the possible reasons for indeterminacy, I can list four classes. Although they somewhat overlap each other, each deserves to be treated separately. 1) Randomness of an event with respect to the significance of the event. Spontaneous mutation, caused by an "error" in DNA replication, illustrates this cause for indeterminacy very well […]. Uniqueness of all entities at the higher levels of biological integration. In the uniqueness of biological entities and phenomena lies one of the major differences between biology and the physical sciences. Physicists and chemists often have genuine difficulty in understanding the biologist's stress of the unique, although such an understanding has been greatly facilitated by the developments in modern physics […]. 3) Extreme complexity. The physicist Elsisser stated in a recent symposium: "[an] outstanding feature of all organisms is their well-nigh unlimited structural and dynamical complexity." This is true. Every organic system is so rich in feedbacks, homeostatic devices, and potential multiple pathways that a complete description is quite impossible. Furthermore, the analysis of such a system would require its destruction and would thus be futile. 4) Emergence of new qualities at higher levels of integration. It would lead too far to discuss in this context the thorny problem of "emergence." All I can do here is to state its principle dogmatically: "When two entities are combined at a higher level of integration, not all the properties of the new entity are necessarily a logical or predictable consequence of the properties of the components." This difficulty is by no means confined to biology, but it is certainly one of the major sources of indeterminacy in biology. Let us remember that indeterminacy does not mean lack of cause, but merely unpredictability". Mayr, E., "Cause and effect in biology", *Science*, vol. 134, núm. 3489, 1961, pp 1501-1506.

[20] For an in-depth analysis of the problem of reductionism in ontology and the philosophy of science, see Gillett, C., *Reduction and Emergence in Science and Philosophy*, New York: Cambridge University Press, 2016.

tive and extra-scientific dimensions of this phenomenon what must be done is to explain the underlying neurobiological principles, in order to elucidate the path that leads from molecules to the conscious thought. In this way, the scientific project of understanding consciousness must strive to insert such an intriguing function of the mind within our neurobiological knowledge; it cannot pretend, in any case, to complete this enterprise by eliminating properties that require an adequate explanation.[21]

It is important to notice, however, that the assumption of continuity between the different levels of reality (which would constitute a vast *catena aurea*) does not prohibit the existence of critical points, broken symmetries and sharp transitions: it simply excludes the possibility of an infinite gap in a finite realm of reality; only imagination could make those leaps.[22] Indeed, abrupt alterations can happen –as certain quantum mechanical processes and phase transitions in condensed matter physics show-, but they can always be examined from the point of view of the continuity in the distribution of probabilities. Thus, the condenser of complexity to which we have referred expresses a summation that tends to infinity through countless intermediary transitions; it does not therefore represent the normalization of a real infinity.

5. Concluding remarks

Given the scope and limits of this paper, our previous considerations have been circumscribed to natural sciences like physics and chemistry, in which the project of identifying fundamental categories whose adequate integration may help formalize the basic results of these disciplines is certainly more plausible. Indeed, we have tried to show the legitimacy of understanding sciences like physics and chemistry as systems of categories bound by operating rules, whose conceptual architecture should allow us to elucidate those ideas endowed with a truly fundamental explanatory potential, thereby helping to reduce vast ranges of complexity and intricacies to the simplest notions upon which they are founded.

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[21] Regarding reductionism and the possible explanatory gap in a philosophical understanding of the mind, see Horst, S., *Beyond Reduction. Philosophy of Mind and Post-Reductionist Philosophy of Science*, New York: Oxford University Press, 2007.

[22] The possibility of assuming the existence of such an infinite gap in the study of human consciousness and, moreover, culture has been discussed in Blanco Pérez, C. A., *La integración del conocimiento*, Madrid: Ediciones Evohé, 2018. In this work ways to transcend the frontier between matter, consciousness and culture are also explored.

Nevertheless, it is clear that a philosophy of science aspiring to cover the entire system of human knowledge must at some point address higher levels of complexity, as those present in biology and the human and social sciences. In any case, we have hope that the mediation of the neurosciences, whose increasing understanding of the brain is revealing major properties and dimensions of the human mind, may act as a bridge between the natural and the human and social sciences. Thus, in this model it would not be necessary to propose different "kinds" of rationality, in accordance with the distinctive ways of "dividing up" reality;[23] rather, a theoretical exploration of the central tenets of a philosophical understanding of mind and culture should suffice to integrate the human world into a common system of scientific rationality.

In our view, however, the greatest problem faced by the social and the human sciences resides in their inability to agree on their fundamental categories and operating rules. The nature of their object of study is reminiscent of the self-referential character that we find in logic and mathematics, because the totality of human culture (the integration of values, symbols and practices that predominate in a given time and space endowed with a sufficient degree of homogeneity) is certainly rooted in biological needs and processes, but it ultimately evokes a historical construction, the fruit of our mental creativity. Hence, Giambattista Vico's celebrated distinction between *verum* and *factum* plays a prominent role, since the "truth" about the human world can hardly be isolated from its historical context.

Furthermore, as the level of complexity of a single entity or system increases, so does its capacity to interact with the environment through a greater variety of itineraries. What we normally call "adaptability" is of striking importance at the biological and cultural scales. These systems should never be regarded as strictly stationary, because they are constantly changing over time. Thus, the importance of time and evolutionary properties acquires a distinctive role, and the influence of the environment cannot be underestimated. This ability to react to changes in often unpredictable ways is perhaps one of the most relevant and "intrinsic" features of biological and cultural phenomena, as opposed to purely physical and chemical states and processes. Therefore, variability becomes a defining feature of biological phenomena; the trace of individual changes then implies that generalizations in terms of abstract properties becomes more difficult, as any single biological entity will show higher degrees of variability with respect to other members of its "class" than in merely physical and chemical structures.

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[23] As it has been suggested, for example, by Carson, E. R. & Flood, R. L., "Model validation: philosophy, methodology and examples", *Transactions of the Institute of Measurement and Control*, vol. 12, núm. 4, 1990, pp. 178-185.

In any case, the search for fundamental categories and operating rules that may be useful for the social sciences has to be combined with our knowledge of the human mind. If culture is the product of the mind's ability to construct worlds within the world, only a deeper understanding of the creative powers of the human intellect will shed light on many questions that today lie in darkness.

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