# The Periodic System: The (Multiple) Values of an Icon

Abstract: The periodic system is one of the most widely used icons of science. It is especially celebrated as an exceptional source of information and a pedagogical tool. Although many publications on the history and philosophy of the system have appeared over the years, few of them deal with its underlying values beyond predictability. In this issue, scholars from different disciplines use the history of the periodic system to discuss what the system signifies and has signified for scientists and teachers, as well as for philosophers and historians. By presenting different layers of underlying values as they appear in the eyes of the users, we aim to provide a richer understanding of the periodic system, past and present.

Key words: periodic system, thing value, pedagogical tool, paper tool, relational tool, resilience.

In his book *Scientific Babel*, Michael D. Gordin states that the periodic system of chemical elements “was the single most important discovery of inorganic chemistry in the nineteenth century – and quite possibly of chemistry in general, in any century,” and it is frequently referred to as an icon in science.[[1]](#footnote-1) Indeed, the fact that we can find the periodic system in more or less every chemistry classroom and lecture hall today testifies to its importance in chemistry, as a source of information or compass, and a pedagogical tool. The periodic system is said to “capture the essence not only of chemistry, but also of physics and biology” and is described as a “unique tool, enabling scientists to predict the appearance and properties of matter on the Earth and in the rest of the Universe.”[[2]](#footnote-2) The position a chemical element occupies in the periodic system informs us about its chemical properties, as elements belonging to the same groups, or families (vertical columns in the most used periodic tables), exert similar chemical behavior (Figure 1). This means, for example, that if the natural source of one element needed for the manufacturing of a product is scarce, or its production is too costly, chemists, material scientists or engineers might successfully replace it with another element from the same family.

Figure 1. A modern version of the periodic system. The vertical columns are called *groups*, the horizontal rows *periods*. Credit: wplclipart (public domain).

We may say that this ‘family resemblance’ serves as a compass to navigate the chemical knowledge accumulated on the elements and their combinations and that it may guide scientists in their search for different elements in nature, as was common in the nineteenth and twentieth centuries. Analogously, the periodic system enables scientists to use the better known elements of the family to conjecture the types of compounds that those elements yet be explored are susceptible to form. For example, to the chemist couple Ida (1896–1978) and Walter Noddack (1893–1960) who were looking for elements assumed to be in the same family as manganese in the periodic system, the periodic system served as a compass in their geochemical search for the right minerals. In minerals containing neighboring elements thought to have properties similar to the unknown elements, they successfully discovered rhenium, element number 75.[[3]](#footnote-3) The cartographic metaphor is still shared by contemporary scientists and resonates in popular accounts such as the *Periodic Kingdom* by the acclaimed textbook writer and teacher Peter Atkins.[[4]](#footnote-4)

As a pedagogical tool, the periodic system gains added meaning by systemizing and condensing basic chemistry for learners, and it teaches them to navigate the diversity of the chemical elements that make up all matter. Information on reaction patterns, metallic properties, even varieties in atomic radii can be extracted from the way the elements are ordered in the periodic system, and there is no need to learn about each element separately to grasp the overall patterns. Indeed, both the Russian chemist Dmitri Mendeleev (1834–1907) and the German chemist (Julius) Lothar Meyer (1830–1895) developed the periodic system in a teaching context, as they wished to present the chemistry of the then known 63 elements in a more orderly way when preparing chemistry textbooks. The periodic system has even been described as a *typology* in chemistry, serving a role similar to collections of minerals and species in natural history museums that represent order, coherence and relationships in nature, although at a more symbolic level.[[5]](#footnote-5) The 150th anniversary of Mendeleev’s celebrated presentation of the periodic system in 1869 provides a good opportunity to revisit the history of the periodic system and its meaning, past and present. The importance of the periodic system is demonstrated by the fact that 2019 was declared the International Year of the Periodic Table by the United Nation’s General Assembly and UNESCO.

The most comprehensive account of the history of the periodic system to date is the classic and acclaimed history of the first hundred years by J. W. Van Spronsen, from 1969. A widely read follow-up to Van Spronsen’s book by Eric Scerri in 2006 includes a consideration of the role of modern physics in evaluating the system as well.[[6]](#footnote-6) Some other accounts have focused on the fine-grained chronology of crucial episodes, like Mendeleev’s day on February 17, 1869 (Gregorian calendar).[[7]](#footnote-7) The multiplication of graphical representations have in turn also acquired their chronicler, the best known one being that of Edward G. Mazurs.[[8]](#footnote-8) Overall, historical publications on the periodic tables have dealt with discoveries of elements, the development of the system and its many representations, priority disputes, the significance of a periodic law, and of its reception in different national communities and textbooks. More recently, the development of the periodic system as a collective effort, including contributions from a range of women, has been in the spotlight.[[9]](#footnote-9) Philosophers of science have also been fascinated with the periodic system, e.g., Michael Weisberg has treated it as a scientific object through which the differences among theories, representations and models could be investigated, while Andrea Woody has used the periodic law as a demonstration device in her plea for more attention to practice in the analysis of scientific representation.[[10]](#footnote-10) However, few contributions deal with the relevance and meaning of the periodic system beyond its predictability and ability to systemize empirical data on the elements. Among these less investigated topics we identify the use and meaning of the periodic system beyond its obvious chemical use; the analysis of the periodic system in terms of values ascribed by the users, be they scientists, historians or philosophers; the diversity of interpretations and uses by scientists from the same time period (instead of presenting a linear account of successive “paradigms”); the ensuing endurance as new developments in science appear; the attempts to explain the order through other means than graphical and the system’s use in the pedagogy of chemistry. The aim of this proposed special issue is to bring together perspectives on the history of the periodic system related to such undercommunicated issues and that come from a consciously heterogeneous pool of standpoints. More specifically, in this issue we will explore different underlying meanings of the periodic system found in historical debates on elements and the system itself. We call these underlying meanings *thing values*.

## Values

The study of values in science is a broad field, encompassing discussions on science as value-free or not, values as norms in science (e.g. Merton’s ethos of science), values as guides in research (serving direct or indirect roles), values from within – or separated from science, language and values, values and the dissemination of science, social values, cultural values, valence values (between science and culture), cognitive values and epistemic values in or derived from science.[[11]](#footnote-11) Although one may argue that the sort of values we are exploring in this issue could be associated with epistemic values (attainment of truth, predictivity, for instance) or cognitive values (successful attributes of theories), our idea of value also involves attributes of physical things as much as criteria or guides in research, or attributes of theories.[[12]](#footnote-12) We nevertheless maintain that they are values in the sense that they give worth to the periodic system. In that sense, they resemble attributes of material models discussed by David Baird in his book *Thing Knowledge*, in particular James Watson (b. 1928) and Francis Crick’s (1916–2004) ‘ball and stick’ model of the DNA molecule from 1953. Values resemble these attributes in that the models perform theoretical functions without using words, they can make explanations and predictions, and by virtue of being models they denote, demonstrate and interpret parts of the world. Beyond those values that are intrinsically linked to the status of models however, other values emerge in the case of the periodic system. Indeed, the periodic system is more than a model; as mentioned earlier it can also be viewed as a classification or a typology – and it has added meaning also beyond such labels. We have coined the term “thing value” to discuss some of the *underlying* or *hidden* values and meanings of the periodic system, in particular those that become apparent from the perspective of the user. We will come back to this shortly.

The concept of “paper tools,” introduced by Ursula Klein in 2003, easily comes to mind when reflecting upon the underlying values of the periodic system. Studying the formulas of the Swedish nineteenth century chemist Jöns Jacob Berzelius (1779–1848), Klein described these formulas as paper tools, tools that made it possible to manipulate and experiment with chemical structures on paper. Michael D. Gordin, using Klein’s concept to study the periodic systems of Newlands and Mendeleev, brings an understudied aspect of paper tools to the fore: namely, that such tools also might negotiate between theory and empirical data.[[13]](#footnote-13) Some of the authors of the essays in this issue make use of paper tools in their analysis, bringing added meaning to the concept. In this introduction, we will expand on the worths and uses of the periodic system even more, by introducing the concept of thing value, which goes beyond paper tools. Paper tools in themselves are – as the name indicates - tools and not values. Once used, however, paper tools carry value for their users, and their ability to serve as manipulative tools is but one example of an underlying thing value carried by the periodic system. Indeed, the concept of paper tools does not cover all aspects inherent in the concept of thing values. Common for the values we have identified from the essays in this special issue, is that they are meanings given to the periodic system *by or through its users*, and that those values can differ even though and when there is a consensus on the use of the paper tool and the resulting conclusions. Indeed, thing values are *attributes of things (material or not) that the actors themselves ascribe to these things (in our case, the periodic system) and which gives it added worth and usefulness, that reaches beyond the straightforward manipulation of the paper tool.* To take an example from chemistry, the way chemists draw structural formula or so-called Lewis diagrams do not contain information about whether or not the chemists believe that atoms exist or that electrons have a fixed position inside atoms. Some thing values can be epistemic or cognitive, but esthetic or social values can also be embedded in things scientists create to model and manipulate, and this is where the thing value carries more than the paper tool, while it obviously expands on it .

This special issue consists of eight essays plus this introduction. Topics discussed include the evolving concept of chemical element (Kragh) and Mendeleev’s use of that concept in organizing the periodic system (Bensaude-Vincent), the iconic nature of the periodic system (Campbell), the different attempts to uncover underlying symmetries (Thyssen and Ceulemans), uses of colour in periodic tables (von Wülfingen), mathematical (Pulkkinen) and pedagogical (Robinson) representations of the periodic system, and the different meanings of the system as seen from the (historical) perspectives of chemistry and physics (Van Tiggelen and Lykknes). While all of them deal with values and meanings associated with the periodic system in their own way – implicitly or explicitly, this wide spectrum of explorations of the periodic system reflects in our opinion the concept of thing value presented above, and fits as umbrella for understanding underlying or hidden values of the periodic system. In the following, we will present themes that cut across several essays while embedding them in a chronological presentation of some main developments in the history of the periodic system. That way, while discussing the different thing values that can be identified from the essays, we aim to provide a fresh perspective that is not disconnected from more traditional historiographical approaches of the periodic system, which we hope to complement and enrich.

## The Success of a Classification

In 1789, the French chemist Antoine Laurent Lavoisier (1743–1794) presented a list of 33 simple substances that is often seen as a list of elements. These included what Lavoisier regarded as the constituents of all the kingdoms of nature, as well as the chemical families of substances such as metals, but also light and caloric (the substance of heat), which are not considered elements today. Lavoisier referred to elements as simple substances, substances that could not be broken down into simpler parts by chemical analysis. In the beginning of the nineteenth century, when the battery was invented as a new powerful analytical tool enabling the separation of compound substances into their constituents, a handful of elements was added to the list of simple substances or elements not capable of further division by chemical means. At about the same time, the British natural philosopher John Dalton (1766–1844) presented his atomic theory, in which he made a connection between atoms and elements. Furthermore, he determined atomic weights, a tradition that was to be continued in the chemical community for the entire nineteenth century. A couple of decades after Dalton’s atomic theory, attempts were made to group the chemical elements based on similarities or patterns when comparing atomic weights. Many of these first attempts are considered to be precursors to the periodic system; however, it is generally agreed that the periodic system itself stems from the 1860s. Six different discoverers from five different countries (England, France, USA, Germany, Russia) are considered among the independent discoverers of the system: the British chemists John Alexander Newlands (1837–1898) and William Odling (1829–1921), the French geologist Alexandre-Emile Béguyer de Chancourtois (1820–1886), the Danish-born American chemist Gustavus Detlef Hinrichs (1836–1923), and the most famous ones, Lothar Meyer and Dmitri Mendeleev. The one who is usually credited as the ‘father of the periodic system’ is Mendeleev. Bernadette Bensaude-Vincent’s essay, “Reconceptualizing chemical elements through the construction of the periodic system”, tells us about his success – that it was in great part due to the fact that he did not seek an optimal classification, but was careful to define what was to be classified. To do so, Mendeleev distinguished the concept of simple substance (the body the chemist is unable to decompose further in his laboratory) from that of element (the abstract concept representing that body in the scientific reasoning). It is the (abstract) element that circulates unchanged through chemical reactions and has an atomic weight conferred upon it. As Bensaude-Vincent explains, the distinction between simple substances and elements was not made simply for pedagogical reasons (although Mendeleev designed the system while working on a textbook); indeed, the distinction represents a paradigm shift from a compositional paradigm emphasizing the composition of compounds based on their constituents, to a combinatorial paradigm based on the circulation of abstract (and invisible) elements through chemical change[[14]](#footnote-14). This shift enabled Mendeleev to clarify what had to be classified (the elements), and his system eventually forced chemists to reconceptualize the element. The ability of the periodic system to be the site for such an epochal shift, in our view constitutes a thing value.

Chris Campbell, in interpreting Mendeleev’s development of a periodic system in light of the philosophy of the American pragmatist Charles Sanders Peirce (1839–1914) in his essay “The periodic table as an icon”,[[15]](#footnote-15) discusses the periodic system as an icon. In using Peirce’s iconicity, Campbell demonstrates that the periodic system has the capacity to generate new knowledge, to serve as a map or a guide, to infer something about the relationships between the chemical objects it represents, and to provide a system of these relationships. In that sense, Campbell demonstrates that the periodic system has all the iconic characteristics in Peirce’s idea of an icon. In particular, he emphasizes that the periodic system has the ability to map the journey to the unknown (i.e., information on new elements), not simply to describe the relationships that could be inferred from the existing empirical data (on elements). Examples of how the periodic system has exercised such iconicity include the predicting of properties of the so-called “eka-elements,” the unknown elements Mendeleev had conjectured to exist and allocated to blank spaces in his system. Less well known is the dispute related to the positioning of beryllium in the periodic system. While some thought of the metal as similar to aluminum, Mendeleev placed beryllium with magnesium instead. When later experimental data confirmed the similarity with magnesium, Mendeleev claimed this confirmation to be as important to the periodic system as the discovery of scandium – which, by virtue of being one of the first eka-elements to be identified (in 1879) – strengthened the idea of the periodic law. Campbell also provides the cases for several rare earth elements discussed by Mendeleev, which was all the more remarkable in that the Russian chemist had early on identified the difficulty of placing the rare earths in the system. Through examples from Mendeleev’s work, Campbell uses Peirce’s concept of icon to take the idea of paper tools further, in line with Gordin’s emphasis on the dynamics between theoretical manipulations and empirical data. Indeed, one of the thing values of the periodic system so demonstrated is its capacity for generating new questions and revealing new knowledge – by being a fruitful epistemic vehicle for thought processes.

Chemical analogy, both across atomic weights and chemical properties, was key to preparing an orderly system. Bensaude-Vincent argues that designing the periodic system simultaneously required defining the element as embedded in a network of relationships. A feedback loop between the system and the notion of element thus pushed for a symbiotic definition of both. As a result, a pragmatic approach to the element gained ground, but at the same time, an element might no longer exist outside the periodic system; according to Mendeleev, if there was no room for it in the periodic system then it could not exist. In his contribution to the notion of chemical element from Mendeleev to modern times, “The periodic system and the idea of a chemical element”,[[16]](#footnote-16) Helge Kragh describes successive instances in which this articulation was endangered, but eventually reinforced: the episodes are in themselves well known, but what is proposed here is the (seemingly) unending accommodation the periodic system offers – a testimony to its stability and an attribute giving it added worth.

Both Bensaude-Vincent and Kragh stress that Mendeleev’s system was successful because he insisted on the individuality and permanence of the chemical element itself. As noted, the element was an abstract entity, and it was defined solely through its presumed atomic weight. However, the many developments in science in the last part of the nineteenth century, and in particular from the 1890s on, challenged both the concept and stability of the element but also the system itself. For example, the discovery of a range of so-called noble gases at first constituted a threat since there was no space for them in the periodic system. The science of radioactivity, too, caused confusion and led to opposition from Mendeleev because of the threat to the individuality and stability he conferred as attributes of the elements. Furthermore, many new radioactive substances were discovered, and were at first believed to be new elements. The introduction of the concept of isotopes helped solve this puzzle, as it turned out that many of these radioactive substances were in fact isotopes of known elements, not newly discovered elements. The acceptance of isotopes, however, created another problem, since by definition isotopes were variations of elements with different atomic weights. The one, unique feature of the element was not unique after all. The new technique of X-ray spectroscopy contributed to solving the puzzle, since it helped link the concept of atomic number with each element’s unique X-ray spectrum. Atomic numbers were introduced in new periodic systems from the 1920s on.

The discovery of subatomic particles – the electron, the proton and the neutron – between 1897 and 1932, opened new avenues in the understanding of elements and the periodic system. In the 1920s, the Danish physicist Niels Bohr (1885–1962) reinterpreted the whole periodic system in light of his quantum atomic theory, assigning electron configurations to each element in the system.[[17]](#footnote-17) Likewise, the proton number became linked to the atomic number, and neutrons were used to bombard atomic nuclei to create new atoms, and through this process, to discover new, heavy elements. As Helge Kragh, and Brigitte Van Tiggelen and Annette Lykknes (in their essay “A tale of resilience: The periodic table after radioactivity and the discovery of the discovery of the neutron”) have pointed out, the shift from a system based on elements with unique atomic weights, determined by means of wet-chemical procedures, to a system based on artificial production of elements and an explanation based on subatomic particles represents a new era apart from tangible chemistry. The periodic system as a site that both supports and enables this shift, represents a value in itself and even more so in being able to endure this change without itself being radically changed. Van Tiggelen and Lykknes call this the resilience of the system, a thing value that describes the ability of the system to adapt and survive stress better than robustness, as robustness implies the return to the initial state, without evolution. Their study of two contributions on the periodic table by the chemist Ida Noddack and the physicist Lise Meitner, both from 1934, reveals the different perspectives the periodic system could encompass. Indeed, it is a source of information at different levels: the microscopic particulate level typical for the physicist and the macroscopic features represented by the analytical-chemical tradition to which Ida Noddack belonged. Ida and Walter Noddack used the periodic system as a compass to their search for unknown elements in the material world; this ability to be navigated so that its users can make inferences or choices constitutes another thing value, related to viewing the periodic system as a paper tool in the expanded sense stated by Gordin.

## Representing the periodic system

Mendeleev’s periodic system was represented by a table, which is also the form of the periodic system that is best known today. Other discoverers, including Meyer, also represented their system as a two-dimensional table. However, Béguyer de Chancourtois presented his system as a helix. Van Spronsen’s book and Mazur’s overview of representations mentioned above show us that there were hundreds of periodic system representations, of which the table was only one form that it took. Others were circles, helices, three-dimensional models and trees or other forms of branched shapes. The many different representations teach us that – contrary to popular accounts – the table presented by Mendeleev (and others) was not accepted once and for all; it was the system, not a table, that eventually was integrated into scientific practice. As noted, new element discoveries posed new challenges, and scientists continued to seek representations that could efficiently display the system. The challenge was twofold: to place known and unknown elements accurately, while also obeying the periodic law on the basis of atomic weight. Early problems included difficulties in positioning the rare earth elements and the inversion of order for e.g., tellurium and iodine, despite their atomic weight values.[[18]](#footnote-18) But as we have seen before, these problems continued as new candidates for elements or new properties of matter were discovered. Conversely, tables were expected to keep these values of accuracy and representativity inscribed in the making and accommodation of the system. Variations included different lengths of the periodic table, e.g., a long form containing 32 columns.

Different representations were thus experimented with, especially in the pedagogical context – in classrooms as well as in textbooks – as Ann Robinson has articulated in her essay, “Chemical pedagogy and the periodic system”. Long- and short-form tables were tried out, as were cylindrical or spiral-shaped periodic systems. Each teacher who presented a textbook with a personal solution, maintained that he had followed the periodic law and found a better way to make it visible and accessible to the students in chemistry. It is noteworthy, from the different cases, that the values of accuracy and representativity are also here deemed essential, and that the value of standardization usually at stake in the context of teaching, comes in second place. As one of the most vital paper tools in chemistry, the periodic system has to be taught and learned, it becomes both an object of teaching and a teaching device. And in that process, while it keeps the imprint of the thing values assigned or aggregated in the making and shaping of the system, teaching is also a moment where these values can surface as they are renegotiated. Thus tensions appear, between standardization that prevailed step by step, and other values pertaining to pedagogy such as representation or simplification. By the 1880s, around the same time as the periodic system had reached most American textbooks, wallcharts had become common in chemistry classrooms and spread beyond colleges, universities and regions – meaning students everywhere encountered a similar framework for the periodic system.[[19]](#footnote-19) Indeed, by the 1890s periodic table wallcharts were widely distributed by chemical supply companies. Eventually, the 18-column table represented by Horace G. Deming (1885–1970) became the most commonly used version in chemistry classrooms.

Bettina von Wülfingen, in her essay “The periodic tableau: Form and colors in the first 100 years”, reminds us that the forms of the periodic systems were never arbitrary. In fact, Mendeleev’s success in the priority dispute with Newlands and others has been ascribed to his reasoning underlying the format of the table, as well as to his sensitive pairing of text and visualization. Von Wülfingen takes the meaning of periodic system representations even further, discussing the use of color as an extra layer added to the table without adding in more forms. Relating to Klein’s concept of paper tool, she emphasizes that the power of such tools lies in their ability to realistically represent relational characteristics of the objects they depict. Von Wülfingen demonstrates how the colored periodic systems by the Estonian-born German chemist Andreas von Antropoff (1878–1956) (from 1925) and Edward G. Mazurs (from 1967) use color to show family relationships among elements, since these tables were not structured according to groups as in Mendeleev’s table and many other tables at the time. Indeed, von Wülfingen presents the periodic system as a depiction of a real object, an icon, and as graphical representations with invisible qualities – attributes that can be made more visible by the use of color. The ability to represent such relational characteristics by expanding the visual palette without completely reworking the structure of tables representing the periodic system thus constitutes a thing value for the periodic system. It also provides one of the factors that explains the resilience of the system, and the interplay between the system and its representations in this process.

In many periodic tables currently in use, color has been added as an extra level of information, normally to denote metallic character or groups of families such as the alkaline metals, the noble gases or the lanthanoids.[[20]](#footnote-20) Von Wülfingen also brings to our attention the use of grids in periodic tables. As the use or lack of grids may at first seem irrelevant, she points to the meaning of such components when looking at the periodic table as a *picture*. Seen from this perspective, the introduction of grids turned the table into a chart with embedded boxes, boxes in which additional information, such as atomic weight and the number of subatomic particles, could be added. Another discussion addressed in this special issue is whether or not the periodic system could be represented by means of mathematical relationships.

## Towards a mathematization of the periodic law?

The eighteenth-century chemist Antoine Lavoisier used arithmetical reasoning to express what was happening during a chemical reaction, though he clearly acknowledged that the desired level of precision was not yet reached in chemistry.[[21]](#footnote-21) To that end, he developed equations to capture the phenomena of chemical reaction and rationalize these transformations within the framework of his so-called law of the conservation of mass, which stated that chemical substances do not disappear nor are they created, they are only transformed into other substances with the same weight, by rearranging elemental substances that cannot be transformed and which are the ultimate result of analysis. Because not only the quantity (mass) but also the quality of matter (the variety of elemental substances) was conserved in chemical reactions, any chemical transformation could from that point on be written in terms of an equation which represented compound substances by chemical formulas. These formulas detailed their composition (in quality and in quantity) and, because of the conservation law, needed to be balanced on either side of the arrow separating the reactants and the products. That form of mathematization paved the way for some fruitful centuries of chemical manipulation and domestication and also the creation of new (chemical) species, a process in which doing and knowing were and still are intimately linked, initiating the development of paper tools as described by Klein. The hope to expand the mathematization of chemistry beyond the chemical equation received a new impetus with John Dalton’s atomic theory, and half a century later, the distinction between atoms and molecules. This remained quite basic mathematics, and except for the newly founded and fast-growing discipline of physical chemistry of the 1870s, where calculus was needed, chemists were still far from using the sophisticated mathematical methods of the physicists.

Notwithstanding Lavoisier’s conviction, the mathematization of chemistry thus actually started later, a process that was negotiated during the second half of the nineteenth century. That is the time when the periodic system was also being presented and eventually accepted.[[22]](#footnote-22) Karoliina Pulkkinen’s essay, “Periodicity and precision: Mendeleev’s reception of the equations of Mills, Chicherin, and Vincent”, examines attempts to put the periodic law in arithmetical or even functional equations instead of the tabular forms we are familiar with today. Looking for periodicity meant being able to describe the plurality of elements in terms of a few, for instance each top of the column (group or family) serves as a typical example for the properties of the whole column. As noted earlier, Mendeleev was seeking to formulate a law that could be used to predict and extrapolate, not just describe, the relationships between empirical data. He also wanted to convince other chemists that he had in hand a *natural* law, which was distinct from the sort of artificial system introduced by Carl Linnaeus (1797–1778) when classifying species of plants, animals and minerals in the eighteenth century. While Mendeleev at first was in favor of expressing the periodic law as an equation, Pulkkinen’s essay shows us that despite that he supported publishing these attempts, his views were in fact unclear, and he never provided assessment of the mathematical models put forward. She explains that Mendeleev’s final rejection of a mathematical law was due to conflicting ideals for the representation of periodicity. He wanted his periodic law to be both precise mathematically and at the same time complete in giving extensive descriptions of chemical phenomena. Clearly, as two (thing) values ascribed to his system were in conflict, Mendeleev chose completeness over the illusion of precision carried by mathematical formulas that were unable to completely describe the periodicity of properties, and retained the tabular representations he had always used.

A first frame of explanation for the structure of the periodic system in terms of early quantum theory and quantum mechanics was developed by Niels Bohr, the Austrian-born physicist Wolfgang Pauli (1900–1958) and the German physicist Arnold Sommerfeld (1868–1951). Mathematical rules have also appeared to provide a simple way to know the order in which electronic subshells are filled in neutral atoms in their ground state, and thus a rationalization of the succession of atomic number in terms of the quantum numbers and atomic orbitals. The Madelung rule (after Erwin Madelung, 1881–1972) is based on the principle that each electron always occupies orbitals with the lowest available energy level. Many scientists in the 1920s, when the principle was introduced, and even now consider this rule part of an effort to ‘reduce’ chemistry to physics and explain chemical properties in physical terms.[[23]](#footnote-23) More details on the Madelung rule can be found in the essay “Particular symmetries: The group theory of the periodic system” by Pieter Thyssen and Arnout Ceulemans, who investigate the use of another powerful tool for classification: symmetry. Indeed, the Madelung rule does not work in all cases, and it remains to be explained according to first principles (*ab initio*). The reductionist program is, however, far from fulfilled, and the periodic system is still waiting for an underlying foundational principle or law that would make it possible to derive the whole structure from some basic theory or concept. To this end, scientists in the 1970s embarked on a quest for symmetries hidden in the periodic system, hoping to be able to treat the periodic system as a whole and to gain a deeper understanding of the substructure of the elements. As Thyssen and Ceulemans explain, the ideas of symmetry are radical to the extent that a paradigm shift was needed.[[24]](#footnote-24) Indeed, symmetry theory treats elements not as different particles but as various possible states of a dynamical system. In this tradition, for example, the neutron and proton are treated as two sides of the same story.

The program of explaining the periodic system through group symmetry remains unfulfilled to this day, yet it demonstrates a few underlying values ascribed to or expected from the periodic system and its law: As demonstrated by Pulkkinen, here too the idea of completeness, the goal to find a principle that can describe and explain the whole system, is in conflict with the wish to come up with a precise explanation of the periodic system. Furthermore, Thyssen and Ceulemans’ study demonstrates that the periodic system can in fact be read on yet another level – in addition to the macroscopic level where family resemblances between chemically similar elements can be found by looking at the positioning of elements in the periodic table, and to interpretation on the atomic level using the distributions of electrons to explain observed similarities and periodic trends. This in turn advocates yet another case for the thing value called resilience – that additional knowledge and new interpretations do not shake the grounds of the system. Rather, they strengthen the system – once they become successfully metabolized or assimilated. It is also worth noting that the case outlined by Thyssen and Ceulemans reminds us of the empirical character of the periodic system, as even the Madelung rule cannot be deduced from first principles.

## Thing values of the periodic system: the many faces of an icon

The periodic system has had many representations. The most widely used of the hundreds of forms that have been suggested is the 18-column tabular form which looks like an extended version of Mendeleev’s 1871 periodic table and which is traced back to a version devised by the prolific textbook author Horace G. Deming in 1923. The negotiations as to which forms represented the periodic system in the most efficient and correct way and at the same time accommodated the growing number of elements, took place both in the scientific community and in a specific subset of that community, the realm of pedagogy. Although it is generally agreed that the periodic system captures the essence of chemistry as well as of other natural sciences, its most common use is in teaching. Ann Robinson, in her essay, traces the shifting role of the periodic system from scientific tool to pedagogical tool back to the 1920s and 1930s. One of the features of the teaching tool is that it presents a standardized format to be used for all, so that all learners and users of chemistry have the same frame of reference.

As pointed out by several of the authors, the representations of the periodic system are never arbitrary. Whether they are tabular, circular, three-dimensional, mathematical, do or do not have a color layer, they have been represented in these forms for a reason. In different ways, these representations serve a purpose and have underlying values which we have termed thing values. Although the periodic system is clearly distinguishable from a material model or a physical object, Baird has inspired us to ascribe thing values to it that help shed light on the underlying meanings of the system, past and present. One of its thing values is that it can be used as a paper tool according to Klein’s meaning and in particular to Gordin’s extended use of the concept, in that it is able to negotiate theory with empirical data. Another previously discussed thing value is that of predictability and explanatory power, attributes which Baird discusses for Watson and Crick’s model for DNA. In keeping with this value, Chris Campbell calls the periodic system a fruitful vehicle for thought processes.

The historical essays collected in this issue have also raised some less widely discussed values of the periodic system. In particular, two values capture ideas discussed in more than one paper. The first value is the periodic system’s capacity to serve as relational tool, both as relating to other concepts, and as adding layers of information to what is already embedded in the system. Bensaude-Vincent and Kragh discuss the relationships and negotiations between the concept of element and the system, which strengthen both and also make sure neither can exist independently of the other. Von Wülfingen stresses the use of color as a relational tool, since by having an added layer of color, the periodic system can communicate extra information without shifting its form or representation. Likewise, the use of mathematics can serve as a relational tool, by conveying values such as completeness and simplicity – although the essays in this issue clearly conclude that achieving both is difficult.

The second of these two shared values is resilience. Imbedded in the title of the essay by Van Tiggelen and Lykknes, this value is also implicitly discussed in other essays. While Van Tiggelen and Lykknes explicitly present resilience as the ability of the periodic system to adapt to changes without being subjected to radical changes itself, the negotiation of the concept of element discussed by Kragh and Bensaude-Vincent also testifies to this kind of resilience, as does the use of symmetry to attempt to an explanation of the periodic system.

As stated initially, the perspectives on the values of an icon presented in this issue come from scholars with different backgrounds. We believe that this makes the issue both innovative and fertile. Bringing together senior and junior scholars from different disciplines (natural science, philosophy, history, semantics) and letting them speak about what the periodic system represents and how it was used and considered by its users beyond the mere manipulation to find or classify information on the chemical elements, brings fresh perspectives to a jubilee that is certainly being widely celebrated and embraced. Implicit or hidden values – once brought to light – can provide a more nuanced and fuller view of an otherwise familiar icon.

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1. Gordin (2017), p. 53. For references to the periodic system as an icon, see e.g. Poliakoff and Tang (2015); Rosen (2019); FCT (2019). [↑](#footnote-ref-1)
2. IYPT (2019). [↑](#footnote-ref-2)
3. Van Tiggelen (2001). [↑](#footnote-ref-3)
4. Atkins (1995) [↑](#footnote-ref-4)
5. Meinel (2009). [↑](#footnote-ref-5)
6. Van Spronsen (1969); Scerri (2006). [↑](#footnote-ref-6)
7. A remarkable example is Kedrov (1958), which is based on a reconstitution from the sparse drafts, or more recently: Dimitriev (2004). [↑](#footnote-ref-7)
8. The first such lists were drawn by the couple Quam and Battell-Quam (1934a), Quam and Battell-Quam (1934b) and Quam and Battell-Quam (1934c). Edward G. Mazurs (1974) has furthermore also organized the wealth of tables into a system. [↑](#footnote-ref-8)
9. Kragh (1996); Giunta (2001); Van Spronsen (1969); Bensaude-Vincent (1986); Gordin (2004); Gordin (2012); Kaji *et al.* (2015), Lykknes and Van Tiggelen (2019). [↑](#footnote-ref-9)
10. Weisberg (2007); Woody (2014). [↑](#footnote-ref-10)
11. Proctor (1991); Merton (1942); Douglas (2013); Douglas (2016); Graham (1981); Allchin (1999); IEP (2019); Merchant (1981); Stanley (2007). [↑](#footnote-ref-11)
12. Douglas (2013); Douglas (2015). [↑](#footnote-ref-12)
13. Klein (2003); Gordin (2018). [↑](#footnote-ref-13)
14. Bensaude-Vincent uses the concept of paradigm shift in the Kuhnian sense. See Kuhn (1962). [↑](#footnote-ref-14)
15. The full title of the essay is “The periodic table as an icon. A perspective from the philosophy of Charles Sanders Peirce» [↑](#footnote-ref-15)
16. The full title of the essay is “The periodic system and the idea of a chemical element: From Mendeleev to superheavy elements”. [↑](#footnote-ref-16)
17. Kragh (2012). [↑](#footnote-ref-17)
18. For the challenges related to the accommodation of the rare earth elements, see Thyssen and Binnemans (2011). [↑](#footnote-ref-18)
19. On the reception of the periodic law in America and Britain, see Brush (1996). [↑](#footnote-ref-19)
20. For two examples, see WebElements (2019) and Scerri (2012). [↑](#footnote-ref-20)
21. Lavoisier (1782), p. 499. [↑](#footnote-ref-21)
22. Brush (1996); Kaji *et al.* (2015). [↑](#footnote-ref-22)
23. Nye (1992). On the reductionist program applied to the periodic system, see Hettema (2012). [↑](#footnote-ref-23)
24. Also in the Kuhnian sense of the word. [↑](#footnote-ref-24)