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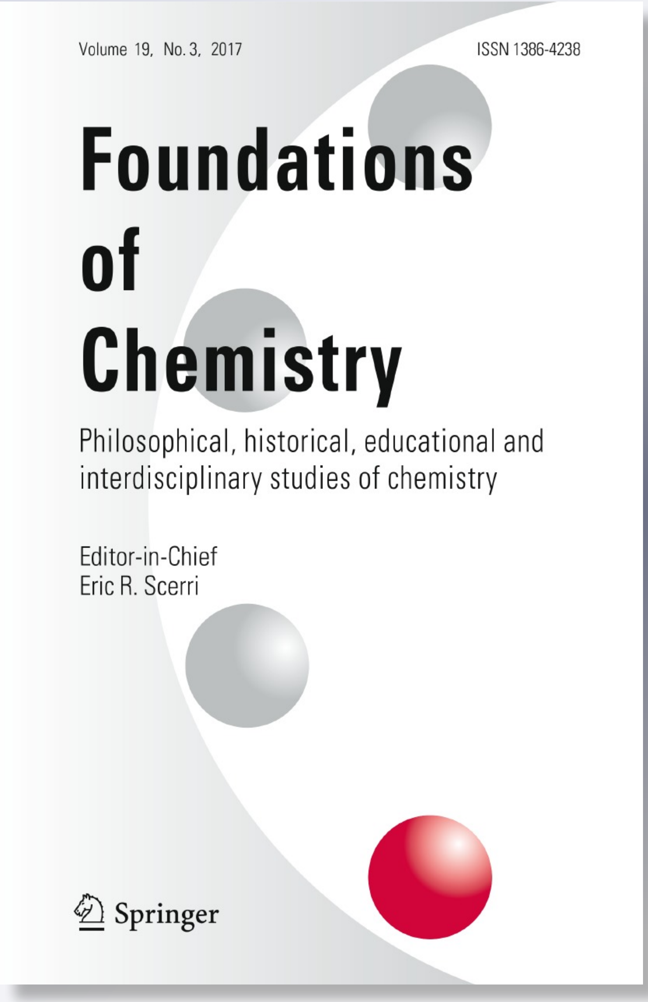
Foundations of Chemistry
Philosophical, Historical, Educational and Interdisciplinary Studies of Chemistry

ISSN 1386-4238
Volume 19
Number 3

Found Chem (2017) 19:185-196
DOI 10.1007/s10698-017-9283-6



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How to handle nanomaterials? The re-entry of individuals into the philosophy of chemistry

Mariana Córdoba[1] · **Alfio Zambon**[2]

Abstract In this paper we will argue that the categories of physical individuals and chemical stuff are not sufficient to face the chemical ontology if nanomaterials are taken into account. From a perspective that considers ontological questions and wonders which the items involved in science are, we will argue that the domain of nanoscience must be considered as populated by entities that are neither individuals, as those of physics, nor stuff, as those items of macro-chemistry. This discussion, in virtue of the analysis of the nature of nanomaterials, leads to propose a proper ontological category for nanoparticles: nanoindividuals. Nanomaterials are sorts of individuals, but they are different from physical individuals and from chemical stuff. We will also claim to contribute to the growing field of the philosophy of chemistry, especially regarding discussions that manifest not only epistemological but also ontological issues. In this scenario, the field on nanoscience is particularly challenging.

Keywords Individuals · Stuff · Nanoindividuals · Nanomaterials · Chemical ontology

Introduction

Nowadays, the philosophy of chemistry has become a deeply fruitful field of epistemological debate. Several traditional philosophical problems have been revisited in this particular area. Problems like realism and instrumentalism, monism and pluralism,

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incommensurability, theoretical change and theory choice -among others- have been discussed from different approaches within the realm of the philosophy of chemistry. An important issue traditionally discussed is the relation between physics and chemistry (the relation of reduction, emergence or supervenience), which has been the focus of a lot of attention. But some epistemological questions regarding chemistry itself -independently of its relation to physics- are brought up in present philosophical debates.

A subject currently debated is the problem of the ontology of chemistry (Ruthenberg and van Brakel 2008; Schummer 2008; Lewowicz and Lombardi 2013). Although it has been discussed from different approaches, there is an agreement about the fact that ontological questions regarding chemistry have gained central relevance and now they cannot be ignored (Scerri 2007, 2008; McIntyre 2007; Lombardi and Labarca 2005). In this fashion, our final aim is to contribute to the growing field of the philosophy of chemistry regarding some peculiarities of the discipline, paying special attention to ontological discussions, by means of a very important technological feature of current science: the existence of nanomaterials. The huge relevance of nanotechnology is considered here as an invitation to wonder about the ontological nature of nanomaterials. So, by agreeing with views that consider epistemological problems from an ontological perspective, we will analyze the issue of *what nanomaterials are*.

In order to do that, we will take the concept of *ontological category* as referring to what carries the responsibility of *structuring reality*. Ontological categories, as we will see, impose structure to scientific domains, in a way that the ontological structure of a given domain can be captured by the formal categories of a language organized by those categories as well. The elucidating power of this notion consists in the fact that it can account for the existence of meaningful discourse about a scientific domain and, consequently, for the successful ways of making inferences about what occurs in it.

We will analyze the inspiring distinction between the perspectives of matter and form proposed by Schummer (2008) ("The problem of chemical ontology: an epistemological approach"), and the also inspiring distinction between an ontology of individuals-and-properties and an ontology of stuff proposed by Lewowicz and Lombardi (2013) ("The problem of chemical ontology: an ontological approach"). We will examine what nanomaterials are from an ontological perspective, i.e., what the *nature* of nanomaterials is ("What are nanomaterials?"). It is our purpose to argue that an ontological category suitable for nanomaterials must be found, since the traditional categories of physical individuals and chemical stuff fail to be so ("Searching for the proper category for nanomaterials"). Finally, we will argue that nanomaterials are sorts of individuals, that we will call *nanoindividuals*, different from physical individuals and from chemical stuff. In this sense, we assert that the category of individuals re-enters chemistry by means of nanomaterials ("Re-entering individuals: an ontological perspective"). In our concluding remarks ("Concluding remarks"), we will consider some philosophical consequences of our approach and point out some questions that would require further philosophical discussions.

The problem of chemical ontology: an epistemological approach

The question about which are the ontological items that chemistry -particularly macrochemistry- refers to has been largely discussed in the philosophy of chemistry. In the philosophical literature, the notion of chemical substance has been associated with the philosophical concept of natural kind; but natural kinds are considered as collections of individuals in traditional philosophy of science. The reason for this is the prevailing ontology of *individuals and properties* in western philosophy and also in physics. In the context of chemistry, by contrast, substances are more accurately understood when conceived as *stuff* (Ruthenberg and van Brakel 2008): they are not individuals; they are not individual objects or kinds of individual objects. In this scenario, the opposition between individuals and stuff has drawn some attention.

Joachim Schummer (2008) refers to a popular image in the XIX century, according to which there is a hierarchical order in the world, from basic entities, subatomic particles, to higher levels, composed by atoms, molecules, and biological organisms (including human beings and societies). Each scientific discipline focuses on a particular level. Hence, scientific disciplines also present a hierarchical order, from particle physics to chemistry, biology, psychology and sociology. Reductionism in philosophy of science has been nurtured by this picture; there is a basic underlying intuition, the certainty that "(…) a simple metaphysical scheme could provide order to the entire world. It is more than likely that the hierarchical picture is appealing still nowadays for the same reasons." (Schummer 2008: 3). According to Schummer, this hierarchical picture is challenged by the notion of *matter* or *stuff*. Chemistry provides, precisely, knowledge about stuff, and it has been ignored in that image.

Schummer states that two mutually exclusive traditions, found in the history of western metaphysics, have served as models to think physical ontology and chemical ontology in turn. These traditions emerge from the opposition between the philosophical notion of *form* and the philosophical notion of *matter*. Whereas items belonging to the chemical ontology have to be considered from the *matter perspective*, physical items fit in the *form perspective*. The former deals with the composition of bodies—which particular materials bodies are composed of, whereas the latter focuses on geometrical and spatial properties in order to describe bodies. This one has been the main perspective in philosophy, and its roots can be traced back to the Pythagorean School, Democritus, Plato, Descartes and Galileo.

One of the fundamental differences between the matter perspective and the form perspective is that properties of reality are clearly different in each tradition. According to the form perspective, the essential properties of bodies are intrinsic geometrical ones, such as size and shape. These kinds of properties are always manifested in an object, independently of its contextual conditions. On the contrary, according to the matter perspective, essential properties of the world are dispositions, i.e., properties that describe the behavior of an object under some certain contextual circumstances; the typical example of a dispositional property is solubility in water. The fact that the form perspective has prevailed in western thought until XX century accounts for the attempts to reduce dispositional properties by defining them in terms of underlying intrinsic properties in analytic philosophy (see, for instance, Goodman 1965; Armstrong 1968). For instance, the solubility in water of a body should be explained by the molecular composition of the body. Dispositions have been considered as the second-class citizens of the worlds of properties, shameful properties unlike *real* categorical properties. (Mellor 1974).

The fact that the properties considered essential are different from the two perspectives grounds different conceptions of change. From the form perspective, change is understood as motion in space -the kind of change that mechanics deals with since the beginning of Modern Age. From the matter perspective, on the contrary, change is manifested as reaction and transmutation -the kind of change as typically conceived in Middle Ages and early Modern Age alchemy, which would later gave rise to chemistry.

The notions of matter and form have been considered as mutually exclusive in western metaphysics. However, Schummer asserts that they should not be so, that they are complementary. The two perspectives should be combined in order to get a better understanding of reality, since they are not *opposed metaphysical principles*, but different *epistemic perspectives* on the world.

According to Schummer, the limitations of both approaches arise if one of them is considered an absolute perspective, if they are conceived as metaphysical principles in terms of which the world is organized. For him, difficulties are due to suppose that the world consists exclusively of form or exclusively of matter, or to treat form or matter as the essential and defining features of reality. In fact, each perspective is useful in chemistry, and both show limitations—Schummer asserts. Considered as an absolute approach, the matter perspective faces the problem that stuff properties of solids, such as metals and semiconductors, do not depend exclusively on their chemical composition. Although it is considered as the appropriate perspective in chemistry because it deals properly with the prediction of dispositional properties and the making of new substances, the stuff perspective is limited at the nanoscale. In fact, if the size of the particles of the same chemical substance is reduced to the nanometer scale, their stuff properties begin to vary at a certain size. On the other hand, the problem of the form perspective is the impossibility of reduction: it is not possible to explain the stuff properties on the basis of properties conceived according to the form perspective. This perspective pays attention to the structural features of molecules, such as geometrical properties like angles and distances, but it cannot account for dispositional properties. Schummer states that, since both perspectives have limitations, it is necessary to combine them in order to achieve a better scientific understanding.

Schummer's proposal, although appealing, can be considered limited since restricted to the epistemological domain: it is an *epistemological approach*. This proposal says nothing about how reality is. Schummer could say that whatever reality is, it can be deemed from an epistemological perspective focused on form properties or focused on stuff properties. Since the two perspectives are only ways to approach reality, he can propose two incompatible perspectives to be complementary. As said above, this is what Schummer proposes: although incompatible, the two perspectives can and must be used together, in a complementary way, in order to achieve a better science.

Nevertheless, the problem of chemical ontology can be faced from a different approach, one based on the distinction between two kinds of ontologies, that is, two ways in which reality can be structured. In our opinion, the advantage of this approach is that it goes beyond the idea that there is a world that *can be deemed in a way or another*. The next section will be devoted to recall that ontological distinction.

The problem of chemical ontology: an ontological approach

Following the line initiated by Schummer with the distinction between matter and form, the problem of chemical ontology can also be thought as an issue concerning *ontological categories* (Lewowicz and Lombardi 2013): the physical ontology is an individuals-and-properties ontology, whereas chemistry deals with stuff. In order to understand this ontological viewpoint, it is necessary to understand in what sense different ontologies result from different ontological categories.

Ontological categories must not be confused with properties, since they are responsible for structuring the world; they form, constitute reality, imposing a form on it. They are also responsible for how language is used, for how real items are perceived and known. Categories—as understood by Lewowicz and Lombardi- are not *taxa*, such as "dog" or "mammal"; they are not concepts of kinds, such as "blue" or "rounded" either. Categories are logical and ontological prior to taxa and concepts of kinds. Both taxa and concepts classify individuals, so they presuppose the category of *individual*. Ontological categories, on the contrary, determine which kinds of items inhabit the world; they determine if reality is populated by individuals with properties, only by properties, by events, by processes, etc. In order to understand the distinction between *individuals* and *stuff* from an ontological perspective, it is necessary to conceive these two notions as ontological categories.

Individuals must satisfy a principle of individuality (see French and Krause 2006): the principle is what allows an individual to be different from the remaining individuals, but to preserve its individuality through time. The principle of individuality usually involves spatial and temporal position: individuals are located in space and time, independently of the fact that we can or cannot know such a location.

An individual is a complete indivisible entity. This means it cannot be divided, or if it is, different individuals result. An individual is either one individual or either many individuals -a plurality of individuals. When individuals are grouped according to their properties, the result is a kind, some of which are natural kinds. Given a group of individuals, they can be counted because they have their own individuality, and they can be re-identified within the group.

The commitment with the existence of individuals implies the acceptance of an individuals-and-properties ontology. In western philosophy, individuals are conceived as the substratum on which properties inhere. In turn, properties are either essential (those which allow an individual to be re-identified in time through change), and accidental (those that can change through time because they are not essential). Spatial and temporal properties use to play a fundamental role in individuality, because two individuals cannot occupy the same spatial location at the same time. As we have pointed out, categories are responsible for the structure both reality and language show: the category of individual has a linguistic correlate in singular terms and in the logical subjects of propositions (Strawson 1959; Tugendhat 1982).

The macro-chemical ontology, on the other hand, is better understood as a stuff ontology: as Ruthenberg and van Brakel (2008) stated, chemical substances are stuff. A kind of stuff must be distinguished from any other kind of stuff, but what distinguishes them has nothing to do with spatial and/or temporal location. Although portions of stuff exist in space and time, it makes no sense to ask for the space–time position of certain stuff.

Unlike individuals, a portion of stuff can be divided into portions of the same stuff, but a particular stuff is not a mere addition of its portions. A stuff is one and multiple (it is multiple since there are multiple manifestations as portions of the same stuff) at the same time. Once two portions of the same stuff are joined, the result is not "two stuffs" but "more stuff"; moreover, the portions cannot be counted or re-identified in the addition.

Summing up, the ontological perspective considers that form and matter are useful to understand science. But they are not merely different epistemic approaches: they involve two different ontological categories, the category of individual and the category of stuff. In order to understand the distinction properly, stuff and individual must be understood as two basic ontological categories that are responsible for the fundamental structure of the world.

We are interested in this kind of philosophical approaches, specifically, approaches that pay attention to the ontological questions underlying certain ideas that may pretend to be only epistemological. Besides this, the movement from "pure" epistemological questions to ontological questions manifests some ontological commitments that are necessarily involved not only in some philosophical debates (about realism and reductionism, which are very important regarding the relations between chemistry and physics), but also in the proper scientific practice -we will come back to the motivation of our ontological concerns regarding chemistry in "Searching for the proper category for nanomaterials".

Although the analysis of the ontology of chemistry as an ontology of stuff is appealing, we think that something is missing: the treatment of nanomaterials. That ontological view is accurate regarding the treatment of traditional macroscopic chemical substances, but not to be applied to the nanoscale, since nanomaterials manifest peculiar chemical and physical properties. Those properties are very interesting not only from a theoretical viewpoint, but also in the application to fields as different as design of new materials, electronics, synthesis of new catalysts, or creation of devices of drugs liberation. We will devote the next section to consider the main features of nanomaterials.

What are nanomaterials?

The purpose of *nanoscience* is to understand, explain and handle the phenomena occurring in an extremely small world. It also intends to understand the relation between those kinds of phenomena and the macroscopic world. "*Nano*" is a Greek prefix meaning small, tiny. The prefix is used in the International System of Units (S.I.) to indicate a factor 10^{-9}. In that scale, many molecules usually studied by chemistry appear.

Jointly with nanoscience, some specific techniques known as *nanotechnology* were also developed. Although there are many definitions of 'nanotechnology', it can be understood as the fabrication of materials, structures, devices and functional systems through control and assemble matter at the nanometer scale (between 1 and 100 nm: 10^{-9} m). It also involves the application of new concepts and properties (physical, chemical, biological, mechanical and electrical properties) that emerge as a consequence of such reduced scale (Gago 2010; Cao 2004).

When matter is exposed to nanotechnological methods, *nanomaterials* appear. Even though nanomaterials are not precisely defined, it is usually considered that the specificity of nanomaterials is their length scale: their structure is manifested between 1 and 100 nm - a scale of molecular order (Whitesides et al. 1991; Drexler 1992; Buzea et al. 2007). Nevertheless, nanomaterials' dimension is above the atomic or the molecular scales. It is precisely this particular scale what leads to their peculiar chemical and physical properties (Gago 2010; Cao 2004).

The best-known examples of nanomaterials are *carbon nanotubes*, a stable form of carbon with unexpected properties of traction and temperature resistance, and *graphene*, an allotrope of carbon that has many extraordinary properties of strength. These materials result from the reduction of particles of a chemical substance till the nanometric scale, in which the material can show properties that are very different from the properties showed by the substance at the macro-level. While macro-substances are continuous and homogeneous, in the nanoscale atoms and their structural relations acquire central importance.

The lecture "There's plenty of room at the bottom", given by Richard Feynman in 1959 at the California Institute of Technology, is considered foundational for nanoscience. In that lecture, the possibility of controlling materials at the atomic scale, is considered feasible: "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big." (Feynman 1959, online).

Feynman did not use a specific terminology for nanoscale, and he neither worked in the development of the field. It was Norio Taniguchi who used the term 'nanotechnology' for the first time. In his 1974 article "On the Basic Concept of Nanotechnology", he referred to nanotechnology as the technology that can separate, consolidate and deform materials atom by atom and molecule by molecule (Taniguchi 1974; cited in Gago 2010). More than a decade later, the publication of the book *Engines of Creation* by Drexler (1986) was a milestone in the development of the discipline. The author conceived the ability of nanomachines to build a large amount of devices through assembling molecule by molecule autonomously as a possibility in a relatively near future. The wide repercussion of this book gave nanoscience and nanotechnology a huge visibility.

In 1981, a group of researchers of IBM developed the Scanning Tunneling Microscope (STM), which permitted to control handling techniques in the nanoscale by obtaining images with a good resolution in that scale. The operation of the STM is based on the smooth interaction between the tip and the sample: the tip moves through the sample obtaining signals that can be decoded; in particular, a bias current applied between the tip and the surface allows electrons to move from side to side (tunnel effect) obtaining a current that can be monitored. Later, other related microscopes were developed, such as the Photon Scanning Tunneling Microscopy (PSTM), the Scanning Tunneling Potentiometry (STP) and the Atomic Force Microscopy (AFM).

Among the most relevant achievements obtained by these techniques, in 1985 the structure of fullerenes was synthesized. Fullerenes are built exclusively by carbon atoms: they are composed of 60 carbon atoms and have a structure given by 12 pentagons and 20 hexagons, showing an odd image of a "football ball". Their strength 100 times higher than that of the strongest steel, they have high efficient heat and electricity conduction and are almost transparent. Currently they are applied to electronics and biomedicine, but their potential applications include many fields under research. Another relevant fact occurred in 1994, when graphene was rediscovered—it had been synthesized several decades earlier. It is an allotrope of carbon, also built exclusively by carbon atoms arranged in a hexagonal regular pattern similar to graphite, but in planar sheets which are a single atom thick. Graphene also shows several peculiar properties, such as its high values of electron mobility, flexibility, hardness and chemical stability.

Nowadays, the specific properties of nanomaterials are studied from an interdisciplinary approach, leading to one of the most dynamic and fruitful fields within scientific research. The applications of nanomaterials include material science, the obtaining of devices for drugs liberation, analytic chemistry, among others (Whitesides et al. 1991; Buzea et al. 2007).

As we will see, the category of stuff, which can be considered appropriated in the realm of macro-chemistry, is not accurate when dealing with nanomaterials. Nevertheless, this does not mean that nanomaterials can be treated in terms of the ontology of quantum mechanics, since all the difficulties that threaten the account of molecular shape in quantum terms (see, for instance, Hendry 2010; Fortin et al. 2016) apply directly to the nanoscale, since the spatial geometrical structure of nanomaterials is essential to their behavior. Our purpose is to show why the consideration of nanomaterials leads to the re-entry of the category of individuals into chemistry and its philosophy.

Searching for the proper category for nanomaterials

As we have seen in "The problem of chemical ontology: an ontological approach", from an ontological perspective, Lewowicz and Lombardi (2013) consider that stuff is the proper ontological category of chemistry, and that the category of individual, although the accurate ontological category of physics, is not adequate in the field of chemistry in order to think correctly about philosophical problems of that discipline.

In this scenario, we ponder over the advantages and limits of giving up the ontological category of individual in the chemical realm. If we agree in that strategy, the following questions arise: Which ontological category can be used to think the nanomaterials scale? What kind of entities are nanomaterials?

According to Hasok Chang's proposal, formulated precisely for the realm of chemistry, scientific theories must not be considered as systems of propositional knowledge, but as systems of practices (Chang 2012). Theories must not be considered, then, true or false. This proposal makes possible to think about different philosophical problems typical to chemistry in a new way. Chang's idea of systems of practices and of the abandonment of a correspondence notion of truth, might suggest that chemistry must be understood from an instrumentalist position. However, this is not necessary so, tempting as it may sound. In fact, Chang himself adopts a minimal realism, what he calls "active realism".

Besides the debate between realism and instrumentalism, there is a very important and compelling idea in Chang's proposal. The way he conceives scientific theories is the most suitable for the peculiarity of the scientific activity proper to chemistry. This is, in turn, extremely relevant not only in the field of the philosophy of chemistry, but also for general philosophy of science, which has been mostly built on the basis of an image of science modeled by physics. In fact, chemistry focuses on "making", even on creating new entities, more than on describing and predicting the behavior of things that exist independently from our activities. Chang refers to science as a "know how" more than a "know what". Since its origins, chemistry was built as a practical discipline, endowed with technological purposes more than theoretical aims. Chang's realism, jointly with his "active pluralism", promotes the idea that the objective of science is to continuously and actively search for multiple knowledge understood in terms of practice. In this context, it seems natural to think, following Bernardette Bensaude-Vincent (2008) that the ontology of chemistry arises from action guided by utility and efficiency.

In turn, if chemical practice is considered in its specificity, it is clear that nanomaterials do exist in this practical sense. The idea proposed by Hacking (1983) is also useful in this context. According to this author, the criterion for the existence of scientific entities has to be searched in the effective practice of science; we accept the existence of unobservable 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" (Hacking 1983: 265). On the basis of this view, we can be sure that nanomaterials exist, because we have managed to interact with them and to use them for many technological applications.

We feel inspired by the ideas of Chang, Bensaude-Vincent and Hacking, especially regarding the distinctive features chemistry shows. Nevertheless, Chang's active realism, although attractive, can be considered excessively minimum, since he refuses to deal with any ontological question. The whole metaphysics Chang is willing to accept only goes as far as to admit that there must be something out there compelling our scientific practice (not any idea is acceptable in science: although "many things go", not "anything goes").

By contrast, we consider that the existence of nanomaterials—we can say, "pragmatically proved"—invites us to go beyond those otherwise appealing ideas. The huge success of nanotechnology is an incentive for moving from the practice of science to the ontological question about the nature of nanomaterials. We really wonder *what nanomaterials are*; we want to know what their nature is. If we also think—as we have already said—that nanomaterials can be subsumed neither under the category of stuff nor under the traditional category of individual, it is necessary to find the proper ontological category that would allow us to understand their nature.

Re-entering individuals: an ontological perspective

In "The problem of chemical ontology: an ontological approach", the ontological categories of individual and stuff have been clearly distinguished, precisely as *ontological* categories. We have also stressed that this is a relevant perspective because it supplies a basis to address the ontological problems involved in the philosophy of chemistry, problems that arise when certain significant questions are considered, such as the problem of the relation between chemistry and physics. Nevertheless, we wonder if those two categories are sufficient to conceive reality in the field of chemistry and, particularly, to account for nanomaterials. Is a third category necessary to think the nanochemical world?

The word 'nano*material*' has strong ontological weight: the notion of *material* can be understood as matter, substance or stuff. So, nanomaterials would belong to the same ontological category as that corresponding to macro-chemistry, but in this case referring to something much smaller. Nevertheless, a careful consideration shows that this is not the case. In fact, a nanomaterial cannot be divided in portions of the same kind of thing; if it is divided, it ceases to be the original nanomaterial. A nanomaterial is not one and multiple at the same time, since it is manifested under the form of nanoparticles: nanoparticles, unlike a portion of stuff, can form an aggregate where they can be re-identified.

On the other hand, nanomaterials are different from chemical substances in a traditional chemical sense. Whereas, within certain limits, the properties of substances are intensive, i.e., they do not depend on the size of the material, the properties of nanomaterials change with the size of the nanoparticles, since they depend on the features of the external surface of the nanoparticles. Moreover, the properties of a set of nanoparticles may be different from those that the corresponding substance shows at the macroscopic level. Summing up, the ontological category of stuff, which is the category to which the substances of macrochemistry belong, is not the adequate ontological framework for nanomaterials.

The peculiarities of nanomaterials suggest the possibility of conceiving a third ontological category to account for them: the category of *nanoindividuals*. It is important to emphasize that the notion of nanoindividual does not arise from a conceptual synthesis between the notion of physical individuals and the notion of chemical stuff, but refers to something different from traditional individuals and from stuff. Nanoindividuals are neither mathematical nor chemical artifices created in order to deal with some practical problems. They are not theoretical instrumental constructs, but entities with real existence. This clarification is necessary, because it might be tempting to dissolve the question of what nanomaterials are by means of the adoption of an instrumentalist position.

The ontological category of nanoindividuals proposed here is a category that picks up certain existent "things" or items that share some features with traditional individuals and some others with substances subsumed under the category of stuff. Like individuals, nanoparticles can be counted. If they are divided, nanoparticles of different kind are obtained, with different optical, magnetic, chemical, etc. properties. They can form an aggregate, and when they do it, they can be re-identified in the aggregate.

Nevertheless, nanoindividuals are not particles in the physical sense, since they have a specifically chemical property: reactivity. Nanoparticles participate in chemical reactions, like chemical substances in macroscopic chemistry; in those reactions, they lose their individuality and become something else. This kind of chemical behavior has nothing to do with what happens to physical particles, which interact through forces without losing their identity. For instance, in order to use nanoparticles in many different applications, the technique of self-assembly is used. In this technique, nanoparticles of some metals, such as Ag, Au, Cu, Ge, among others, react chemically with molecules acting as ligands, such as thioethers amino acids o siloxanes. The properties of the metallic nanoparticles are different before and after the application of the ligand, whose use is due precisely to its capability of producing such a change of properties. Another example is that of the nanocatalysts, whose properties vary considerably when the catalytic reaction is produced. A further case is that of systems of drug administration based on the transport of the drug into a nanoparticle capable of forming a chemical bond with a specific fraction of a biological receptor: when the drug is liberated in the place of the interaction, all of the properties of the nanoparticle vary appreciably.

In summary, nanomaterials are not "materials" subsumed under the category of stuff, like chemical substances; nanoparticles are not "particles", like physical particles belonging to the category of individual. From an ontological viewpoint, the nanodomain is inhabited by elusive items that resist to be classified by those traditional categories of metaphysics that were the basis to conceive the world of natural science up to the present. The rapidly evolving area of nanoscience supplies a strong motivation to undertake the philosophical effort of conceiving new ways of approaching scientific ontology.

Concluding remarks

Nanoscience is usually defined in terms of a length scale: it is the science that studies particles between 1 and 1000 nanometres. Consequently, it is understood as the study of "small things", a sort of half way between the molecular and the macroscopic scales. It has been our purpose to think nanoscience in a different way, not simply in terms of the size of the items involved, but taking into account the ontological nature of those objects. In other words, nanoscience should not be philosophically conceived as a matter of size, as if it had the same object of study as macro-chemistry but smaller. From our perspective, the macrodomain is essentially different from the domain of macro-chemistry since it is structured by a different ontological category.

In this article we have tried to show that, although it is usually supposed that physics handles individuals while chemistry handles stuff exclusively, a more complex picture of science arises when nanomaterials enter the scene. We have argued that, from a perspective that considers ontological questions and is interested in the nature of the items involved in science, the domain of nanoscience must be thought as populated by entities that are neither individuals, as those of physics, nor stuff, as those items of macro-chemistry.

Therefore, the traditional categories of stuff and individual are not sufficient to account for the chemical ontology.

According to our view, the "particles" involved in the chemistry of nanoparticles must be conceived as a new kind of "individuals", different from the individual particles of physics. We have called them 'nanoindividuals'. In this way, we can understand the peculiarities of the chemical behavior of nanomaterials, and conceive nanochemistry as a genuine and differentiated branch of chemistry, and not as the methodological combination of macroscopic and molecular chemistry.

It is also usually assumed that the domain of nanomaterials brings chemistry closer to physics. From our perspective, this is not the case. The fact that the items studied by nanoscience are not the substances of macrochemistry does not mean that they can be assimilated to the particles of physics. The nanodomain is structured by its own ontological category; this fact is independent from the distance between chemistry and physics, which does not decrease from an ontological viewpoint.

Besides our main purpose, we intend our approach to shed some light on other problems in the field of the philosophy of chemistry. For instance, regarding the relations among subdisciplines of chemistry itself, is it possible to talk about reduction within chemistry, among domains structured according to different categories? Which is the relation that can be established between macrochemistry and nanochemistry? Is it reduction, emergence, or another kind of relation? How can these problems be addressed if we consider the items involved in sciences -and subdisciplines- from an ontological perspective as the one adopted here?

On the other hand, some traditional philosophical problems, such as those related with identity and distinguishability or with the status of properties, among others, can be faced from a new perspective if nanoparticles are taken into account from an ontological point of view. The consideration of the ontological nature of the items involved in science - particularly in nanoscience- can give rise to a new dimension of traditional philosophical debates, in general anchored in traditional assumptions. In this sense, our work intends to contribute to opening new questions that demand further philosophical research.

Acknowledgements This publication was made possible through the support of CONICET and of grant 57919 from the John Templeton Foundation. The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the John Templeton Foundation.

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