

On the Autonomous Existence of Chemical Entities

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Abstract: According to a traditional assumption, in principle chemistry could be derived from physics because chemical entities are nothing else than very complex physical entities. This assumption counts against the autonomy of chemistry as a scientific discipline or, at least, supports its secondary position with respect to physics. In this paper we review the arguments used for and against the idea that chemistry is nothing else than a branch of physics. In particular, we consider the status of chemical entities in the light of the discussions around the supposed visualization of orbitals. On this basis, we defend the autonomous existence of the chemical world.

Keywords: Molecular chemistry, Quantum mechanics, Reduction, Orbitals, Wavefunction, Semiclassical-electrons, Born-Oppenheimer approximation, Autonomy of chemistry.

1. INTRODUCTION

Historians of science know very well that chemistry and physics are inheritors of very different traditions [1]. Modern physics is the result of an unexpected but fruitful combination of the mechanicism propounded by Descartes with the corpuscularism propounded by Robert Boyle and other British thinkers, whereas chemistry can be considered as a derivation of medieval alchemy, of which it maintained a major interest in practical applications. While physics aimed at describing and explaining reality “in itself”, the main goals of chemistry always involved the manipulation and transformation of substances [2]. As a consequence, until the second half of the 19th century, chemistry and physics were two independent disciplines, and each had its own purposes and methodologies.

The situation began to change with the advent of quantum mechanics, whose impressive success supported the idea that chemistry is a branch of physics [3]: chemistry supposedly deals with complex systems and particular processes which, nevertheless, could in principle be described and explained by quantum theory alone. As early as 1929, Paul Dirac expressed the conviction that, since the underlying laws governing the behavior of the atom’s components became known, to do chemistry meant to deal with the equations supplied by physics:

“The underlying laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact applications of these laws lead to equations which are too complicated to be soluble” [4].

Dirac’s words have often been considered the clearest pronouncement about the derivability of chemistry from physics. However, an earlier claim made by the physicist Paul Langmuir in 1921 is scarcely known, although it expresses an even stronger position:

“I think that within a few years we will be able to deduce 90 percent of everything that is in every textbook on chemistry, deduce it as you need it, from simple ordinary principles, knowing definite facts in regard to the structure of the atoms” (quoted in [5]).

This view rapidly acquired the status of a dogma, and was adopted by many authors active in the fields of chemistry, physics and philosophy (for a review of those opinions, see [6]).

This traditional assumption about the relationship between chemistry and physics counts against the autonomy of chemistry as a scientific discipline or, at least, supports its secondary position with respect to physics. In fact, while physics is defined to be a “fundamental” science which describes reality in its deepest aspects, chemistry is conceived as a mere “phenomenological” science, which only describes phenomena as they appear to us. This supposed difference between the two disciplines agrees with the traditional hierarchical classification of natural sciences, rooted in the positivistic thought of the end of 19th century, which assigns the seat of honor to physics –due to its fundamental scope and aims, while chemistry is relegated to an inferior position, since it can supposedly be derived from fundamental physical laws.

In previous works we have critically analyzed the traditional assumptions about the relationships between chemistry and physics [7-10]. The aim of the present paper is to review those works in order to consider the arguments used for and against the idea that chemistry is nothing else than a branch of physics. In Section 2 we shall recall the arguments that

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stress the impossibility of deriving chemistry from physics. Section 3 is devoted to consider the status of chemical entities in the light of the discussions around the supposed visualization of orbitals. In particular, we shall show that the arguments against the observations of orbitals are rooted on an implicit reductionism, that is, the position according to which the only real entities are those described by fundamental physics. In Section 4 we shall propose further arguments against reductionism. Finally, in Section 5 we shall draw our conclusions and introduce some non-reductionist, pluralist perspectives.

2. WHY ASSUME THE DERIVABILITY OF CHEMISTRY FROM PHYSICS?

During the last decade, several authors have begun to defend the autonomy of chemistry by stressing the impossibility of deriving chemical concepts and descriptions from the concepts and the laws of physics. For instance, Vemulapalli and Byerly [11] claim that the derivation fails even in relatively simple cases: in general, the properties of a chemical system cannot be explained in terms of the properties of its physical micro-components; and even when the properties of a chemical macro-system can be derived from those micro-components, this requires additional assumptions related to macroscopic phenomena. One of the situations considered by the authors is equilibrium in non-ideal multicomponent systems: although there exists a method for relating the properties of a system to the activities of its components, the numerical values of the individual activities must be derived empirically from experiments on the system or theoretically from postulated intermolecular forces or from other *ad hoc* hypotheses coming from the outside of the main body of the theory; in neither case can the individual activities be deduced from the properties of the micro-components of the system. Analogously, where non-ideal systems are concerned, the statistical-thermodynamical equation of state used to estimate the interaction energies between molecules cannot be deduced from any fundamental theory.

In the same line of argumentation, Scerri and McIntyre [12] distinguish between “quantitative” and “conceptual” matters regarding the relationship between chemistry and physics. Quantitative matters refer to the calculation of chemical properties from physical theories, in particular, quantum mechanics. This requires approximation techniques that can only be justified on a *post hoc* basis, that is, on the basis of the experimentally observed data which one is trying to calculate. On the other hand, conceptual matters are concerned with the definition of chemical concepts in terms of physical concepts. According to Scerri and McIntyre, this kind of definition is impossible due to the very nature of the chemical concepts themselves: the concepts of composition, bonding or molecular structure can be expressed only at the chemical level.

Van Brakel [13] addresses the traditionally alleged deduction of thermodynamics from statistical mechanics from a similar perspective. He correctly points out that, in general, temperature cannot be defined as mean molecular kinetic energy: this is true for perfect gases compounded of idealized “billiard-ball” molecules in random motion, but not for solids, plasmas or vacuum. According to van Brakel, all the

problems for an effective derivation seem to be related to the macroscopic notion of equilibrium, the central notion of thermodynamics: for instance, the macroscopic concept of temperature only makes sense for systems in equilibrium; but there is no such thing as equilibrium at the microscopic level.

Summing up, the traditional assumption that chemistry is just a branch of physics has begun to be challenged by noting that chemical concepts and laws can hardly be deduced from physical theories. In particular, crucial chemical notions such as chemical bond, chirality, molecular shape or orbital among others, are not amenable to rigorous quantum mechanical treatment. Of course, such a failure guarantees the methodological autonomy of chemistry as a scientific discipline: to the extent that there are specifically chemical concepts, chemists can continue with their work with no worry, since physicists will not replace them in the laboratories. As Benfey says:

“we will continue to carry out the work of chemists because no non-chemists are equipped to do it” [14].

However, this fact does not answer yet a relevant question: Why is chemistry a “secondary” science?

The answer to this question can be found in the still widespread assumption of *reduction*: although chemical concepts and laws cannot be directly derived from the laws of quantum mechanics, chemical entities are in themselves nothing else than physical entities. Therefore, the chemical concepts non definable in quantum-mechanical terms refer to apparent or secondary entities endowed with a derivative status. For instance, molecular shape turns out to be only a

“powerful and illuminating metaphor” [15].

Under this assumption, whereas physics describes the deepest and fundamental structure of reality, chemistry is a secondary science which studies “metaphorical” objects. In other words, the fundamental physical entities are the only real entities, and chemistry exclusively describes apparent phenomena or, at best, an inferior level of reality.

The professional chemist might consider that this topic could comfortably be confined more to a “philosophical” discussion, rather than to a scientific discussion about chemistry. However, the issue of reduction acquires a special importance when it relates to so significant experimental results as the direct observation of orbitals.

3. THE CASE OF ORBITALS

In an issue of September 1999, the prestigious journal *Nature* broke shocking news to the communities of chemists and physicists. On its front page it announced that atomic *d*-orbitals of Cu₂O had been imaged for the first time [16]. More than ten years after that announcement, the story is now well-known. That news was immediately followed by a number of comments, and the images obtained by the Arizona State University group were uncritically identified with the atomic orbitals that are dealt with in textbooks [17-19]. The result was rated as one of the most spectacular results obtained in both chemical [20] and physical [21] research during the year 1999.

By way of contrast, other authors expressed serious reservations concerning the interpretation of the experiments: different arguments were put forward to conclude that, conceptually speaking, the visualization of orbitals is virtually impossible [22-23]. Even John Spence, the leader of the team who conducted the experiment, conceded that point [24]: any similarities between the images which were recorded in the laboratory and the orbitals which are depicted in textbooks are completely fortuitous. Apart from analogous arguments, which were proposed by some theoretical chemists [25-27], let us consider in some detail the conceptual arguments denying that the above similarities have any basis in fact.

3.1. The Arguments Against the Existence of Orbitals

A very common argument used to deny the existence of orbitals relies on the fact that approximations are involved in any model describing many-electron atoms. In fact, only the atom as a whole possesses a well defined stationary quantum state represented by its total wavefunction, which results from the interactions between the nucleus and each electron, and the interactions of the electrons with each other. As a consequence of the latter interactions, neither can the total Hamiltonian of the atom be obtained as the mere addition of the Hamiltonians of the component electrons, nor can the Schrödinger equation be analytically solved. Moreover, bear in mind that neither can the electrons be conceived as having individual and dynamically independent states, nor – consequently – can well-precise quantum numbers be independently assigned to them. Any decomposition of the total wavefunction of the atom as a product of electron wavefunctions is a mere approximation, as it neglects the electron interactions. According to Scerri [22], the only value of orbitals lies in their serving as basis sets, or as a form of coordinate system, with which the wavefunction of an atom, ion, or molecule can be expanded mathematically to any degree of accuracy afforded by the computational powers in hand.

Oddly enough, the fact that the computations based on the factorization of atomic wavefunctions provide approximate results is invoked by some authors to argue against the existence of orbitals. For instance, Jenkins' denial relies on experimental grounds, not on philosophical grounds:

“We reject orbitals in particular cases because they do not predict experimental results with an accuracy sufficient for those particular cases” [23].

From this perspective, when the mathematical technique used in a description is not sufficiently accurate, we should consider all the concepts involved in such a description as non-referring, that is, as concepts that do not designate any real entity. This amounts to turning a mathematical limitation into a question about existence. But matters can get even worse than that: if the limit of an approximation denied by itself the existence of the entities which the model attempts to describe, we would be left with a science which is a total “void”, that is, a science that deals with non-existing objects. As Ostrovsky points out [28], when we say that the exact solution of the Schrödinger equation can be obtained only for the hydrogen atom, we are talking about a non-relativistic description. Indeed, the Schrödinger equation is itself an

approximation since it does not account for relativistic effects. An exact solution can be obtained also through the Dirac equation, which takes relativistic effects into account: it grants a better agreement with experiment but, again, it is itself an approximation. If we want to achieve more accurate results, we have to turn to quantum electrodynamics which takes into account the interaction of the atoms, and so on until one comes to the conclusion that:

“physics is nothing else than a hierarchy of approximations [...]. This is not a pitiful temporary drawback that might be removed in the course of time. It will continue forever, since it reflects the essence of the approach of physics to describing nature” [28].

As a consequence, if approximation implied non-existence, not only orbitals would cease to exist, but the entire world described by science would vanish as a whole.

This argument applies only to many-electron atoms (since only in these cases is the atomic wavefunction non-separable), but not to the hydrogen atom and any other one-electron atomic system. This sounds rather puzzling, as one would expect that, if orbitals do not exist, such a conclusion should apply to any kind of atoms involving electronic orbitals. In fact, those authors who deny the existence of orbitals (which they define as electronic wavefunctions) developed a conceptual argument that is not confined to the many-electron systems, and runs thus:

“Orbitals depict a quantity called probability amplitude, which has been known to be unobservable in principle since the birth of quantum mechanics as distinct from the old quantum theory” [29].

This second strategy does not aim at computational approximations as the target of its critique: it denies the existence of orbitals for purely conceptual reasons. This new argument, however, relies on an essential premise: the identification of the term ‘orbital’ with the term ‘wavefunction’. The clue is, then, to ask whether the concept of orbital as wavefunction is just the same that chemistry uses to describe orbital shapes and to explain chemical bonding.

3.2. The Conceptual Breakdown Between Molecular Chemistry and Quantum Mechanics

In physics the description of the atom is only a particular case of application of quantum mechanics, that is, a theory dealing with systems composed of sub-atomic entities. In this context, the orbital of the hydrogen atom is the *wavefunction* of its single electron, that is, a mathematical item that does not designate a real entity although it is the orbital of a one-electron atom. This should not surprise us: since its early days, quantum mechanics strongly stated the view that the wavefunction is not a wave in physical space, but only one of the many possible representations of a state-vector belonging to a Hilbert space [30]. Moreover, quantum mechanics contemplates the existence of non-commuting observables; as a consequence, at sharp variance with the classical state, the quantum state of a system does not assign a definite value to all its observables. This result was originally interpreted as a limitation of the theory, which could be

removed by means of definite-valued “hidden variables” [30]. But the hope of recovering a classical picture vanished when Kochen and Specker showed that it is not possible to assign a precise value to all the observables of a quantum system without raising a logical contradiction, a statement which is commonly referred to as the “contextuality of quantum mechanics” [31]. In this way, quantum mechanics strongly challenges the classical notion of individual entities, which possess definite properties at all times [32]. Another central feature of quantum mechanics is its non-locality, as manifested by Einstein, Podolsky and Rosen [33] in the so-called EPR-type experiments: the behavior of a quantum system cannot be accounted for independently of the correlations with all the other systems with which it interacted in the past, no matter how long those interactions have ended, and how far those systems are at present [34 (a), 34 (b)]. This notion of non-locality conflicts sharply with the classical assumption that an object can be located at a well-precise spatial position all the time. These concepts of quantum mechanics, which have puzzled a great many physicists and philosophers for several decades, show that no classical picture of *locally individual* objects fits into the quantum domain.

Chemistry, on the contrary:

“is not the science of atoms, [...] but the science of molecules” [35].

The main purpose of molecular chemistry consists in identifying the different kinds of molecules and in studying their individual and collective properties [36]. A central feature of a molecule is its shape, the knowledge of which is essential for a better understanding of the physico-chemical properties of matter. As Woolley claims, the notion of molecular shape is

“the central dogma of molecular science” [37].

This notion is a spatial, classical notion: the shape of the molecule is explained in terms of the spatial relationships among the component atoms and the shape of its orbitals. Indeed, the term ‘orbital’ needs to have a spatial content in order to account for the geometrical dispositions of the atoms in the molecule. According to molecular chemistry, the orbital of the hydrogen atom is thus understood as the *region of space* where the single electron of the atom is most likely to be located.

In the chemical context, molecules are non-quantum objects in both an individual and local sense: they have definite properties all the time, keep their identity unchanged even when some of their properties change, and always possess not only a definite position but also a definite shape. As Primas says:

“The alpha and omega of molecular chemistry is the doctrine that molecules exist as individual objects and that every molecule has a shape, characterized by its molecular frame” [38].

Even the notion of molecular frame is a classical concept, which relies on the assumption that all the nuclei possess well-precise positions and momenta, an assumption which marks a sharp break from the afore-mentioned notion of

quantum contextuality. Since the non-locality of quantum mechanics excludes the spatial concept of molecular shape [39], in order to conceive the molecule as an individual object with its own shape it is necessary to ignore quantum correlations. In other words, in molecular chemistry a molecule:

“exists separately and independently in the sense that it can consistently said to ‘have’ certain properties, whether or not it interacts with anything else” [40].

In turn, the state of the molecule determines its properties, as in classical physics; molecular chemistry does not include the possibility of superpositions in Hilbert space [41]. For instance, if chemical isomers, with their own shape, correspond to different state vectors, then superposition makes sense from the quantum-mechanical viewpoint:

“What is the shape of the hypothetical superposition of (state vectors corresponding to) these two species? Is there a proper reason to exclude such superpositions? What reason can be given –from a quantum-mechanical point of view– for chemical systematics?” [40].

Summing up, the shape of the molecule depends on the spatial disposition of its individual atoms, the locations of which are given by the definite positions of nuclei obeying the laws of classical theory; and although they do not follow definite orbits, the electrons, too, are individual objects whose location lies in a region of space close to the nuclei, and whose probabilistic distribution is given by the total wavefunction. In other words, the molecule is constituted by classical nuclei and semi-classical electrons, that is, individuals whose behavior is not governed by classical equations of motion but by an equation that determines their position only in a statistical way. This picture is completely alien to quantum mechanics, where one could strictly speak only of the molecule-system, described by its whole non-separable state vector, maintaining its quantum correlations with other quantum systems, and whose components are not classical individuals but quantum subsystems with the same quantum features, that is, contextuality and non-locality.

The traditional strategy to combine the chemical description with the quantum description of molecules usually appeals to the Born-Oppenheimer approximation, which in general supplies good predictions because the mass M of the nucleus is much greater than the mass m of the electrons. From a formal viewpoint, the approximation is an asymptotic expansion around the singular limit $m/M \rightarrow 0$. This means that the combination of the two descriptions can legitimately be applied only to systems involving nuclei with an infinite mass. But nuclear masses are never infinite: the Born-Oppenheimer approximation implies a:

“qualitative change in the theory which is expressed in the mathematics by a discontinuous approximation” [42].

As Amann claims, the innocent-looking Born-Oppenheimer approximation actually amounts to a “declara-

tion” that molecular chemistry smuggles into quantum mechanics:

“the nuclei of the involved molecule are declared to behave like classical particles” [43].

Therefore, the link between the chemical and the quantum description of the molecule is not a mere deductive relationship, to the extent that it involves a qualitative discontinuity between the related concepts. In fact, as Woolley and Primas point out, the Born-Oppenheimer approximation is analogous to the quasi-classical WKB (Wentzel-Kramers-Brillouin) approximation, with its corresponding limit $\hbar \rightarrow 0$. Such an analogy becomes natural when the issue is viewed from a more general perspective: both approximations are attempts to answer the still unsolved problem of the classical limit of quantum mechanics, that is, the problem of explaining how the local individuals of classical science arise from the non-local and contextual domain described by quantum mechanics.

3.3. The Underlying Reductionism

Once the *conceptual discontinuity* between molecular chemistry and quantum mechanics is recognized, the question is to decide what conclusion can be drawn from it. Let us consider two theories T_1 and T_2 , both containing a term ‘ C ’, which does not refer in T_1 , but refers to the entity C in T_2 . Moreover, T_2 cannot be derived from T_1 . For what reason can we say that the entity C does not exist *simpliciter*? Since derivation fails, the entity C described in T_2 does not exist only under the assumption that T_1 is the “true” theory or, at least, the theory most appropriate to describe reality. This assumption underlies Scerri’s claim:

“it is essential for scientists to be more discerning in attributing physical reality to entities which are theoretically defined and which the theory itself informs us do not exist physically” [44].

Which is the theory that informs us that orbitals do not exist? Quantum mechanics, of course. But why we do not ask molecular chemistry about the matter? What privilege does quantum mechanics carry for becoming the key witness about what exists and does not exist in the world? There seem to be no other grounds for that privilege than a reductionist attitude, according to which quantum mechanics is the best theory to describe the only “true world”: any description that disagrees with the quantum picture is unavoidably confined to a strictly non-referring realm.

Certainly, there is no logical contradiction in reductionism, but it is interesting to see the consequences implied by a coherent defense of it. If quantum mechanics were the only theory that describes (at least, approximately) reality, it would dictate what exists in the world, and it would be entitled to deny the existence of all the entities referred to by non-quantum theories (such as the local, individual objects of non-quantum science). As a consequence, not only would chemical orbitals not exist, but even any entities referred to by non-quantum theories would be merely “metaphorical”: molecules would vanish along with their shapes, gases with their temperatures, planets with their orbits, biological organisms with their cells, and so on. If the observation of chemical orbitals implied

“an outright refutation of quantum mechanics” [45].

then the observation of any entity not belonging to the domain of quantum mechanics would also refute it; nevertheless, all non-quantum science is supported by those observations. According to Scerri, orbitals do not exist and, then,

“they cannot be observed, period” [46].

If we replace in this sentence the term ‘orbital’ with any other term which is not covered directly by quantum mechanics, such as ‘cell’, ‘planet’, ‘virus’, ‘galaxy’, etc., the scholars who coherently hold the reductionist view would be forced to accept the logical consequences resulting from that replacement.

4. FURTHER ARGUMENTS AGAINST REDUCTIONISM

Although widespread, reductionism argument largely conflicts with historical evidence: the success of a relationship between scientific theories does not support the assumption of the reduction of some entities to other more fundamental ones. In fact, the history of science shows how certain intertheoretic links, which had previously proved successful, were later modified due to the replacement of the theory underpinning one of the poles of the relationship. The paradigmatic example is, again, the link between thermodynamics and the theory describing the supposedly underlying domain. In this case, the “fundamental” theory changed—from caloric theory (Carnot), to classical mechanics (Boltzmann and Gibbs) and, finally, to quantum mechanics (since the advent of the theory)—and the intertheoretic links changed with it; however, the “phenomenological” theory—thermodynamics—remained immune to the modifications throughout the historical process. So, we can conclude that there is no reason to expect that our best intertheoretic relationships will not be replaced in the future because of the eventual replacement of the supposedly fundamental theory. Nevertheless, as van Brakel claims:

“[i]f quantum mechanics would turn out to be wrong, it would not affect all (or even any) chemical knowledge about molecules (bonding, structure, valence and so on)” [47].

On the other hand, there are good pragmatic arguments to reject reductionism. In his well-known book *Representing and Intervening*, Hacking stresses that, in the discussions about the foundations of science, we have paid too much attention to theoretical considerations, forgetting the effective practice of science: it is in this pragmatic context where the criterion for the existence of scientific entities has to be searched for. According to Hacking, we accept the existence of inobservable entities when we can “spray them”, that is, when we can use them for intervening in other aspects of nature:

“We are completely convinced of the reality of electrons when we set out to build—and often enough succeed in building—new kinds of devices that use various well-understood causal properties of electrons to interfere in other more hypothetical parts of nature” [48].

In other words, it is scientific experimental practice, and not descriptive matters about theories, what gives us the best support for our commitments about scientific reality.

When the shift in perspective proposed by Hacking is taken into account, the conclusions about the existence or non-existence of chemical entities are no longer grounded exclusively on considerations about intertheoretic relationships. From this pragmatic viewpoint, molecular chemistry holds the winning card: its astonishing success in the manipulation of known substances and in the production of new substances is the best reason for accepting the existence of the entities populating its realm. In other words, we are entitled to admit the reality of the molecular world –inhabited by, among others, chemical orbitals, bonding, chirality, molecular shapes– on the basis of the impressive fruitfulness of molecular chemistry itself, independently of what physics has to say about that matter.

5. CONCLUSIONS: NON-REDUCTIONIST PERSPECTIVES

The arguments against reductionism do not amount to charging it with an unacceptable self-contradiction, but they intend to show that it is a metaphysical position which lies beyond any evidence. In fact, formal, historical and pragmatic evidence, far from supporting reduction, provides arguments for autonomy. Therefore, who still wants to defend reductionism, has to leave aside the search for support in evidence, and to acknowledge the metaphysical nature of her/his belief.

On the other hand, at present there are significant alternatives to reductionism. In recent works, Scerri revises his original views, and defends the autonomy of chemistry as the result of a form of liberation of the “physics imperialism”. According to this new view, each science, and even each theory, operates on its own level of reality, where the entities referred to by the theory may be legitimately considered as real: there is no contradiction in conceiving orbitals as existent entities at the chemical level but not real in the quantum-mechanical world. It is in this sense that Scerri argues for the view of:

“autonomous though related levels of reality” [49].

in terms of which the autonomy of the secondary sciences can be consistently defended.

In a similar vein, van Brakel rejects the traditional conception about the reference of the physical and the chemical discourses, designed under the paradigm of the mirror of nature:

“Each mirror gives a different autonomous picture of (part of) the world, but one mirror –the ideal physical one– mirrors reality as it *is*. All other mirrors [...] picture mere appearances, without cosmic significance” [50].

According to this author, such a paradigm should be abandoned by denying the asymmetric relationship between chemistry and physics:

“The same event can have a chemical and a physical description, [...] but no privileged description exists” [51].

As a consequence, the relationships between chemistry and quantum mechanics are best seen as symmetrical relations. If there is no privileged description,

“we could be tolerant enough to leave equal *ontological* room for manifest water, water in terms of the thermodynamic theory of substances, the molecular structure of water (‘constructed’ out of spectroscopic measurements), the ‘proper’ quantum mechanical equations for an isolated water molecule, and experiments with isolated water molecules which, depending on the measurement technique, show more of less of the ‘classical’ molecular structure” [52].

In recent works, we have proposed a Kantian-rooted realism [7-10, 53], according to which the perspective of God’s Eye does not exist: the world of science is always the result of applying a theory to the independent reality. In other words, it only makes sense to ask the question ‘What objects does the world consist of?’ within a theory or description. But we usually have different theories for a single domain; for instance, we describe the content of a balloon as a gas from thermodynamics or as interacting particles from mechanics. Nevertheless, since the privileged viewpoint of God’s Eye does not exist, there is no reason to believe that one world has priority over the other: in this pluralist reality, all the scientific worlds have the same status, because all of them are constituted by equally objective descriptions.

Of course, we cannot claim that in the present article we have covered the whole topic of the relationships between physics and chemistry. In particular, there remains still much to be said about non-reductionist perspectives and other epistemological aspects which lie far beyond the purposes of this work. However, we would content ourselves with it, if it succeeded in conveying the message that reductionism is not the only possible approach for establishing the ontological status of chemical entities.

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