**Structural Realism in the realm of the periodic system of chemistry**

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These divisions and definitions, namely ‘cells,’ ‘molecules,’ and ‘electrons,’ are possibly very imperfect; it may be that with time science will establish others, but the principle will remain always the same and lower cosmoses will always be in precisely such relation to the Microcosmos (George Gurdjieff, as quoted by Ouspensky, 1949)

**Abstract**

After briefly reviewing the meaning and recent literature on structural realism in general, the authors propose that the periodic system provides an example of structural realism in chemistry, a subject that has received very little attention. The dual meaning of the term element is discussed, as previously described by Mendeleev and Paneth. It is argued that the structure of the periodic system, which concerns the abstract elements, is ‘more real’ than the elements in the sense of simple substances. The challenges that the periodic system has faced since its discovery are reviewed, as are the evolving theoretical explanations for the periodic system, in order to illustrate its resilience. It is also proposed that considering elements as abstract basic substances, as they were called by Paneth, can serve to settle various ongoing debates regarding the placement of certain elements in the periodic table.

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**1. Introduction**

Structural realism was introduced to the world, or perhaps resurrected from previous incarnations, by John Worrall in a highly influential article that he published in 1989 (Worrall, 1989). In it Worrall admits that there are many precursors to the general view that he argues for, and most notably the work of Henri Poincaré and Pierre Duhem. Briefly put, Worrall’s view is that the long-standing debate between realists, who believe that the entities posited by scientific theories actually exist, and anti-realists who do not, can be mediated by accepting a position dubbed structural realism. Worrall thinks that scientifically posited entities do not necessarily exist but that the underlying mathematical structure does. In doing so, Worrall is partly responding to the pessimistic meta-induction, made famous by Larry Laudan, which points out that many previously posited scientific entities, such as phlogiston, the ether, and caloric, have now been abandoned, even though they may have featured in what were successful theories at one time (Laudan, 1981). If this is the case, so the meta-induction says, why should we believe that currently posited scientific entities should fare any better?

Worrall presses his case for interpreting structure rather than entities realistically by appealing to theories of light. For example, in the 19th century, Augustin-Jean Fresnel developed a theory in which light waves propagated through an all-pervading mechanical medium. Fresnel’s theory was later succeeded by that of Maxwell, for whom light was to be regarded as consisting of an electromagnetic field. Some of Fresnel’s equations, however, were successfully retained in Maxwell’s theory. Worrall and others, therefore, conclude that whereas entities may come and go, the underlying mathematical structure survives across theory change.

Worrall’s article has spawned a veritable cottage industry, especially among philosophers of physics who have applied this intriguing idea in many areas of classical, as well as modern physics. These authors include Ladyman, French, and Saunders, among many others (Ladyman, 2009, 2011; French, 2016; Saunders, 2003). However, suppose structural realism (SR) is to be of lasting value. In that case, one imagines that it should apply to other disciplines than physics, although one then runs across the problem that these other disciplines do not possess the same degree of mathematical structure that physics obviously does. This difference has not deterred many philosophers of science from attempting to extend SR into other areas of science, such as biology (French, 2011, 2014; Sarkar, 2020), the social sciences (Kincaid, 2008; Ross, 2008), cognitive science (Beni, 2019) and sociology (Donati, Archer, 2015) and, in some cases, from arguing that SR does not in fact apply across the board (Tulodziecki, 2016) in the case of medicine.

**2. Can SR be applied to chemistry?**

In spite of all these attempts, few authors have yet ventured to examine whether SR has any relevance to the discipline of chemistry, which is frequently described as being the central science. In addition, it may be said that chemistry is the next most mathematical of the sciences after physics and, therefore, the most fertile ground in which to attempt to enlarge the domain of SR.

One exception to the lack of SR talk in chemistry is the historical case of phlogiston, one of Laudan’s examples of a scientific entity that was successful in many ways, but which was subsequently deemed not to exist following the Chemical Revolution. While some authors have argued that phlogiston can be said to have been retained in the modern concept of combustion involving oxygen, or in terms of oxidation and reduction, others have criticized these proposals (Carrier, 2004; Ladyman, 2011; Schurz, 2009).

In a previous article, one of us (MP) has argued that the modern concept of oxidation number does not represent a natural extension of phlogiston because oxidation numbers apply to particular elements rather than compounds as a whole (Pizzochero, 2025).

But phlogiston is a case of an entity that has ceased to exist. There are no studies of SR in the context of modern or contemporary chemistry. This is surprising given that one of the longest-running debates since the start of the 19th century was the question of whether atoms should be regarded realistically or anti-realistically/instrumentally. A possible reason for this state of affairs may be the development of scanning tunneling microscopy, which now provides rather plausible evidence for the real existence of atoms. For example, Figure 1 shows the surface of a layer of graphite, which clearly displays the hexagonal shape of this form of carbon that students invariably learn in their high school chemistry courses.

Strictly speaking, these are not direct images of atoms but the result of the interaction between a probe in the scanning tunneling microscope and the atomic surface in question. Nevertheless, it would be a remarkable coincidence if these images were to somehow conjure such a set of interlocking hexagons by chance, as they seem to in the case of graphite.

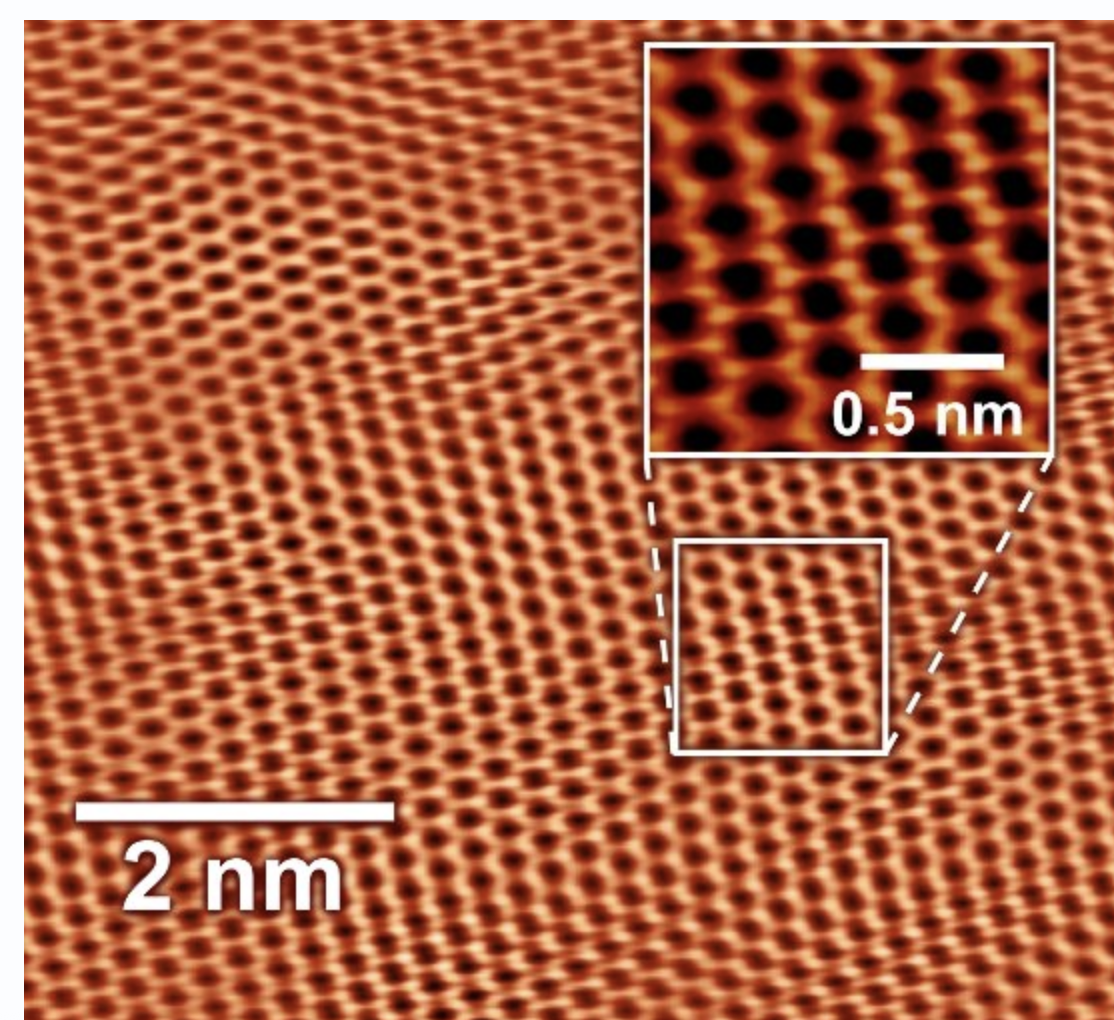


Figure 1. Scanning tunneling image of a sheet of graphite

**3. The evolution of the periodic system?**

In the present section, we will be making the case for regarding the periodic system, rather than the periodic table, in the light of structural realism. In addition, we will consider what insights can be gained into some of the long-standing questions in the historical and philosophical study of the periodic system. For example, nobody has yet given an account of why none of the five co-discoverers of the periodic system, other than Mendeleev, found it necessary to consider the philosophical nature of the term ‘element’ as well as the dual sense of this term, which will be discussed below.

One way to understand the nature of the periodic table, and the periodic system which it attempts to represent graphically, is to consider its historical development. Although tables of chemical affinity existed as many as 300 years ago and even though Lavoisier produced a famous table of the 33 known ‘elements’ in 1789, none of these developments can be considered to be a periodic system for the simple reason that they did not feature periodicity among the properties of the elements. Our brief historical survey begins with the rebirth of atomic theory in the early 1800s at the hands of the Manchester school teacher John Dalton. Dalton published his five postulates about the nature of atoms, including the fact that they were indestructible, in his view, and that the atoms of each element had a distinct weight. This development can be identified as the starting point of all the later steps, which culminated in the discovery of chemical periodicity and its representation in various periodic tables in the 1860s.

The first hint of chemical periodicity came from one Wolfgang Döbereiner, a German chemist who noticed a remarkable property concerning several sets of three elements that behaved similarly in terms of chemical and, in some cases, physical properties. Using Dalton’s atomic weights, Döbereiner noticed that the atoms of lithium, sodium, and potassium, to take the classic example of such a triad, had two important properties. First, the atomic weight of one of the atoms of these three elements was approximately the numerical average of that of the other two. The approximate weights of the atoms of these elements are as follows: lithium = 7, sodium = 23, and potassium = 39. Consequently, the weight of an atom of sodium, or 23, is the mathematical average of that of lithium + potassium or (7 + 39)/2 = 23. In addition, the chemical properties possessed by the element sodium are intermediate between those of lithium and potassium. For example, if one places small samples of equal size of each of these elements into basins of water, they show an increasing degree of reactivity, starting with lithium, which reacts slowly, sodium, which reacts moderately, and potassium, which reacts very vigorously.

Döbereiner had discovered a numerical regularity that underlies and connects the behavior of three quite distinct elements. This can be regarded as the first hint of an underlying structure among the different elements and one which eventually morphed into the familiar periodic table that today hangs in chemistry lecture halls and laboratories throughout the world.

What followed were various attempts to discover other triads of elements, some of which research lapsed into mere numerology in the sense that the numerical coincidences were seized upon while neglecting the fact that many claimed new triads concerned elements that did not display chemical similarities (Scerri, 2019). While the notion of chemical triads fell into disrepute, the germ of the idea seems to have survived. In addition, many more elements were discovered following the initial publication of Döbereiner’s triads in 1817. The eventual periodic system consisted of connecting the various legitimate triads that existed, but it is doubtful that the periodic table could have emerged by doing just that, since many elements still remained to be discovered.[[1]](#endnote-1) Nevertheless, as one of us has claimed elsewhere, the discovery of triads essentially marks the discovery of chemical periodicity, a notion that will be elaborated a little further as this historical trajectory continues to unfold (Scerri, 2022).

The next decisive development took place at the Karlsruhe conference of 1860, when the Italian chemist and physicist Cannizzaro provided a definitive and consistent set of the atomic weights of the elements. and the six discoverers of the periodic table. Two chemists who attended this meeting were Lothar Meyer and Mendeleev, each of whom was to produce versions of the periodic table a few years later, based on an increasing order of elemental atomic weights.

**4. What is an element?**

The true nature of elements has been debated since the dawn of human knowledge, starting from the time of the pre-Socratic philosophers, for whom four elements existed, namely earth, fire, water, and air. Moving to the Middle Ages and the field of alchemy, more substances became regarded as elements, such as gold, silver, copper, iron, tin, lead, antimony, mercury, sulfur, and carbon.

In modern times, the list of substances considered to be elements grew to as many as 33 by the time of Lavoisier. While previous thinkers had viewed elements metaphysically, Lavoisier is well known for emphasizing them as substances that could actually be isolated, thus reducing any metaphysical interpretation.[[2]](#endnote-2) Undoubtedly, these two perspectives greatly contributed to the development of modern chemistry and the decline of the ancient discipline of Alchemy.

Nevertheless, the metaphysical aspects of elements remained in the background of chemists’ thoughts, only to be prominently revived by Dimitri Mendeleev, who is widely considered the leading discoverer of the periodic system. In many passages of his books and articles, Mendeleev goes to considerable lengths to emphasize the dual sense of the term element as denoting simple substances that can be isolated, as well as the abstract sense of elements that can neither be isolated nor observed but which nevertheless persist in the course of chemical reactions. Moreover, Mendeleev makes the seemingly unusual claim that the periodic system is primarily a classification of the elements as abstract entities, contrary to the generally held belief that the system is entirely based on the observable properties of elements.

In the course of developing his version of the periodic system, Mendeleev acknowledged the question of how the elements can survive in any compound in which they might occur. For example, sodium chloride consists of the gray poisonous metal sodium and the green poisonous gas chlorine, which seem to have disappeared after their combination to form a white crystalline compound, namely sodium chloride.

Mendeleev answers this question by appealing to a long-standing notion dating back to the pre-Socratic philosophers, who regarded the elements as being abstract, and simultaneously giving rise to all the variety of substances that are observed.[[3]](#endnote-3) The four elements (fire, earth, water, air) were also considered as property bearers responsible for the observable features of all substances, while remaining intrinsically unobservable. Said in other words, the four elements were regarded as immaterial qualities impressed on an otherwise undifferentiated primordial matter and which were present in all substances.

This view survived for a long period until it was eventually challenged by Antoine Lavoisier and others during the Chemical Revolution, and gave rise to a ‘new chemistry’.

The new view drew upon the pre-Socratic tradition of elements as principles, but also made some important modifications. In particular, the new chemistry introduced the concept of a simple substance, meaning one that could not be decomposed by any known means. The inclusion of the word known is important, since the scheme proposed that simple substances were to be regarded as such only provisionally, because future refinements in analytical techniques might reveal that they were, in fact, decomposable. Lavoisier no longer talked of undifferentiated primordial matter, but the focus of attention became the many elementary constituents, or simple substances, each of which possessed observable properties. On this philosophical basis, Lavoisier and his contemporaries created a list of the 33 simple substances known at the time.[[4]](#endnote-4)

Over time, simple substances became regarded as the only form of an element, while the abstract counterpart to each simple substance was largely forgotten. And yet the abstract sense of elements was not completely neglected, and continued to serve a function in nineteenth-century chemistry. Any remaining attention to abstract elements seems to have been put aside because of the parallel development concerning the reality or otherwise of Dalton’s atoms (Brock, Knight, 1965).

**5. Mendeleev**

The culmination of the nineteenth-century element scheme was achieved with the discovery of the periodic system and, in particular, with the work of Mendeleev, who began his landmark book by paying tribute to Lavoisier. Interestingly, Mendeleev appears to have been more concerned with the philosophical status of the elements than any other of the six co-discoverers of the periodic system (Scerri, 2020). Mendeleev’s approach to the periodic system consisted of distinguishing very deliberately between a simple substance and an element. To quote Mendeleev,

It is useful in this sense to make a clear distinction between the conception of an element as a separate homogeneous substance and as a material but invisible part of a compound. Mercury oxide does not contain two simple bodies, a gas and a metal, but two elements, mercury and oxygen, which, when free, are a gas and a metal. Neither mercury as a metal nor oxygen as a gas is contained in mercury oxide; it only contains the substance of the elements, just as steam only contains the substance of ice, but not ice itself, or as corn contains the substance of the seed but not the seed itself (Mendeleev, 1891, p.23)

Mendeleev regarded an element as unobservable but forming the inner ‘essence’ of simple bodies. Whereas any particular abstract element was thought of as unchanging, its corresponding simple body aspect could take many forms, such as diamond or graphite, in the case of the element carbon, for example.

Mendeleev recognized that while the abstract sense of element survived intact in the course of compound formation, its atomic weight was the only quantity that likewise survived in the course of chemical reactions. Mendeleev, therefore, proceeded to associate these two features together so that an element or a basic substance, as it has become known in the contemporary literature,[[5]](#endnote-5) would be characterized by just its atomic weight. An abstract element, therefore, possessed a single, measurable, but not observable, attribute that would remain unchanged in the course of all its chemical combinations.[[6]](#endnote-6)

In so doing, Mendeleev was providing a fundamental justification for using atomic weight as the basis for the classification of the elements, unlike the writings of other discoverers or precursors of the periodic system, who just used atomic weights to order the elements. Following this interpretation, it becomes possible to understand Mendeleev’s otherwise rather naive-sounding claim that he had realized the need to order the elements according to atomic weight, given that several other pioneers of the periodic system had done so before him. However, unlike the co-discoverers of the periodic system, Mendeleev provided a detailed philosophical account of why this was the correct approach to take.

But it would be incorrect to believe that the abstract sense of element is the only aspect to focus upon when classifying the elements, as some passages in Mendeleev’s writings suggest, since periodicity also concerns properties in the observable sense.[[7]](#endnote-7) Atomic weight alone can only provide the sequence of the elements and not the points at which they repeat approximately. The sole use of atomic weight would therefore not reveal the chemical and physical periodicity among the elements.

The Japanese historian of chemistry, Masanori Kaji, has argued that Mendeleev began his textbook by using the concept of valency as a means of ordering the elements. This is clearly seen in the fact that Mendeleev considered the elements in the order of hydrogen, oxygen, nitrogen, and carbon, whose valences are 1, 2, 3, and 4, respectively. Mendeleev then turned to the halogens, beginning again with the valence of 1, followed by a consideration of the alkali metals, also of valence 1, and then the alkaline earths, which show a valence of 2.

It appears that, while making the transition between the alkali metals and the alkaline earths, Mendeleev made the crucial discovery that led to publishing his periodic table. It was at this point that he realized that the key to classifying the elements lay in atomic weight rather than valence, or as Mendeleev writes:

The purpose of my paper would be entirely attained if I succeed in turning the attention of investigators to the very relationships in the size of the atomic weights of non-similar elements, which have, as far as I know, been almost entirely neglected until now.

Whereas Lothar Meyer and Newlands preceded Mendeleev in making minor predictions for the existence of unknown elements, Mendeleev made far more extensive and, as it turned out, successful predictions. Furthermore, Mendeleev also corrected the atomic weights of a number of already known elements, as well as correctly reversing the positions of the elements tellurium and iodine (Scerri, 2019).

There is currently an extensive literature which aims to understand why Mendeleev was able to make such striking predictions rather than Lothar Meyer or others (Gordin, ). Some authors have claimed that the other chemists lacked the courage to do so; others have proposed a sociological explanation concerning the contrasting academic climates in Russia compared to those in Germany. Meanwhile, one of us has suggested that Mendeleev’s advantage was due to his philosophical attitude regarding the nature of the elements, which provided him with the insight that his less philosophically minded contemporary chemists lacked (Scerri, 2020).

As was argued above, Mendeleev believed that the abstract sense of elements should be regarded as more foundational than their simple substance aspects. Consequently, if the periodic system were to be of fundamental importance, it would primarily have to classify the abstract elements. In making predictions, Mendeleev considered the abstract aspect of elements more than their concrete instatiations. If observational data on a particular simple substance, available at the time, pointed in a particular direction, this feature could be overlooked, since periodicity was deemed to depend primarily on the abstract aspect of elements.

Because he was mainly attempting to classify abstract elements, not simple substances, Mendeleev was not misled by nonessential chemical properties. For example, the halogen elements (fluorine, chlorine, bromine, and iodine) appear to be very different from each other if one focuses on the simple substances, since they consist of two gases, a liquid, and a solid, respectively. But if one considers the similarities between the compounds that each forms with sodium, all of which are crystalline white powders, their kinship becomes clearer. The main point is that fluorine, chlorine, bromine, and iodine, in these compounds, are present not as simple substances but in their latent, or abstract, form as basic substances.

Armed with this view of the elements, Mendeleev could maintain the validity of the periodic law even in cases where observational evidence seemed to point in a different direction. Such a bold approach presumably resulted from his belief that the periodic law applied to the abstract elements or to elements as basic substances. Mendeleev also held that this law was as fundamental and equal in status to Newton’s laws of mechanics, a claim which he expressed in several of his writings. Had he been more of a positivist and had he focused on elements as simple substances, Mendeleev might have lost confidence in the importance of the periodic law and might have harbored doubts about his predictions. In the spirit of the present article, Mendeleev can be seen as a structural realist who regarded the periodic system realistically, but not the entities that populate it. Thus, Mendeleev may also be said to have promoted a ‘thingless ontology’ which focuses on abstract, rather than concrete, elements.

It would appear that Mendeleev might also be considered as an early exponent of structural realism in the sense of placing greater emphasis on an abstract system, and on structure, than on the entities that chemistry is concerned with, be it atoms or elements as simple substances. This proposal can be further supported by examining Mendeleev’s negative views about the reality of atoms, even some sixty years or more after they had been successfully reintroduced into science by John Dalton in the early 1800s.

A frequently neglected fact about Mendeleev, and one that surprises modern readers, is that he remained steadfastly opposed to the reality of atoms, which some chemists had been willing to embrace since Dalton published his views on the subject in the early 1800s.[[8]](#endnote-8) Mendeleev’s position regarding atoms has itself been the source of much debate, although it appears that he was generally not in favor of conceiving of atoms as real entities and preferred to refer to atomic weights as element weights instead.[[9]](#endnote-9)

It is rather well known that Mendeleev, the leading discoverer of the periodic system, was opposed to thinking of atoms realistically. Many passages in his writings clearly express this view, including the following two examples,

One may replace the term atomic weight by elementary weight in order to avoid recourse to the atom, which in any case is purely conventional (Mendeleev, 1868).

The atomic hypothesis seems to me to be useless, if only because it does not lead to any general law and because it is not assured of a solid basis (ibid).”

Nevertheless, Mendeleev placed a great deal of attention on the question of the existence of *elements*, as we have discussed above.

**6. Friedrich Paneth on the nature of elements**

Even though Mendeleev upheld a view of elements as abstract entities, the prevailing positivist attitude among chemists and physicists of the years that followed resulted in the erosion of such a notion. Returning now to the historical evolution of the periodic table, we must return to the discovery of isotopes of some elements by Soddy and others, starting in the 1910s and 1920s. In addition, many discoveries in atomic physics, as well as the development of quantum mechanics, as seen in the work of Bohr, led to a microscopic and reductive explanation of the periodic table and the underlying periodic system (Scerri, 2020).

Nevertheless, the Austrian-born radiochemist Friedrich Paneth redirected the attention of chemists to an accompanying abstract view of elements. While some of his contemporaries, like Kasimir Fajans, were in favor of defining an element entirely through atomic physics, Paneth insisted on the need to retain an abstract, some might say even a metaphysical, conception alongside the more concrete definition.

Paneth’s dual definition was as follows,

1. Element a simple substance (einfacher Stoff), the material form of an element that can be isolated and studied in the laboratory.
2. Element as basic substance (Grundstoff), the abstract principle or kind common to all forms of that element; it persists through chemical change but is never found in pure form.

Once again, one sees the underlying structure of the elements being taken to be equally, if not more, fundamental than their concrete or more realistic aspects. Stated otherwise, Paneth appears to be ascribing realism to the underlying structure of elements and affirming that the metaphysical nature of elements has a role to play in attempts to understand the field of chemistry.

Indeed, Paneth’s return to Mendeleev’s dual view of elements has been partly enshrined in the current official definition of the term element, as given in the IUPAC Gold Book (International Union of Pure and Applied Chemistry, 2019). More specifically, following several changes carried out by successive committees of chemists, the IUPAC organization has maintained the spirit of Paneth’s desire for a dual definition, although it has become distorted to the point of effectively eradicating any mention of the abstract sense of any element. This is unfortunate, but thankfully, this state of affairs is currently under review within the IUPAC community.[[10]](#endnote-10)

The current Gold book definition reads as,

1. A species of atoms; all atoms with the same number of protons in the atomic nucleus.
2. A pure chemical substance composed of atoms with the same number of protons in the atomic nucleus. Sometimes this concept is called the elementary substance but mostly the term chemical element is used for both concepts.

**7. The challenges faced by the periodic table**

Mendeleev’s periodic table provides a structural entity that has not been refuted in spite of many challenges. These episodes in the history of chemistry have included the following,

1. The case of pair reversals
2. The discovery of the noble gases
3. The discovery of isotopes,
4. The discovery and accommodation of the rare earth elements,
5. The relativistic effects that occur in the atoms of elements with high atomic weights

Pair reversals consist of several pairs of elements that would appear in an incorrect order if one adheres strictly to ordering the elements according to their atomic weights. The best-known example is the case of iodine and tellurium. The atomic weight of iodine is less than that of tellurium. However, the chemical properties of the two elements require that the elements should be reversed in the way that they are placed in the periodic table to be consistent with their chemical properties. Iodine is a halogen that should be grouped with the elements fluorine, chlorine, and bromine, while tellurium has many properties in common with the preceding group of the periodic table, which includes oxygen, sulfur, and selenium. To their credit, Mendeleev and other discoverers of the periodic system reversed these elements but also recognized the challenge that this situation posed for the underlying ordering principle. Matters were eventually resolved more than 40 years later when it was discovered that a better ordering principle was provided by the atomic number of each element, rather than its atomic weight. As a consequence of this change, the reversal of iodine and tellurium was placed on a secure foundation, given that tellurium has a lower atomic number (52) than iodine (53).

The first noble gas to be discovered was argon, which had an atomic weight of 40. This posed a problem for the periodic table since there was already an element, namely calcium, which possessed the same value, and it therefore appeared that argon could not be accommodated into the table. Over the course of a few years, a total of four further noble gas elements were discovered, which meant that the periodic table seemed incapable of accommodating a total of five elements, thus leading to something of a crisis in the chemistry and physics community, some of whose members began to think that the periodic table was in danger of being overthrown. However, one of the co-discoverers of these elements, William Ramsay, eventually solved the problem by creating an entirely new column on the table, between the halogens and the alkali metals (Scerri, 2020).

Another major challenge to the very existence of the periodic table occurred in the 1910s when Frederick Soddy and others discovered what appeared to be many new elements, each having a particular atomic weight. As in the previous challenging events already mentioned, some chemists reacted by doubting the validity of the periodic table, given the rapid profusion of what seemed to be new elements that could not be accommodated in the body of the traditional table. But it was also discovered that the more accurate criterion for the identification of any element was given by its atomic number as mentioned above, with the result that the newly discovered species were not in fact new elements but variations or isotopes of those that already existed.

A fourth challenge that was successfully overcome was the case of the rare earth elements, which for many years seemed to defy all attempts at placing them correctly into the periodic table. The solution came from the recognition that chemical periodicity involves period lengths of varying length and that the rare earth elements required an expansion of the periodic table to encompass periods consisting of 32 elements (Scerri, 2025).

Yet another challenge to the periodic table comes in the form of relativistic effects, which result in the profound modification of the properties of elements that have high atomic numbers and which require the application of relativistic quantum mechanics in order for their properties to be successfully explained. Briefly put, as the number of electrons in an atom increases, the innermost electrons begin to move at a speed which approaches that of light and therefore need to be considered from the perspective of Einstein’s special theory of relativity.

These effects were first detected in the superheavy elements of rutherfordium (element 104) and dubnium (element 105). It was discovered that rutherfordium atoms behaved unlike the elements that belong in the same group of the table, but more like plutonium, which falls quite far removed from the position of rutherfordium. Meanwhile, atoms of the element dubnium behaved similarly to atoms of protactinium rather than the elements niobium and tantalum with which it is grouped in the periodic table. The upshot of these and several subsequent studies has been that relativistic effects need to be invoked to explain what at first sight appear to be anomalies and thus further apparent challenges to the robustness of the periodic table.

The simple fact is that the periodic table has withstood all five of these challenges, which leads one to think that it represents a secure underlying structural foundation for chemistry.

As one of us (ERS) wrote in a semi-popular article some 13 years ago the periodic system of the chemical elements offers a good candidate for structural realism in that it is literally, as well as metaphorically, the underlying structure for much of the discipline of chemistry and one that has also survived several theory changes such as the invasion of quantum theory into chemistry (Scerri, 2012).

Similarly, the structure that underlies the periodic table, referred to as the periodic system, has survived many changes in the underlying physical theory that purports to explain the periodic system. Such explanations have included the following, arranged in historical order,

1. At the time of Mendeleev’s discovery, there was no explanation
2. J.J. Thomson’s pre-quantum theoretical explanation
3. Bohr’s explanation rested on the original quantum theory, or the old quantum theory.
4. The explanation that draws on axiomatic quantum mechanics, which assigns four quantum numbers to each electron
5. Quantum Relativistic explanations for superheavy elements

It took a period of about 40 years before anybody produced an explanation for why the periodic table has the form that it has, or more specifically, why some particular elements, such as lithium, sodium, and potassium, for example, behave in chemically similar ways. Such an explanation was provided by the discoverer of the electron J.J. Thomson, who suggested that electrons, which were embedded in the main body of the positive atom, were located in a number of concentric rings. By assigning particular numbers of electrons to each ring, Thomson hypothesized that atoms of the elements that shared chemical properties did so because of analogous electron ring arrangements. In providing this explanation, Thomson used arguments entirely arising from classical physics since quantum theory had not yet been applied to the structure of the atom (Thomson, 2009).

Although Thomson had provided a rudimentary form of an explanation that essentially stands to this day, namely that the analogous behavior in the atoms of certain elements lies in their analogous electron arrangements. However, his explanation failed in a significant manner since he claimed that the atoms of elements with 5 electrons would be chemically similar to those having 16 electrons. In modern terms, this amounts to claiming that the element boron would be similar to sulfur, which is incorrect.

Next came the important contribution from Niels Bohr, who began to use the old quantum theory in order to attempt to explain the periodic table. According to Bohr, an atom of boron has an electron arrangement, or configuration, of 2,3, meaning two electrons in the first shell and three in the second one. In the case of the element aluminum, which does belong in the same group of the periodic table as boron, Bohr assigned a configuration of 8,2,3.

However, Bohr’s explanation consisted of a judicious use of semi-empirical arguments rather than an appeal to the first principles of the old quantum theory. In many ways Bohr was led to his assignment of electron configurations by a consideration of chemical properties and spectral evidence instead of a strict derivation from theory.

In the years 1925-26, a more rigorous version of the quantum theory was developed by a number of contributors, most notably Heisenberg, Schrodinger, Pauli, and others. It then became possible to specify a more detailed set of electronic configurations and to resolve a number of remaining anomalies arising from Bohr’s assignments. The more recent development has been the application of relativistic quantum mechanics, which is required to account for the apparent anomalous behavior of the superheavy elements, as was mentioned earlier.

The main point we wish to stress is that the periodic table as a representation of the periodic system has not been altered by any of these successive theoretical developments, thus further emphasizing the resilience of the periodic table our claim that it provides an example in favor of structural realism.

**8. Putting structural realism in chemistry to good use.**

There are a number of long-standing debates among chemists regarding the correct positions of several elements in the periodic table. These disputed placements include hydrogen, helium, lanthanum, actinium, lutetium, and lawrencium. Some of these disputes could benefit from a structural realist approach to the periodic system, which puts more emphasis on the existence of the underlying structure rather than on the individual properties of individual elements regarded as simple substances.

For example, the element hydrogen is typically placed in group 1 of the periodic table, where it sits somewhat uncomfortably along with several reactive metals such as sodium, potassium, and rubidium. Meanwhile, some designers of periodic tables place hydrogen among the halogen elements due to its ability to form singly negatively charged ions, its gaseous state under normal conditions, and its occurrence as diatomic molecules. Yet others place hydrogen on its own, floating above the main body of the periodic table in view of its anomalous status.

The element helium is typically placed at the head of the noble gas group of the periodic table in view of its highly unreactive chemical nature, like the other members of the group that include neon, argon, krypton, and xenon. Other authors prefer to locate helium at the head of group 2 of the table in view of its two electrons and the fact that this feature is analogous to the members of group two, all of which possess two outer electrons in their atoms.

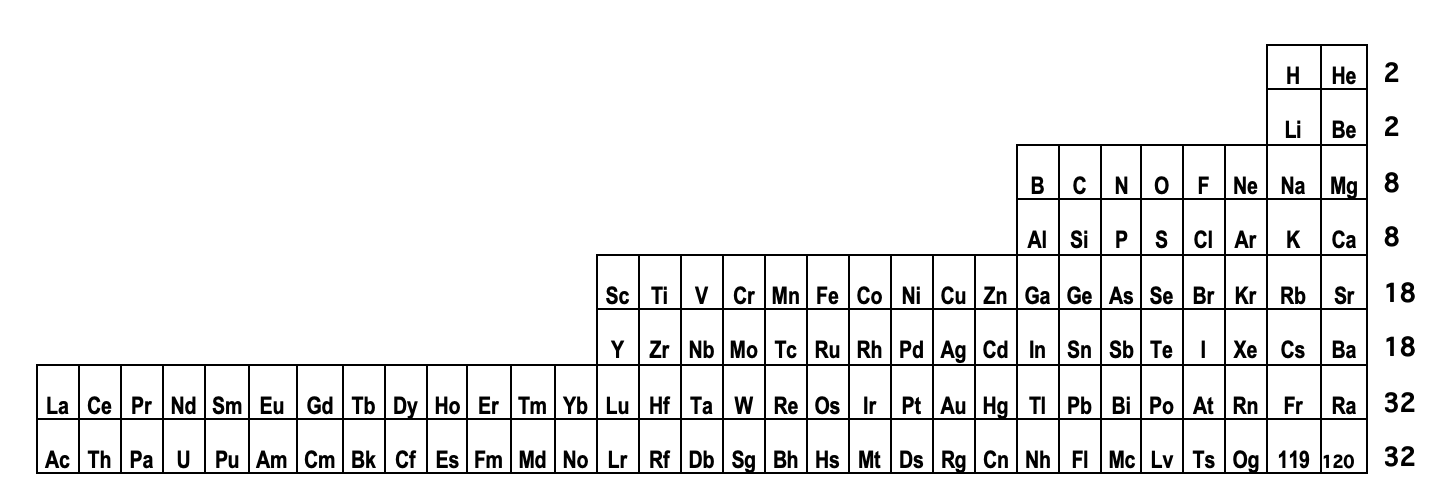


Figure 2. Janet’s left-step periodic table, showing all period lengths, including the first one,

repeating.

One way to solve this issue categorically is to consider the adoption of the left-step periodic table, in which the emphasis is very much on the regularity of the periodic table, which, among other things, features the repetition of all period lengths whereas the conventional table is anomalous in not incorporating the repetition of the very first period of two elements as shown in figure 2 (Janet, 1928; Stewart, 2010; Scerri, 2007).

The dispute concerning the placement of the elements lanthanum, actinium, lutetium, and lawrencium appears to remain completely unsettled if chemists restrict themselves to the chemical or physical properties of these elements or even their electronic configurations. It has been suggested that a categorical resolution to this question is available if one places more emphasis on the regularity of the entire periodic table in terms of smoothly increasing atomic number ordering, rather than on the individual properties of the four elements in question regarded as simple substances (Scerri, 2021).

If one regards the periodic system in a structural realist manner, one is more likely to believe that there is a fact of the matter about chemical periodicity and that it is not merely a matter of human classification. The classification is rather viewed as resulting from 'Nature being carved at its joints'. Periodic classification is, in fact, frequently regarded as the finest example of a natural system of classification.

Nevertheless, many chemists balk at the notion that one optimal system of periodic classification might exist and revert to the view that one can arrange the system in many ways and claim that there is no one 'best system' of classification. The present author believes that this view is incorrect.

It is proposed that one should seek the optimal system of classification even if it may not be possible to arrive at this point based on currently known science. It should also be stressed that when we speak of optimal arrangement, we are not speaking of the shape of the periodic table or whether it is represented as a spiral, in a clockwise fashion, or in three dimensions. These forms of arrangement are indeed arbitrary and a matter of taste. We are referring to the placement of certain elements such as hydrogen, helium, lanthanum, actinium, lutetium, and lawrencium.

**9. Possible objections**

A possible objection to the claim that structural realism applies to the periodic system

might be that the periodic table is merely a compilation of the observable properties of the elements. Structural realism, as it has been discussed in physics, is of course a view concerning theories, while the periodic system is seldom regarded as a theory.[[11]](#endnote-11) Our response to such a rebuttal would be to point out that the periodic system draws on the observed properties of the elements but goes well beyond tabulating and organizing observations of individual elements. Instead, the periodic system expresses the relationship between completely diverse elements in a pattern of regularities.

Another concern may be that the periodic system deals in entities rather than theories. It should be pointed out that this is not necessarily the case since the periodic system applies equally well to entities on a microscopic level as it does to macroscopic samples of elements. There are therefore no particular entities in question, but perhaps elements in the abstract sense that subsumes all possible entities spanning from the microscopic atoms, to nanoscopic samples, and to macroscopic observable samples of the ‘elements’. Indeed, there is a rich and well-developed literature on the nature of elements that needs to be brought to bear on the question being discussed in the present article (Scerri, Ghibaudi, 2020).

1. **Conclusions**

The **periodic table** may be seen as an **empirical manifestation of structural realism** in that it reflects objective relational features of the elements and therefore the natural world. The table’s enduring predictive power, as first illustrated by Mendeleev’s successful predictions of undiscovered elements, supports the realist claim that its structure corresponds to real features of nature*.* When quantum mechanics later explained periodicity in terms of electron configurations, it preservedthe structural relations Mendeleev originally discerned, thus showing **continuity of structure through theoretical change. Structural realism** in the context of the periodic table, or more correctly the periodic system, asserts that what the system captures and preserves, its relations among the elements through all scientific revolutions, in a structure that reflects real features of the world, even if our theories about sub-atomic components of atoms continue to evolve. Given that structural realism maintains that what endures through scientific revolutions is the structure of relations and not necessarily the entities we assume to explain them, the **periodic system** is arguably one of the most vivid examples of such an enduring scientific structure.

1. **Notes**

   A total of 16 elements were discovered between the time of Döbereiner’s first recognition of triads of elements (1917) and the discovery of the mature periodic table by Mendeleev in 1869. Theese elements were lithium, selenium, cadmium, silicon, aluminum, bromine, thorium, lanthanum, terbium, erbium, ruthenium, cesium, rubidium, thallium, indium and helium. [↑](#endnote-ref-1)
2. This ststement represents something of an oversimplification, given that Lavoisier’s list of elements also included some principles such as heat and light. [↑](#endnote-ref-2)
3. As discussed in the present article, Mendeleev’s notion is also rather different in not being entirely metaphysical. [↑](#endnote-ref-3)
4. Once again, this does not explain the inclusion of certain principles in Lavoisier’s list. [↑](#endnote-ref-4)
5. The terminology in the contemporary literature is one of element as basic substance (the abstract sense of element) and element as simple submstance (the observable and isolable or even the everyday sense of element). The terms simple and basic are due to the philosopher-historian Heinz Post who translated the work of his father, Fritz Paneth, who used the words grundschtoff and einfacherstoff respectively. [↑](#endnote-ref-5)
6. The reader should note the difference between observable and measurable in this context. Atomic weight is clearly not observable can can be measured or deduced from some complicated procedures. [↑](#endnote-ref-6)
7. Some authors have pointed out this apparent contradiction in Mendeleev’s writings. [↑](#endnote-ref-7)
8. This is an oversimplification since there were major disagreements and debates on the question of whether atoms were to be regarded realistically or as usueful fictions (Brock, Knight, 1965; Rocke, 1984). [↑](#endnote-ref-8)
9. Pieter Thyssen has written an excellent analysis of Mendeleev’s view on atomism in which he argues that Mendeleev was indeed against the literal existence of atoms as entities but that he may have veered towards a realistic view in his later life when confronted with the problem of classifying the rare earth elements (Thyssen, 2025). [↑](#endnote-ref-9)
10. See E.R. Scerri, What is an element, and how is it defined in the IUPAC Gold Book?

    Submitted to *Chemistry International*. [↑](#endnote-ref-10)
11. With the possible excpetion of Michael Weisberg who has claimed that the periodic table should be considered as a theory (Weisberg, 2007). See the ctitique of this article by one of us (Scerri, 012b)

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