Plenitude Philosophy and Chemical Elements

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Abstract: According to the principle of plenitude, or what in a different version is also known as the totalitarian principle, what can possibly exist does actually exist. This metaphysical idea has in the past played an important heuristic role in the life sciences and can still be found in some areas of modern science. The paper critically examines how chemical ideas about elements and their compounds have on occasions been inspired by plenitude reasoning if mostly implicitly. The emergence and interpretation of the periodic table is one case and the existence of exotic forms of matter, such as muonium and superheavy elements, is another. Generally the principle of plenitude problematizes the fundamental ontological notion of what it means for a chemical entity to exist in nature.

Keywords: *Plenitude, totalitarian principle, elements, periodic table, potential existence.*

1. Introduction

Scientific arguments are usually based on a disciplined dialectical interplay between theories and relevant experiments or observations. But in addition to these standard elements there often enter, in a few cases explicitly but more often implicitly, elements of a less rational and well-defined nature in the form of regulative methodological or ontological principles. The best known and most widely used of these principles is the principle of simplicity or parsimony, an entirely metaphysical assumption that nonetheless has played and still plays a considerable role in the world of science (Baker 2016, Hoffmann *et al.* 1997). In the version of Occam's razor the simplicity assumption entered *Principia Mathematica*, where Newton (1999, p. 794) famously stated that "No more causes of natural things should be admitted than are both true and sufficient to explain their phenomena. […] For nature is simple and does not indulge in the luxury of superfluous causes."

Less well known but belonging to the same class of meta-scientific principles is the so-called principle of plenitude, which boils down to the ontologi-

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cal claim that what is conceived as possible must also have a physical reality. Or in a slightly different formulation, that potential existence equals actual existence. Plenitude philosophy expresses a rationalist epistemology in so far as its assertions of what exists in the natural world do not rely on experience. In its classical form the dogma rests on the assumption that the cosmos is perfectly rational and totally lacking in arbitrariness and contingency. The name 'principle of plenitude' for this old idea going back to Plato was introduced by the historian of ideas Arthur Lovejoy in his magisterial *The Great Chain of Being* first published in 1936. According to Lovejoy (1976, p. 52), the principle cultivated by pioneers such as Spinoza and Leibniz in what was primarily a theological context, is a "theorem of the 'fullness' of the realization of conceptual possibility in actuality". It implies "that no genuine possibility of being can remain unfulfilled".

Lovejoy carried on his erudite study only to the romantic philosophy of nature in the early nineteenth century. Moreover, he focused on the life sciences and had almost nothing to say about the physical, astronomical, and chemical sciences. As far as chemistry is concerned, a more than fifty-year old paper by the British-American chemist and historian of chemistry Otto Theodor Benfey (1965, 2006) still stands out as the only work attempting to link Lovejoy's idea of a great chain of being to developments in chemical thought. However, it should be pointed out that Benfey did not use the term 'principle of plenitude' but instead referred to the largely synonymous term 'chain of being.' The meaning of this term is, more generally, that all matter and life is seamlessly linked together in a hierarchical structure proceeding upwards from the most basic elements to, ultimately, the highest perfection in the form of either man or God. There are no missing links in the hierarchy, which is a true plenum with all possibilities fulfilled.

In this essay I investigate the role of plenitude reasoning in the chemical sciences with a focus on ideas of elements and related issues, which I discuss in the form of historical examples. But first I need to introduce and clarify some of the many faces of the plenitude principle, a line of thought which may not be generally known to either chemists or philosophers of chemistry. When it is stated that everything possible exists, what does the claim mean and what are its implications?

2. Lovejoy's Principle of Plenitude

Concepts such as 'possible' and 'potential existence' are evidently key terms in plenitude philosophy. As to the apparently innocent term 'possible' I find it useful to distinguish between three classes or levels: (i) what is imaginably or conceivably possible; (ii) what is logically possible; and (iii) what is physically possible.

What is absolutely impossible is often equated with what is logically impossible, such as an object having the shape of a round square or a point with extension in space. On the other hand, what is physically impossible is contingent in so far that it is relative to experience and the known laws of nature. It is a matter of philosophical debate whether level (i) is broader than and different from level (ii), that is, whether or not the logically impossible and not only the physically impossible can be conceived (Berto 2013). Mermaids, electrons with fractional charges, molecules with the formula C_3H_{21}, and spaceships accelerated to superluminal speeds are not illogical and they can easily be imagined, but they do not qualify as premises in the plenitude formula.

From a scientific point of view it is undoubtedly the last and most restricted form of possibility, level (iii), which is of interest. What is physically or genuinely possible and not merely conceivably possible depends on the best scientific knowledge at any given time. Thus, the C_3H_{21} molecule was a theoretical possibility until about 1860, when Kekulé established that carbon always has four valences and hydrogen just one. To mention an example from Lovejoy's book (p. 184), some enlightenment philosophers, and surprisingly John Locke among them, had no problem with using the plenitude postulate in support of the claimed observations of mermaids and sea-men. After all, there were no biological laws known at the time that prohibited the existence of such creatures – so why should they not exist somewhere? In his famous *Essay Concerning Human Understanding* from 1689, Locke exuberantly supported the principle of plenitude as a manifestation of God's great design of a harmonious universe.

Although plenitude shares with the principle of simplicity that it is a meta-scientific heuristic postulate, obviously plenitude and parsimony do not go easily together. As pointed out by Alan Baker (2002), they point in opposite directions. While the first is a 'maximizing principle', the latter is a 'minimizing principle'. However, in scientific practice this is rarely considered a serious problem as scientists seem to be able to subscribe to parsimony and, at the same time and in specific contexts, also to appeal to plenitude. After all, principles of simplicity and economy are no less ambiguous than is the principle of plenitude.

Not only is the plenitude principle hard to reconcile with the idea of simplicity or parsimony, it also seems to run counter to the general aim of unification which over centuries has acted as a powerful force in the progress of science. In its ontological version the principle of nature's unity has successfully guided physicists and chemists in their attempts to reduce the phenomenal diversity of matter to a manifestation of just a few building blocks. But the philosophical dream of unity is entirely different from the picture of nature's infinite diversity and richness which underlies the classical plenitude principle. For example, by the late nineteenth century all matter was thought to consist of approximately 80 different and indivisible atoms corresponding to the chemical elements. Thirty years later the number of massive fundamental particles had been reduced to two, namely the proton and the electron (this picture broke down in the early 1930s). Ontological plenitude had been transformed to ontological paucity.

There is more than one version of the principle of plenitude in Lovejoy's treatise . The one cited, stressing the fullness of the chain of being, is a static formulation. But during the late eighteenth century, under the impact of evolutionary ideas in natural history, scientists such as Jean-Baptiste Lamarck in biology, William Herschel in astronomy, and James Hutton in geology transformed the static version into a historical or temporal version. The focus was now on becoming rather than being, with the great chain of being becoming a progressivist *scala naturae*. All possibilities still had to be realized, but not all of them at the same time. In the words of Lovejoy (1976, p. 244), "While all the possibles demand realization, they are not accorded it all at once. […] It is only of the universe in its entire temporal span that the principle of plenitude holds good." In this way we arrive at a broader formulation of the principle of plenitude, namely that no genuine possibility can remain forever unrealized. From a philosophical rather than historical perspective Robert Kane (1976) echoes Lovejoy's division, which he refers to as the 'all times' version versus the 'some times' version.

In the temporal version of the plenitude formula, existence may refer to an arbitrary far future or a past restricted only by the big bang some 13.8 billion years ago. We may have no evidence at all that a genuine possibility is realized today or was it in the past, but from a plenitude point of view this is not necessarily a problem, for it will surely be realized in the future. As the extended plenitude formula puts no restriction on time, so it puts no restriction on space. An apparently unrealized possibility may be real in a galaxy billions of light years from here. All this underlines that the plenitude postulate is a metaphysical statement and not a scientific principle subject to experimental testing.

The principle of plenitude in its general form does not refer to life, but it is abundantly clear from Lovejoy's study that when people in the seventeenth and eighteenth centuries spoke of the great chain of being they had principally life forms in mind. Plenitude was not only about the amazing variety of living species on Earth but also about the extent of the diffusion of life in space. Richard Yeo (1986) suggests a distinction between two different versions of plenitude, both of them concerned with life but in different ways. According to 'conceptual plenitude' all possible forms of life have – or have had or will have – an actual existence. 'Spatial plenitude,' on the other hand, postulates that celestial matter exists to sustain life or that there is no such matter without life. There is no logical connection between conceptual and spatial plenitude as it is possible to deny the first and maintain the latter, or vice versa.

3. The Totalitarian Principle

Most writers on the subject of plenitude agree that the principle has been of limited scientific importance, especially in the modern era, and more a preoccupation of philosophers and historians than of scientists. As far as the ordinary macroscopic world is concerned the principle of plenitude rests on the premise that nature actualizes all possibilities, which plainly disagrees with what we know about the world. We find neither tartan elephants on Earth nor diamonds of the size of a basketball; nor find we anywhere in the universe anti-atoms much heavier than the anti-hydrogen created in minute amounts in the laboratory. And yet such objects would seem to be perfectly possible according to the laws that govern biology, chemistry, and physics. Only in the quantum regime does the premise have some plausibility, apparently allowing unlikely objects and phenomena if only with an exceedingly small probability.

On the whole there is very little scientific justification for the plenitude principle in its strict form, and yet plenitude arguments have entered and still do enter the scientific discourse from time to time. When this happens it is almost always heuristically, in the context of discovery, and often facetiously and in popular contexts. Contrary to the situation in eighteenth–century natural history, in modern science plenitude does not enter and cannot reasonably enter the context of justification.

Since the 1970s a few philosophers have reconsidered the role of plenitude in science, suggesting that the principle has played, and indeed continues to play, a significant if limited heuristic role in areas of modern physics in particular (Kane 1976). The physics literature frequently contains references, mostly implicitly but sometimes explicitly, to what is called the 'totalitarian principle'. This principle, which can be considered a variant of the plenitude principle, is generally but wrongly associated with the American physicist and Nobel Prize laureate Murray Gell-Mann (1956). Whatever the paternity of the totalitarian principle, its standard formulation is that 'everything that is not forbidden is compulsory', or the equivalent statement that 'what can exist does exist'. The essence is that if an object or phenomenon is not ruled out by some conservation law or other law of nature and in this sense is allowed, it must exist. Like other versions of the plenitude principle this is clearly a metaphysical claim as the actual existence does not follow logically from ‘can exist’ or ‘is not forbidden’.

By far most uses of the totalitarian principle occur in particle and quantum physics, but it may also be found in theoretical chemistry. I suggest that it played a limited role in the much-discussed controversy over anomalous water or ‘polywater’, centering on whether a new polymeric form of water existed or not (Franks 1981). One of the approaches in this debate was theoretical, namely to evaluate if stable polywater was allowed by thermodynamics and models of quantum mechanics. If this were the case, polywater most likely existed. This was what two American chemists argued from computer-based calculations in a paper of 1970 (Allen & Kollman 1970), only to revert the conclusion the following year when they had developed an improved theoretical model. The new model led them to conclude that “polywater does *not* exist” (Allen & Kollman 1971). We are now, they wrote, “led to view the potential existence of a new water allotrope as highly unlikely” (*ibid.*). In the end it was experiments and not the ambiguous results from theory that settled the matter and proved polywater to be an illusion.

Contrary to Occam’s razor, the principle of plenitude is of an ontological nature and does not exist in a corresponding methodological version. Nonetheless, in its totalitarian version the principle induces scientists to look for conservation laws that explain the nonexistence of certain entities and processes, and in this sense it often acts as a methodological guide. As a metaphysical principle it is logically prior to epistemic considerations of how scientific knowledge changes, and yet it relates to such considerations and can be used to illustrate scientific change.

The laws of nature play a central role in the totalitarian principle as they restrict what can exist. These laws are not known a priori but are ultimately based on experiment and observation and for this and other reasons subject to change as science progresses. What is scientifically allowed at one time may be forbidden at a later time, meaning a further restriction in what qualifies as potential existence. Or it may be the other way around. Generally, as older theories are replaced by new and better theories, what can or cannot exist will change. Transmutation of metals by chemical means was thought possible during the renaissance era, after which it became impossible. Spontaneous heat transfer from a colder to a warmer body was an allowed phenomenon in the age of enlightenment but not in late nineteenth century.

Consider the negation of the totalitarian principle in the curious and seemingly paradoxical formulation ‘what cannot exist does exist’. It may appear to be self-contradictory, but it is not if the last ‘exist’ refers to what is actually found in nature. Just as there are many possible (theoretically allowed) things that do not actually exist, so there are many impossible (theoretically forbidden) things that do exist. More cautiously one may propose the formula that, 'what is thought to be impossible, sometimes does exist'. Examples from the history of science come easily.

When radioactivity was discovered in 1896 it was widely considered a puzzle, something inexplicable which, in a sense, should not exist. In an address of 1900 Marie Curie referred to the phenomenon as "perhaps in disagreement with the fundamental laws of science" (Pais 1986, p. 112). A few years later it was realized that radioactivity implied the spontaneous disintegration of radium and other elements apparently without a distinct cause. But this was impossible, meaning that it defied the known laws of physics and chemistry – and yet spontaneous atomic decay was undoubtedly real. Another example may be the 1894 discovery of argon, which for a time seemed to contradict the well-established periodic system and in this sense to be impossible. As the Italian chemist Rafaello Nasini (1895) expressed it, "We must abandon either the conclusion universally deduced from the kinetic theory of gases or the periodic system." Mendeleev (1895) likewise objected that "If we admit that the molecule of argon contains but one atom, there is no room for it in the periodic system" (see also Giunta 2001). For more about argon and the noble gases, see below.

4. The Periodic Table

The plenitude assumption stimulated eighteenth-century naturalists to search for missing organisms in the supposedly unbroken chain of being. In a brief passage Lovejoy (1976 [1936], p. 232) suggested an analogy to the later periodic system of the chemical elements: "Thus the theory of the Chain of Being, purely speculative and traditional though it was, had upon natural history in this period an effect somewhat similar to that which the table of the elements and their atomic weights had upon chemical research in the past half century." Writing forty years later, the philosopher and sociologist Lewis Feuer (1978, p. 379), a former colleague of Lovejoy, expressed the view that Mendeleev's table was the "great embodiment" and "supreme example" of the principle of plenitude. Moreover, he attributed Mendeleev's deep insight to his "pantheistic, mystical longing to see a Chain of Being ramify through the chemical facts". However, although Mendeleev did have metaphysical ideas which to some degree influenced his work, these included neither mysticism nor plenitude belief (Gordin 2004, Scerri 2007). On the contrary, he was a staunch opponent of mystical and spiritualist tendencies in science.

Were Mendeleev and other contributors to the periodic table guided to any extent by plenitude reasoning? There are obvious differences between the two cases, not least because the atomic weights of the chemical elements vary discontinuously whereas the chain of being was supposed to be continuous or nearly so. Nonetheless, as argued by Benfey (1965) and Robin Le Poidevin (2005), there are also some similarities which suggest a structural identity between the periodic table and the older idea of a great chain of being. Eighteenth-century naturalists paid lip service to the continuum of life forms, but in reality they conceived the chain of being as discrete. If they observed a significant gap between two organisms of the same kind, they searched for the existence of one or more organisms intermediate between the two. The chemists' search for elements largely followed the same pattern.

Mendeleev tended to believe that there were no holes in his system and what appeared to be vacancies – mere possibilities – would eventually materialize in the form of real elements. As he pointed out in his 1889 Faraday lecture, before the establishment of the system there was no reason to believe that gaps in the sequence of atomic weights implied the existence of missing elements, and hence there was no motivation to search for them (Mendeleev 1889, p. 648). On the other hand, he did not appeal to the idea of plenitude in any of its forms. In the late 1860s Mendeleev was not motivated by any metaphysical longing for a system satisfying the plenitude principle, and he only suggested with some reserve that the vacant places were filled with elements unknown so far. Even if these elements were not actually found, he thought that the periodic table was a valid classification of the system of the elements, a supreme law of chemistry. At least initially, to him the important thing was that the missing elements *could* exist and therefore *perhaps* would be discovered (Jensen 2002, p. 30). He did not conclude that for this reason they *must* exist, such as a true plenitude believer would have argued.

It should also be kept in mind that despite his remarkable predictive successes, several of Mendeleev's predictions based on his system were erroneous. The impression of consistent predictive success is unhistorical and an effect of selection bias. In fact, he made as many failed predictions as successful ones, but the first class is often conveniently disregarded in the chemical literature (Scerri 2007, pp. 140-143). Altogether there is reason to doubt that plenitude ideas played a significant role in the discovery of the periodic system and its early development.

With the discovery of gallium and some of the other elements predicted by Mendeleev, most chemists came to believe that the remaining gaps in the system represented *bona fide* elements waiting to be discovered. But some defended the unorthodox view that the gaps might be un-actualized and therefore refer to non-existing elements. This view, as argued by the prominent British chemist William Crookes, went against the plenitude doctrine. According to Crookes (1886, p. 566), the empty spaces in the periodic table do not "necessarily mean that there are elements actually existing to fill up the gaps; these gaps may only mean that at the birth of the elements there was an easy potentiality of the formation of an element which would fit into the place".

Crookes' ideas are of interest in a plenitude context because he suggested a non-superficial analogy between chemical elements and living organisms. Both evolved according to "a preconceived plan" pointing towards "an ascending scale of excellence", a reference to the *scala naturae*. As Crookes (1886, p. 561) put it, "The array of the elements cannot fail to remind us of the general aspect of the organic world". He realized that the analogy was far from complete, for other reasons because "there cannot occur in the elements a difference corresponding to the difference between living and fossil organic forms". Writing a decade before the discovery of radioactivity he confidently asserted that existing elements could never become extinct like animals and plants of the distant past.

After having discovered or co-discovered argon and helium William Ramsay turned his attention to other gases of a similar kind. The topic of his address to the 1897 meeting of the British Association for the Advancement of Science was a new gas which "has not yet been discovered" and "not yet been named". On the basis of the regularities of the periodic system he confidently predicted the existence of a new inert gas with atomic weight close to 20. Although an elaborate search for the unknown gas failed to reveal it, Ramsay (1897, p. 381) boldly asserted that "it by no means follows that the gas does not exist; the only conclusion to be drawn is that we have not yet stumbled on the material which contains it". The new gas had to exist and indeed it did. A year later it turned up in the spectrum of fractions of argon and was then named neon. Ramsay's expectation that nature does not tolerate unactualized possibilities proved right. As Ramsay and his collaborator Morris Travers realized, the new gases might form a separate group of monatomic elements. In a progress report read to the Royal Society in November 1900, the two chemists introduced their paper with a quote from the English polymath Thomas Browne's *Religio Medici* published in 1643. The quote encapsulates the essence of the classical principle of plenitude: "*Natura nihil agit frustra* [nature does nothing in vain] is the only indisputed Axiome in Philosophy. There are no Grotesques in Nature; not anything framed to fill up empty Cantons, and unnecessary spaces" (Ramsay & Travers 1901).

As more elements were found and the system of atomic weights became more fine-grained, some chemists began to wonder why the atomic weights represented in nature exhibited so little order. Why do the elements in the first period have atomic weights approximately 7 (Li), 9 (Be), 11 (B), 12 (C), 16 (O) and 19 (F), while there are none with weights close to 8, 10, 13 and so forth? This kind of questions was associated with the many attempts in the late nineteenth century to represent the periodicity of the elements by some mathematical function, attempts which Mendeleev disliked and considered fundamentally flawed. To his mind, the periodic table expressed a necessary and irreducible discreteness in atomic weights.

Mendeleev (1889, p. 641) stressed that there were no intermediate elements between two neighboring elements in the same period, say silver and cadmium, and "according to the very essence of the periodic law there can be none". Moreover, "the periodic law has clearly shown that the masses of the atoms increase abruptly, by steps," a feature which he justified by means of Dalton's law of multiple proportions. Mendeleev's view as expressed in his Faraday lecture is at odds with the traditional strong version of nature's plenitude and infinite richness. Because several of the proposed mathematical functions were continuous, they implied, at least implicitly, the absurd idea of an infinite number of potential elements. Whether infinitely many or just very many potential elements the question arose of how to pick out those actually existing. Although the hypothetical atomic weights might vary on a continuous scale, no chemist ever entertained the ridiculous notion that the whole scale was represented in nature.

5. Possible Atoms and Molecules

While plenitude arguments did not figure explicitly in the late-nineteenth century discussion of chemical elements, another principle of a metascientific nature did, namely the principle of unity of matter in the version of Prout's well-known hypothesis (Brock 1985). A significant minority of chemists speculated that all atoms might be conglomerates of very small primordial particles, either hydrogen atoms or possibly something smaller. For example, this was the view of Lothar Meyer (1872, p. 293), a co-discoverer of the periodic system who furthermore suggested that the supposedly ponderable ether was part of all chemical atoms. Speculations of this kind were typically associated with the no less speculative hypothesis that the existing elements were the result of a grand cosmic evolutionary process. From the perspective of the temporal version of the plenitude principle the chain of being was no longer static and continuous but more like a ladder from the simple to the complex on a time scale. With the development of evolutionary thought the plenitude postulate came increasingly to mean that all non-forbidden possibilities must be or have been realized at some time and not necessarily at the present.

Inspired by the discussions concerning Darwin's theory of organic evolution this kind of thinking was adopted by several eminent chemists. "Existing elements", Crookes argued in his address of 1886 (p. 560), should be viewed “not as primordial but as the gradual outcome of a process of development, possibly even of a ‘struggle for existence’”. Without offering an answer he asked: “Might there as well have been only 7, or 700, or 7,000 absolutely distinct elements as the 70 (in round numbers) which we now commonly recognize?”

To some fin-de-siècle chemists and physicists the electron was the long-sought primordial particle, the ultimate chemical element. This was the belief of the Swedish physicist Johannes Rydberg, who in versions of the periodic table dating from 1906 and 1913 included the electron as an element on par with other elements. He wrote, “One must try to find either the substance itself or the reason for its nonexistence, for it [the nonexistence] forms an exception to an otherwise generally valid law” (Rydberg 1906, p. 17). This argument is clearly an example of plenitude reasoning and akin to how particle physicists, relying on the totalitarian principle, argued some sixty years later. Thus, referring to what they called “Gell-Mann’s totalitarian principle”, Bilaniuk and Sudarshan (1969) wrote about the hypothetical faster-than-light particles known as tachyons: “If tachyons exist, they ought to be found. If they do not exist, we ought to be able to say why not.”

Rydberg was not the only one to speculate that the electron might count as a chemical element, an idea which for a period of time was also entertained, apparently independently, by Ramsay. Like Rydberg, Ramsay proposed E as the chemical symbol for the electron. This was initially the idea also of J.J. Thomson in his famous experiments with cathode rays that in 1897 led to the discovery of the electron(or ‘corpuscle’ as he called it) as a subatomic material body. Thomson addressed the same question as raised by Crookes, namely why the atomic weights of the elements did not vary in a nearly continuous manner. But he now formulated it in the framework of his new electron theory of atomic structure.

According to Thomson’s original atomic model the mass of the atom was made up entirely by electrons, meaning that even the simplest atoms consisted of thousands of electrons moving in various configurations in a massless positive fluid. But Thomson’s calculations showed that only certain configurations were allowed in the sense that they were mechanically and electromagnetically stable. There was in Thomson’s theory a definite cause for the nonexistence of certain potential atoms, namely that they were unstable and thus ruled out for physical reasons. The merely potential electron structures represented impossible and hence unrealized atoms. Incorporating the evolutionary aspect Thomson (1907) argued that the matter existing in the far past differed completely from present matter, and likewise that in the distant future new kinds of matter would dominate the world.

The basis of Thomson’s atomic speculations, that out of the plenitude of possible atoms only the stable structures have a real existence, was carried over into later models of the atom. With the emergence of the quantum nuclear atom, stability was relegated to the atomic nucleus, but it was still a matter of whether atoms were stable or not. For example, the beryllium isotope with mass number 8 does not exist on Earth. For a long time it was unknown whether it was stable or strongly unstable, a question which was important in theories of stellar element formation (Shaviv 2009, pp. 275-299). It eventually turned out that the Be-8 nucleus decays into two alpha particles with a half-life of less than 10^{-16}s, which is why no trace of it is found in nature. But for a brief fraction of a second it does exist and must exist in the interior of stars. One may object that this is perhaps to stretch the meaning of 'existence' too far. After all, atomic nuclei with a lifetime less than 10^{-14} s are not formally recognized as belonging to a chemical element and yet, in a sense they do exist (Kragh 2018, p. 66).

In Niels Bohr's semi-classical quantum theory of atoms and molecules, only those configurations that satisfied certain theoretical conditions could exist. Bohr tended to believe that these allowed configurations corresponded to real atoms and molecules. Based on such considerations he wrote in a paper of 1919 that, "we shall on the theory expect that a molecule of this type, which in the following for the sake of brevity will be denoted H_3, may exist permanently in the absence of external disturbances" (Bohr 1974, p. 484). According to Bohr, the chemically unknown triatomic hydrogen molecule was real and likely to turn up in experiments. Although Bohr's guarded and weakly plenitude-inspired prediction of H_3 was unsuccessful, much later spectral lines with the unmistaken fingerprints of the molecule were detected in the laboratory (Kragh 2012). Triatomic hydrogen does 'exist' if only in a highly unstable ground state and it quickly dissociates into three hydrogen atoms.

6. From Missing to Artificial Elements

With the combined introduction of isotopy and atomic number in about 1913 the existence of elements lighter than hydrogen was ruled out. Previously, one or more sub-hydrogen elements could still be maintained as a possibility, if not a very likely one. Elements below hydrogen were seriously considered also by Mendeleev, who in the 1897 edition of his widely used *Principles of Chemistry* placed the ether at the beginning of the periodic table, ascribing it an atomic weight of about one millionth of hydrogen's (Gordin 2004, pp. 217-227). He also found a place in his table for the hypothetical element 'coronium' with atomic weight ca. 0.4. However, after 1913 and the introduction of the atomic number the door was closed to sub-hydrogen elements. What had formerly been a possibility now became impossible. In this case it was not a conservation law that forbade the existence of hypothetical objects but a reconceptualization and redefinition of what an element is.

On the other hand, there remained the question of the upper limit of the periodic system. Although it was generally agreed that uranium was the heaviest element, in the early part of the twentieth century a few chemists and physicists considered the possibility of transuranic elements. There was even a short-lived claim of having discovered an element ('carolinium') of atomic weight ca. 256. With the emergence of the quantum theory of atomic structure, Bohr and a few other physicists came up with theoretical reasons that apparently justified the nonexistence of transuranic elements, meaning that they were physically impossible (Kragh 2018, pp. 5-11). As to the elements below uranium, still in the mid-1930s several positions in the periodic table were unoccupied. Were these missing elements existing on Earth and only undiscovered so far? If they did not exist on Earth, had they once existed but now vanished because of a high radioactive decay rate or for some other reason? Or did they simply not exist whether on Earth or elsewhere in the universe? Reflecting the spirit of the plenitude principle, physicists and chemists generally dismissed the third option.

As mentioned, not only is there a temporal component in the concept of existence, there is also a spatial component. Existence surely refers to nature, but what is this nature more precisely? In so far as chemical elements are concerned, 'nature' traditionally referred to the accessible surface of the Earth, but of course, the heaven is no less natural than the Earth. Recall that the element helium was first hypothesized and detected as a constituent of the Sun's atmosphere and only later found in terrestrial sources.

Plenitude philosophy has recently re-emerged in an extreme form in cosmological ideas about the multiverse, the controversial hypothesis that there exist a huge number of other universes different from ours. According to the 'landscape' multiverse model the different universes are actualizations of vacuum states computed from the equations of string theory. In a popular book on the landscape multiverse the leading physicist Leonard Susskind (2007, p. 177) claims that *all* objects consistent with the fundamental laws of physics actually exist, the reason being that, "What physicists […] mean by the term *exist* is that the object in question can exist *theoretically*". As Susskind points out, perhaps facetiously, this implies that "perfectly cut diamonds a hundred miles in diameter exist [and] so do planets made of pure gold". Since this bizarre claim derives from an idiosyncratic redefinition of the concept of existence, without implying that the unusual objects exist as physical bodies, it does not reflect the plenitude principle in its ordinary version.

No less problematically, does the nuclear laboratory and its sometimes ephemeral products count as nature? Would we say that something synthesized in the laboratory, and detected only there, exists in the same sense as an entity found outside the laboratory? According to the old meaning of the principle of plenitude the answer will be no, but this meaning reflects the conditions and knowledge of eighteenth-century science. From a modern point of view it is natural to modify the meaning and turn the answer into a yes.

Modern scientists undoubtedly think of synthetic objects as no less really existing than natural objects. After all, it would be ridiculous to call nylon, DDT, synthetic drugs, and plastic products non-existing bodies. These objects were born in the laboratory but have long ago left it and become parts of the ordinary world, perhaps unnatural but definitely real.

Other synthetic molecules may be highly unstable and produced only for scientific reasons, and yet these too count as really existing even though they may exist only for a fraction of a second or under highly artificial circumstances. For example, the sodium-helium compound Na_2He first synthesized in 2016 required a pressure of more than one million atmospheres. At very high pressure other compounds have been found which are not allowed by classical chemistry, such as the sodium chlorides Na_3Cl, $NaCl_3$, and $NaCl_7$. Some of these ‘forbidden’ compounds may exist in the interior of the Earth or other planets. Although they violate the classical rules of chemistry, they are allowed according to quantum-chemical and high-pressure thermodynamic calculations. As noted by a research team specializing in this kind of chemistry, “Strongly compressed matter may exist in totally counterintuitive chemical regimes” (Zhang *et al*. 2013).

The ontological problems of artificial elements appear in a more extreme form in connection with the so-called superheavy elements at the very end of the periodic table (Kragh 2018). These elements are produced in the form of a small number of atoms only and in several cases not even atoms have been formed, but only a handful of their nuclei. Moreover, since these nuclei have a very short lifetime, as short as the order of a millisecond, they disappear almost instantly after being formed and detected. The potential existence of elements such as livermorium (atomic number $Z=116$), tennessine ($Z=117$) and oganesson ($Z=118$) is turned into actual existence not by finding them in nature but by creating them in the laboratory. Strictly speaking, it is unlikely that even a single atom (or atomic nucleus) of these elements exists today, and yet they have won official recognition from IUPAC as real and not merely potential elements.

Since it takes only about 10^{-14}s for an atomic nucleus to attract electrons from its surroundings and form an atom, it is possible that some of the ephemeral atoms were formed in the experiments. Although no atom has actually been detected, it *could* have been formed and its electron configuration can in any case be calculated. From a plenitude point of view atoms and not only nuclei of the three elements do exist.

Without explicitly referring to the plenitude principle, Amihud Gilead (2016; see also Kragh 2018, p. 97) has recently suggested that superheavy elements exist as 'chemical pure possibilities' whether or not they are synthesized and thus turned into new elements that can be detected experimentally. Apparently he endows any theoretically predicted atom, however large its atomic number, with reality. Although Gilead admits that the actualization of pure possibilities is a question of experimental evidence, he insists that these possibilities are accessible to the human intellect without relying on empirical data. As he says, pure possibilities "exist independently of our mind or of our knowledge and, hence, they can be discovered by us". Gilead's ideas concerning chemical elements are based on a metaphysical system he calls 'panenmentalist realism' which seems to be far from the idea of reality adopted by working scientists.

To repeat, the principle of plenitude rests on theories or laws that distinguish between what is allowed and forbidden. If the potential existence of X violates a well-established law, X can have no real existence. But the law in question, however well-established, may be wrong, insufficient or wrongly interpreted. From about 1920 to the early 1960s it was generally taken for granted that the noble or inert gases form no compounds since this would violate the generally accepted octet rule and related ideas of chemical bonding. Nonetheless, in 1962 the British chemist Neil Bartlett succeeded in synthesizing the first noble gas compound $XePtF_6$ and, later the same year, the first binary noble gas compound XeF_4. Since then many other compounds of this 'forbidden' class have been found (Gay 1977, Kauffman 1988). As it turned out, the usual understanding of the octet rule was inadequate, such as noted retrospectively by three chemists: "The nature of the binding in the recently discovered compounds of xenon and fluorine is of particular interest since their stability seems to violate one of the oldest and most accepted rules of valence theory" (Jortner *et al.* 1963). Properly understood chemical bonding theory does allow xenon and most other noble gases to form compounds. While in some cases the belief in plenitude has motivated experimental searches, in this case it discouraged chemists from looking for what apparently could not exist.

7. Muonium and Other Exotic Forms of Matter

Superheavy elements are not the only objects of a chemical nature which are unusual and whose existence is or has been subjects of debate. Ordinary matter consists of tightly bound protons and neutrons surrounded by shells of electrons, but there are more elementary particles than those three familiar building blocks. Consider the suggestion that exotic atoms consisting solely of electrons and positrons might exist in stellar atmospheres, such as the little-known Yugoslavian physicist Stjepan Mohorovičić speculated in a paper of 1934 (Kragh 1990). For the lightest of these super-light elements, one electron and one positron revolving around each other (e^+, e^-), Mohorovičić proposed the name 'electrum' and symbol Ec. His arguments for electrum and its absence from the Earth's atmosphere were strikingly similar to Mendeleev's earlier speculations of the ether as a sub-hydrogen element. But contrary to Mendeleev, he wisely avoided to place electrum or other of his electron elements in the periodic table.

Mohorovičić's electrum is today known as positronium, a name coined by Arthur Ruark (1945) who reasoned that since the system could exist, albeit in an unstable form only, it did exist. As he wrote, "no physicist will doubt the existence of these hydrogen-like atoms". Note that at the time there was no empirical evidence supporting the existence of positronium. There have been suggestions of natural but short-lived positronium on Earth, but none of these have been verified. On the other hand, the atom-like electronic system was first detected by Martin Deutsch in experiments from 1951 and since then it has been widely studied by chemists. What is more, spectral lines from natural positronium have been identified in outer space, first in 1984 in the spectrum of the Crab Nebula.

Mohorovičić seems to have come to his unorthodox idea by means of a plenitude argument, namely that there was no reason in either physics or chemistry why such electron elements should not exist. In a critical review of Mohorovičić's paper, the British astronomer Richard Wooley (1934) noticed that these very light elements were "not debarred from existing by the lack of room in Mendeléef's table". Moreover, "If a proton and an electron combine to form a hydrogen atom, why should not the newly discovered positron and an electron combine to form a super light hydrogen?" Here we have the principle of plenitude in operation, in its classical and admittedly vague version.

The electron (e) and the heavier muon (μ) both belong to the lepton family of elementary particles. Given the similarity between the electron and the muon one might think of replacing the positron in positronium with a positively charged muon; or to replace both electrons with muons. If so we have what may be called leptonic atoms. Indeed, short-lived atomic systems of the kinds (μ^+, e^-) and (μ^-, μ^+) have been detected in experiments and the first kind of 'muonium' even form chemical compounds and has officially been assigned a chemical symbol (Mu). Also 'muonic helium' is known, consisting of an electron orbiting a nucleus consisting of an alpha particle and a negative muon very close to it. Although the atomic nucleus is that of a helium atom, the atomic system (α, μ) behaves chemically as were it a heavy hydrogen isotope.

A few chemists have made the remarkable suggestion that super-light atoms of the kind mentioned should be considered isotopes of hydrogen and thus occupy the same place as hydrogen in the periodic table (Goldanski 1970, Goli & Shahbazin 2015). Generally, modern physics and chemistry has led to a proliferation of new forms of exotic matter in addition to the classical baryonic matter. This development may perhaps be seen as in agreement with the plenitude principle and its claim of ontological richness. As Hamlet reminded Horatio, "There are more things in heaven and Earth, […] than is dreamt of in your philosophy."

8. Conclusions

The essence of the age-old principle of plenitude is that potential existence corresponds to actual existence. Explicit references to the plenitude postulate or the equivalent totalitarian principle are largely absent from the literature on chemistry including its historical and philosophical contexts. Nonetheless, the ideas behind the plenitude postulate are of considerable interest as they offer a novel perspective on certain episodes in the history of chemistry. Thus, chemists' conceptions of chemical elements, their place in the periodic table and their possible combinations have sometimes been inspired by plenitude reasoning, and in a few cases explicitly so. The claim works first and foremost as a heuristic tool, as one motivation among many others for chemists and other scientists to explore if something theoretically allowed is in fact part of nature's fabric.

As pointed out in this paper, the meanings of crucial terms such as 'existence' and 'nature' have changed over time. While in the past existence simply referred to objects and events in the observed nature, today one has to take into account also the synthetic objects created in the chemical and physical laboratories. The extended plenitude formula thus becomes 'what can exist, either exists (or has existed or will exist) in nature or can be created'. The case of superheavy elements is particularly relevant in this respect, and so is the case of counterintuitive or 'forbidden' molecules and atomic systems.

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