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The Periodic Table and its Iconicity: an Essay

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Abstract. In this essay, we aim to provide an overview of the periodic table's origins and history, and of the elements which conspired to make it chemistry's most recognisable icon. We pay attention to Mendeleev's role in the development of a system for organising the elements and chemical knowledge while facilitating the teaching of chemistry. We look at how the reception of the table in different chemical communities was dependent on the local scientific, cultural and political context, but argue that its eventual universal acceptance is due to its unique ability to accommodate possessed knowledge while enabling novel predictions. Furthermore, we argue that its capacity to unify apparently disconnected phenomena under a simple framework facilitates our understanding of periodicity, making the table an icon of aesthetic value, and an object of philosophical inquiry. Finally, we briefly explore the table's iconicity throughout its representations in pop art and science fiction.

Keywords. Dmitri Mendeleev, the periodic table of elements, philosophy of chemistry, science and pop art, science fiction.

> *The Periodic Table was incredibly beautiful, the most beautiful thing I had ever seen.*
> *(Oliver Sacks)*
>
> *An exposition of all that matters in matter.*
> *(Bruce Greenhalgh)*

INTRODUCTION

The periodic table of elements is chemistry's most universal 'tool', used both as a teaching method and research instrument. But it is also a sign and icon that unites all chemical knowledge. In philosophy of language, 'iconicity' is the name given to a certain similarity relation between the form and the meaning of a sign. The lack of similarity is arbitrariness, which means that there is nothing in the form of the sign that resembles its meaning, and simple convention associates the two. We borrow such terminology to claim that the periodic table is truly an icon, not just convention. Each of the little 'squares' in any of the table's representations encloses the totality of chemical and physical knowledge about a given element. In this sense the table is truly iconic: it is perceived as being so closely similar to that which it represents (the totality of chemical knowledge), that form and meaning become intrinsically bounded.

Since its first formulation, the table has become a universally accepted icon which transits in many places of knowledge. It transits in classrooms and books as a didactic tool, it transits through research laboratories as a reference source, and it transits in annals and records of chemistry as a repository of scientific information and interpretations collected over time. Considering its widespread presence, we believe the table parades a dual nature: it *is* the consolidation of current chemical knowledge, but also a heuristic tool used by chemists in their attempts to expand and consolidate such knowledge. Surprisingly perhaps, the 'tool' has not changed much since its conception.

In the words of Scerri:

> *The periodic table of elements is one of the most powerful icons of science: a single document that consolidates much of our knowledge of chemistry [and] despite the dramatic changes that have taken place in science in the last hundred years [relativity and quantum mechanics] there has been no revolution in the basic nature of the periodic system.*[1]

Let us next say a few things about how the table came about, from early attempts to find analogies among chemical elements, to more refined views on periodicity.

ANALOGIES

The practice of classifying is an important task in any science. It is a task that involves obtaining the particulars (objects) to be classified, finding non-spurious similarity relations – analogies – between the object and other entities thought to be of the same kind, and drawing empirical and logical conclusions from the way entities are organised. Scientific disciplines often make great efforts to divide particulars into kinds and theorise about the nature of these kinds. If one has realist inclinations regarding scientific knowledge, one will often think of a kind as being 'natural', i.e. a grouping of particulars that is made possible by how nature *is* (and not by one's interests or actions). If this is the case, then scientific taxonomies correspond to real natural kinds. And, as Bird and Tobin put it, "the existence of these real and independent kinds of things is held to justify our scientific inferences and practices."[2]

A classic example is Carl von Linné's (1707-1778) botanical and zoological classification in his *Systema Naturae* (1735), which became a 'model' of classification for other sciences as well. It inspired, for instance, Johann Beckmann (1739-1811) to classify technological activities in his *Entwurf einer allgemeinen Technologie* (1806).

Chemists too felt the need to classify elements and substances. Lavoisier himself, in presenting his table of elements in 1789, classified them. Each of the four groups of 'simple substances' presents similar or even identical qualities. If we look more closely at a Table of Affinities, such as that of Torbern Bergman (1735-1784) from 1775, we will find a classification: each group of substances presents qualitatively equal and quantitatively decreasing properties.

After Lavoisier, the concern of chemists in classifying became more evident, and we can cite classificatory attempts of Richter (1792), Döbereiner (1817, 1829), Meinecke (1819), Thenard (1813), Ampère (1816), Gmelin (1842), Gibbs (1845), among many others. All these attempts are analogical in form, i.e., elements are grouped together based on how the author 'perceives' similarities and differences among the elements' properties. There is an obvious challenge for objectivity here, as similarity relations of one kind will often take priority over other similarity relations, depending on the authors' theoretical preferences. None of these attempts was a periodic classification, however.

The concept of analogy was important to the prevailing *Naturphilosophie* at the time, especially in Germany. Associated with Romanticism, such classificatory attempts were motivated by a desire to formulate a system of thought capable of encompassing both empirical knowledge and *a priori*, deductive reasoning. Natural philosophy has been gradually eliminated from scientific thought; thanks to the rise of empiricism. John Locke, for example, argued that the prior formulation of hypotheses and the use of analogical reasoning played a minor role in science – a view consistent with that of experimental philosophy.[3] With the decline of speculative philosophy, early classificatory attempts – except maybe Döbereiner's and Gmelin's – became of little philosophical relevance. Furthermore, there is an element of subjectivity motivating the formulation of such classificatory systems. An author's philosophical preferences will often play a decisive role in what counts as relevant in analogical arguments, and therefore on how the elements are classified. Let us see how.

For Jeremias Benjamin Richter (1762-1807), once a student of Kant, some mathematical relations are *a priori* hypotheses – a view he formulated based on his studies of ponderal and stoichiometric relations. For him, any chemical classification had to consider the laws (such as the law of definite proportions, which says that the ratio by weight of the compounds consumed in a chemical reaction stays always the same) according to which substances unite to form compounds. Eduard Farber[4] and Georg Lockemann[5] consider Richter to be the first chemist to consider mathematical aspects in his theories.

Johann Ludwig Meinecke (1781-1823) reasoned from analogy by giving priority to the notion of chemical affinity, i.e., the tendency exhibited by atoms or compounds to combine (chemically react) with certain atoms or compounds (of unlike composition) in preference to others. This is, of course, a well-established theory today, but during his time 'affinity' referred only to bodies who reacted intensively, perhaps 'unavoidably', one with the other. It was this older conception of affinity that inspired Goethe to write his metaphorical novel *Elective Affinities*, in which human passions appear to be governed by the laws of chemical affinities, with the potential to undermine social institutions such as marriage.

André-Marie Ampère (1775-1836), criticising what he saw as an exaggerated importance given to oxygen, attempted a natural classification or order, or even in the words of Jean-Baptiste Dumas (1800-1884), "a classification of bodies into groups based on primary properties capable of determining all secondary properties." Ampere used an experimental criterion for the classification of the elements, as he focused on "associations and products to which elements are known to be committed."[6]

Johann Wolfgang Döbereiner (1780-1849), in his "An Attempt to Group Elementary Substances according to Their Analogies" (1829), ascribed great importance to numbers representing the atomic weights of the elements forming the four "Döbereiner Triads". Döbereiner identified a pattern with the elements of the triads: if you order them according to their atomic masses, the average of the molar mass of the first and third element of the triad equals the molar mass of the second element (sulphur, selenium and tellurium, for example). On a modern periodic table, these elements are stacked vertically. His work started on the same insight that would later result in the formulation of the periodic law and classification of the elements.

For Leopold Gmelin (1788-1853), another forerunner of the periodic table, physical and chemical relations among simple substances (= elements) are important, but the structural basis for their classification lies in their electronegativity or positivity, as defined by Jöns Jacob Berzelius (1779-1848) in his *Lehrbuch* (1823).

Getting into the details of such early classificatory attempts falls outside the scope of this article. But we wish to highlight the motivation that guides them all: to find a form of representing observations of similarities and order among elements that could be *universally* accepted while containing all the relevant information known about the elements, their 'kinds' (grouping) and ordering.

This desire for universality sometimes surpasses the limits of chemistry. John Alexander Newlands (1837-1898) formulated in 1864 his "Law of Octaves", according to which the ordering of the elements accruing to increasing atomic weight reveals a periodic pattern of similarity after each interval of seven elements. Newlands' detection of periodicity was overlooked possibly because of the analogy he drew between chemistry and the musical scale, thought to be naïve and distracting. Striving for universality, Newlands tried to force all known elements to fit into his octaves – but some new discoveries (heavy elements) escaped the pattern. Also, James Blake (1815-1893) went beyond chemistry when he attempted to classify some elements based on their pharmacological effects (1848).[7] While such attempts were not well received, if one thinks of kinds as being natural, and not socially constructed, there is no reason to assume any periodicity would confine itself to conventional disciplinary boundaries.

THE PERCEPTION OF THE PERIODIC TABLE

Let us now focus on the mainstream periodic tables of Dimitri Mendeleev (1834-1907) and Lothar Meyer (1830-1895). Mendeleev ordered the elements according to their increasing atomic mass. He placed elements underneath other elements with similar chemical behaviour. For example, he placed sodium underneath lithium because both exhibited similar chemical behaviour: shiny and soft metals which react promptly with oxygen and violently with water.

Sometimes the atomic mass of an element would not be in the right order to put it in the group of elements with similar behaviour. He placed a question mark (?) next to its symbol to indicate he was uncertain the atomic mass had been measured correctly. Some other times the next heaviest element would not display the properties expected of the next element in the table, and he thought important to only group together elements with similar properties. He postulated the existence of an unknown element to occupy that place, and left blanks, allowing for (temporary) holes for undiscovered elements in the table. Mendeleev used dashes (-) to indicate the predicted mass of the element to be discovered. It was precisely this abductive reasoning that allowed for the future discovery of gallium (1875) and germanium (1882), for example, to be accommodated by the table. Germanium's fit in its group and its behavioural contrast with neighbouring elements gave Mendeleev's classification strong empirical support. As Kemp puts it: "Mendeleev's periodic table permitted him to systematise crucial chemical data. But its real triumph was as an exercise in theoretical modelling, allowing the prediction of the discovery of previously unknown elements."[8]

The table formulated by Mendeleev is a *tour de force* in terms of resilience. Since its first appearance 150 years ago the table has been able to accommodate the discovery of new elements (lanthanides), and groups of elements (noble gases, transuranic and transfermic elements). New theories and philosophical positions did not affect the solidity of Mendeleev's formulation, nor did the revolutionary empirical discoveries since the end of the nineteenth century: the discoveries of atomic divisibility and subatomic particles, radioactivity, artificial transmutation, and innovations generated by quantum mechanics. It is certainly this capacity to accommodate (and help predict) novelties, and withstand theoretical criticism, that gave Mendeleev's periodic table its iconicity and universal appeal. Eventually, it became a definitive representation of elemental periodicity.

It is interesting to note that none of the previous proposals for classifying the elements had more repercussion outside their context of creation than Mendeleev's. Its high degree of empirical adequacy gave Mendeleev's systematization the status of scientific law (Mendeleev's Periodic Law). Such status was later corroborated by what is now known as Moseley's Law (1913). Up until Moseley's work, the atomic number of an element was just its place in the table, and it was not associated with, or determined by, any known measurable physical property. But Moseley demonstrated that the frequencies of certain characteristic x-rays emitted by atoms are approximately proportional to the square of the element's atomic number. This discovery also supported Antonius Van den Broek's (1870-1926) and Niels Bohr's atomic model, according to which the atomic number is the same as the number of positive charges in the atom's nucleus. It is precisely this degree of consilience, i.e. this 'jumping together' (convergence) of evidence originated from different, unrelated sources, that help explain Mendeleev's success in formulating a definitive and universal representation of elemental periodicity.

The motivation for drawing a table of the elements was to find a way of representing them that could be universally accepted. Representations that were only based on analogies – and did not constitute scientific laws – did not achieve this objective. The discovery of periodicity, followed by Mendeleev's insight when grouping the elements according to their similar properties while allowing for gaps, did achieve universality and, ultimately, iconicity. In part, such iconicity is derived from the table's widespread use as a teaching tool. It is widely used by teachers to aid students with the abstractions necessary for a proper understanding of chemistry. Abstractions such as the ordering of a periodic system, systematization of possessed knowledge, prediction and projections involving new discoveries, chemical properties, correction of data, and finally understanding of the macro and microcosmos in terms of atoms, molecules and substances.

So, what we mean by the universality of the periodic table goes beyond geographic universality. It is endurance in time and space, and unity of meaning and form, of sign and concept. The universality of the periodic table of the elements is so pervading, that it is even capable of connecting intellectual ideas and human passions. In the words of S. Alvarez: "The periodic table of elements is the agora where art, science and culture meet to dialogue about matter, light, history, language and life. It is an extraordinary tool that allows us to find the connections between humanistic culture and science."[9]

The iconic table has a variety of uses:

- as a teaching tool;
- as a heuristic method for scientific practice;
- as an aid to classify and preserve chemical knowledge;
- as a theoretical foundation for the understanding of chemistry;
- as a research tool for other sciences, such as mineralogy;
- as a tool for the popularisation of chemistry;
- as an aesthetic component in the corpus of chemical knowledge;
- as a factor of integration between science and the Humanities;
- as a pop-cultural object.

MEYER'S AND MENDELEEV'S DIDACTIC PURPOSES

Both Mendeleev and Meyer developed their periodic tables confessedly for didactic purposes – the ordering of the contents - in writing their textbooks *Principles of Chemistry* (1869) and *The Modern Theories of Chemistry* (1864), respectively. Lothar Meyer's *Die modernen Theorien der Chemie und Die Bedeutung für die Chemische Statik* (Maruschke & Berendt, Breslau, 1864) is very concise. From the outset, the author makes it clear that he intends to systematise and order, among all available knowledge, those he considers more fundamental (greater reliability and precision). The starting point is the Berthollet *Essai de statique chimique* (1804). Meyer also accepted Dalton's atomic theory and some reductionism. As he writes: "The development followed by chemistry has brought with it the necessity of abstracting every theoretical point of view from a great deal of widely scattered detail."[10]

Speculations about the cause and essence of phenomena are various, and often conflicting points of view coexist.

What theories that remain and which ones will be rejected is a decision that belongs only to the opinion of today's active chemists, and only exceptionally and fragmentary in their writings [as the literature overestimates the amount of disagreement]. The struggle for the systematic ordering of chemistry's body of knowledge seems to be long over.[11]

In Meyer's view, the long-lasting dispute on whether the properties of a compound depend on its nature or on the arrangement of its components seems to be solved to the satisfaction of both parties, for probably no one in the right mind would categorically reject the atomic theory. The didactic aspect to which we refer in the text of Meyer is the systematisation in function of the choice of the most appropriate hypotheses for a rational exposition of the problems of chemistry. Meyer keeps a hypothesis only so long as it is useful.

Let us now focus on the didactic purpose that led Mendeleev to elaborate his classification to better order the contents of his *Principles of Chemistry* (1869/1871). When in 1867 he succeeded Alexander Voskresensky (1808-1880) as Professor of Inorganic Chemistry at the University of St. Petersburg, Mendeleev wrote: "I began to write [the Principles] when I started to lecture on inorganic chemistry at the university after Voskresensky and when, having looked through all the books, I did not find anything to recommend to students."[12] This direct association between Mendeleev's Table and his *Principles of Chemistry* was carefully examined by Bonifaty M. Kedrov (1903-1985).

In another analysis, Masanori Kaji (1956-2016) also considered social and scientific factors as motivations for the table's formulation. Kaji identified a close relationship between the periodic law and Mendeleev's concept of 'element'. Mendeleev participated in the Congress of Karlsruhe in 1860, and the ideas of Stanislao Cannizzaro (1826-1910) exposed there exercised great influence on his chemical thought. He accepted the atomic theory (with certain exceptions, for there were exceptions to the law of constant proportions), allowing him to establish a relation between the properties of the elements and the atomic masses, the origin of the "periodic law". Following in the footsteps of Cannizzaro, Mendeleev distinguished between "simple bodies" (material entities) and "element" (abstract entity). He would later refer to an element as a "chemical individual", highlighting the existence of multiple elements, consistent with his view of natural diversity (as opposed to there being a unity of matter).

In his "Faraday Lecture" (1889), Mendeleev claimed that the periodic law had been arrived at by inductive reasoning, i.e. "a direct outcome of the stock of generalisations and established facts which had accumulated by the end of the decade 1860-1870: it is an embodiment of those data in a more or less systematic expression."[13] Clearly, the more data the better basis for any generalisation. And "sound generalisations – together with the relics of those which have proved to be untenable – promote scientific productivity, and ensure the luxurious growth of science under the influence of rays emanating from the centres of scientific energy [scientific societies]."[14]

As for those who at the time hoped the periodic law would lend support to the notion of a unity of matter (such as Berthelot), Mendeleev showed little sympathy:

> *…the periodic law, based as it is on the solid and wholesome ground of experimental research, has been evolved independently of any conception as to the nature of the elements; it does not in the least originate in the idea of a unique matter; and it has no historical connection with that relic of the torments of classical thought (…) None of the advocates of a unique matter has ever tried to explain the law from the standpoint of ideas taken from a remote antiquity when it was found convenient to admit the existence of many gods – and of a unique matter.*[15]

In this lecture, Mendeleev also defended the use of conceptual structuring as an important complement to the experimental method, foreshadowing much of the 20th century preoccupation in placing "agreement between theory and experiment" at the centre of scientific thought and method. Much of the iconicity of Mendeleev's table lies of course in its success in visually representing an agreement between an inductively identified regularity of nature and vast empirical chemical data. If properly used as a teaching tool, as Meyer and Mendeleev intended, the very same conceptual structuring would help rid the scientific world of obsolete metaphysical notions, and guide scientists towards scientific progress.

THE RECEPTION OF THE TABLE

About the reception of the Periodic Table by different scientific communities, Stephen Brush mentions that at the end of 19th century there were few and irregular citations of the Table. It is therefore difficult to say if it was widely accepted by chemists, or if only a specialised circle of chemists showed interest in the novelty. Brush mentions 236 citations of the Table during the period 1871-1890: 20 from 1871 to 1875, 72 from 1875 to 1880, 61 from 1881 to 1885 and 83 from 1885 to 1890. Concerning textbooks, we should not forget that usually many years elapse from the original inception of a new idea by the author and its inclusion in a textbook: 244 textbooks were published from 1871 to 1890, but only 76 of them mention the Periodic Table.[16]

First "modern" Periodic Tables were presented in Russia and in Germany, and we could suppose that in these countries such a powerful instrument would be accepted without any restrictions. History shows many drawbacks in accepting periodic classification because of singularities related to the scientific *milieu* of the two countries. In Russia, as Kaji and Brooks observe, the main difficulty was just the fact that the Periodic Table was presented by a Russian, deeply immersed in Russian intellectual and scientific atmosphere.[17] Despite a dispute about priorities between Mendeleev and Lothar Meyer (caused by Wurtz's criticism of a German translation of one of his books), Russian chemists of German descent (Friedrich Beilstein, Victor von Richter, Felix Wreden) did much towards the recognition of Mendeleev's system. An early presentation of Mendeleev's first paper at the St. Petersburg Academy of Sciences by Nikolai Menshutkin (1842-1907) was largely ignored. Nikolai Zinin (1812-1880) suggested that Mendeleev should devote himself to actual chemical lab work. After months of silence, Mendeleev's ideas began to be discussed in scientific meetings by important Russian chemists: Markovnikov, Butlerov and even Zinin. The first Russian textbook to include a Periodic Table was Victor von Richter's (1841-1891) "Textbook of Inorganic Chemistry, based on most recent theories" (1874). Most later textbooks included Mendeleev's classification.

In Germany, where precursors like Richter, Döbereiner, Gmelin, Kremers, Pettenkofer, among others, worked on classification before Mendeleev, the adoption of a Periodic Table was delayed.[18] Karl Seubert (1851-1942), Meyer's colleague in Tübingen, explains this delay by a generalised lack of interest by most chemists in Inorganic Chemistry, especially issues like "periodic classification": Meyer's explanations were too short and succinct, while Mendeleev's were deemed too complex and included non-chemical knowledge. Rudolf Fittig (1835-1910) in Tübingen and Eugen von Gorup-Besanez (1817-1878) in Erlangen mention the Periodic Table in 1873: Fittig in an encyclopaedia article, Gorup-Besanez in the 5th edition of his "*Lehrbuch der Arnorganischen Chemie*". G. Boeck considers Victor von Richter's German translation (1874) as the first German textbook to present a Periodic Table. Brush takes the third edition of Carl Rammelsberg's (1813-1899) *Grundriss der Chemie* (Lüderitz, Berlin, 1873; Brush mentions erroneously 1874) as the first textbook outside Russia to discuss periodicity.[19] August Michaelis' (1847-1916) *Ausführliches Lehrbuch der Chemie* (1878) and Karl Arnold's (1853-1929) *Repetitorium der Chemie* (1885) deserve mention. Most of the nineteenth-century college-level textbooks don't include Classification, the famous "Schule der Chemie" by Adolph Stoeckhardt (1809-1896), and not even the last editions from 1881 (19th) and 1919 (22nd).[20]

The introduction of Mendeleev's table in different scientific contexts, in central as well as in peripheral science, met some degree of opposition or reluctance. In many places, there were already prior classifications and tables, some of them with a long tradition and successful in their task in organising the content of textbooks. More pragmatic or theoretical scientific schools considered the efforts of looking for a periodic classification as useless. It is necessary to say that before Mendeleev's classification, other classifications, *e. g.* Thenard's "artificial" classification, or "classifications" not even taken as such, like that of Berzelius, entered the scientific literature of several countries: Thenard in the Latin world, and Berzelius in Germany. And, finally, some local scientific communities produced their own classifications, like those of Lewis Reeve Gibbes (1810-1894) in the United States (published in 1884) or of the Catalan pharmacist Josep Antoni Balcels (1777-1857) in Spain (1838).

In Great Britain, not even classifications suggested by English chemists, like William Odling (1829-1921), in 1865, or John Alexander Newlands (1837-1898), in 1864, were taken seriously.[21] There was little interest in Mendeleev or Lothar Meyer. But the discovery of gallium (1875) by Lecoq de Boisbaudran (1838-1912) changed the situation. After the awarding of the Royal Society's Davy Medal to Mendeleev and Meyer (1882) there was some revival of "Newland's octaves" (Newland's Davy Medal in 1887), but English scientists had little interest in "classifications", although they produced very important empirical data to confirm the "periodic law" as a scientific law (the discovery of noble gases, Moseley's work). First texts to include a Periodic Table were those of William Allen Miller (1817-1870), "Elements of Chemistry" (6th edition, 1876) and George Fownes (1815-1849), revised by his assistant Henry Watts (1815-1884) in 1877. S. Brush mentions Thomas Edward Thorpe (1845-1925) as author of the first English language textbook including Mendeleev's Table (1877).[22]

Also in France Mendeleev's table remained almost unnoticed, a "non-event" in the history of French chemistry in the opinion of B. Bensaude-Vincent.[23] But in the period of precursors of a classification we must remember contributions of Thenard (1813) and Ampère (1816), Dumas' numeric table (1851), as well as the exotic "telluric screw" of Chancourtois (1862) – the "screw" connects chemistry and geology, another example of the universality of the periodic table. The strong influence of Positivism and refusal to accept atomism by influential scientists like Marcellin Berthelot (1827-1907) explain why most French chemists looked for alternative classificatory systems, ignoring Mendeleev (the "equivalentists").[24] Berthelot agrees that Mendeleev's Table may have some practical utility, but for him, it is not a "law" or a theoretical argument, as this would undermine the empirical, logic and positive bases of science,[25] and could also lead to a return to mysticism. In 1885, in his *Les Origines de l'Alchimie*, Berthelot discusses the periodic system as an "artificial construction based on vague theoretical arguments".[26] Among the exceptions are notables like Charles Adolphe Wurtz (1817-1884), who dedicates an entire chapter of his "Atomic Theory" to Mendeleev, Edouard Grimaux (1835-1900) and Paul Sabatier (1854-1941). After 1890, Mendeleev's system began to gain some sympathy: Paul Schutzenberger (1829-1897) published the first French textbook containing the periodic classification (*Traité de Chimie Générale*, 1880). Georges Urbain (1872-1938) was perhaps the first to try to explain the opposition of equivalentists and atomists (1934).[27] Mendeleev himself was not truly an atomist, he used "equivalent weight" instead of "atomic weight".[28] In France, there was not only the opposition between positivists-rationalists but also the opposition between "natural" classifications (Ampère, Dumas) and "artificial" classifications (Thenard). Differently from what happened in Great Britain and in the United States, the discovery of gallium did not contribute to the acceptance of Mendeleev's ideas: Lecoq insisted that his discovery was due only to his skills as a spectroscopist and had nothing to do with Mendeleev's table 'blanks'.[29]

A recently unified Italy presented a fertile soil for the introduction of new scientific ideas. In the case of the Periodic Table this is exemplified by the almost immediate acceptance of Mendeleev's system by important Italian chemists, such as Augusto Piccini (1854-1905), who translated Richter's textbook into Italian (1885), and Giacomo Ciamician (1857-1922). It was accepted that former classifications were based on less reliable properties.[30]

In Spain, Thenard's text (*Traité de Chimie Élémentaire*, 1813) and classification were largely used. Thenard's classification was also present in other French textbooks translated into Spanish, like that of Mateo Orfila (1787-1853). There is no reference to Mendeleev in the extensive text published in 1875 by Rafael Sáez Palacios (1808-1883), but there is such reference in a book (1880) by Santiago Bonilla Mirat (1844-1899).[31] Eugenio Mascareñas (1853-1934) published in 1884 in Barcelona "Introdución al estudio de la Química", discussing Mendeleev's work and presenting his own table.[32] Theoretical and speculative studies on periodicity were done by Ángel del Campo y Cerdán (1881-1944), suggesting interactions of protons with protons and with neutrons as the origin of periodicity (1927): "The properties of the elements seem to be simultaneously a periodic function of the masses of their atoms and the electric charge of their nuclei, that is, of the atomic masses and the atomic numbers."[33] As a consequence of Bohr's studies, Miguel Catalán Sanudo (1894-1957) presented a table relating periodicity to spectra (1923).[34]

Modern Portuguese science has its beginnings with the renovation of the University of Coimbra by the Marquis de Pombal (1699-1782) in 1772. A new reform followed in 1841, and since 1870 a strong influence of positivistic thought in scientific practice can be observed. Antônio Luís Ferreira Girão (1823-1876) did not mention Mendeleev in his *Teoria dos Átomos e os Limites da Ciência* (published 1879), but his student Agostinho de Sousa published (1880) in French *La Loi Périodique*, the first reference to Mendeleev in Portugal. This was later repeated in the 2nd edition (1895) of a textbook by Antônio Joaquim Ferreira da Silva (1853-1923).[35]

In Northern Europe, the reception of Mendeleev's Table occurred in different contexts. In Sweden, Berzelius' *Treatise on Chemistry* (1818) presented a classification of the elements based on their electronegative or electropositive character. In Denmark Julius Thomsen (1826-1909) worked out his own table (1887, 1895), in which he tried to turn more visible the relation between periodicity and atomic structure – a subject studied later by another Danish scientist, Niels Bohr (1885-1962). Lundgren suggests that in Sweden the reception of Mendeleev's system was by no means dramatic: no opposition, but also no enthusiasm.[36]

Swedish chemistry shows no difference before and after Mendeleev, it was a pragmatic and practical chemistry, with a reduced theoretical component (a theoretical revival took place with Svante Arrhenius after 1884). According to Lundgren, Sweden's only contribution to periodicity and the classification of the elements, Lars F. Nilson's (1840-1899) discovery of scandium (1879), was seen as an analytical problem. In Denmark, the situation was similar – a pragmatic, practical chemistry, some theory (Thomsen).[37] In Kragh's opinion, Thomsen presented in 1865 one of the "many incomplete anticipations of the periodic system", but in 1880 most Danish chemists already knew Mendeleev's and Meyer's systems. Odin Christensen (1851-1914) wrote the first Danish paper (1880) and textbook about the Periodic System (*Elements of Inorganic Chemistry*, 1890). The case of Norway is in some sense *sui generis* – linked to Sweden since 1814 but *de facto* independent since 1905, the country used its own chemical terminology and had a small but important scientific community (Peter Waage, Kristian Birkeland). Mendeleev's system had little effect on chemical practice and was introduced relatively late, with a textbook (1888) by Thorstein Hallanger Hiortdahl (1839-1925).[38]

A situation which deserves a wider and detailed study, even outside chemistry, is the reception of Mendeleev's periodic system in scientific communities which used their own language and had their own scientific evolution but were not independent nations at Mendeleev's times. This is the case of Czech and Croatian chemical communities, politically and economically linked to Austria-Hungary until 1918. Somewhat different is the Polish chemical community, spread throughout Russia, Austria and Germany, they did not constitute a united group of chemists. Using their own languages, terminologies and nomenclatures, not only in science but also in literature, philosophy and the humanities, Czech and Croatian scientists saw in Russia a leader, and positive reception of Mendeleev's system was an *a priori* decision.[39]

Use of one's own language in intellectual activities created and fortified emerging nationalisms in the 19th century. In the present Czech Republic,[40] until 1918 Austria's Kingdom of Bohemia, nationalism forced the creation in 1869 of a Polytechnic School (independent from the German Polytechnic) and the separation of the old Prague University (1348) into a German and a Czech University (1882). A textbook authored by Vojtech Safarik (1829-1902) was the first to mention the Periodic Table in the Czech language, but in Strbanova's opinion, the most important defender of Mendeleev's system in Czech lands was his personal friend Bohuslav Brauner (1855-1935). In the face of growing russophylia and anti-German sentiment, Brauner defended Mendeleev's ideas and vindicated the replacement of German scientific influence in Czech lands by Slavic influence. This case illustrates how nationalism and xenophobia may constitute a threat to the autonomy of science. There was some resistance to the acceptance of Mendeleev's work by Safarik (a Slovak), and by Jaroslav Formanek (1864-1936). Both wanted a 'natural' classification of Elements. Ambiguous behaviour of Czech intellectuals may be seen in Cermak's germanisation of his name, Gustav von Tschermak (1836-1927). Tschermak presents his own periodic table (1859), the first to draw attention to 'blanks'.[41]

In Croatia, until 1918 part of the Austro-Hungarian Empire, the reception of the Periodic Table was more straightforward.[42] Since 1861 school textbooks were published in Croatian, and since 1873 there was a University in Zagreb (then called Agram), but only in 1901, an academic textbook by Julije Domac (1853-1928) presented Mendeleev's system. A former text by Pavao Zulic (1831-1922), even in his second edition from 1877, omitted the periodic classification. The acceptance of Mendeleev's system in Croatia is largely due to the Czech chemist Gustav Janecek (1848-1929), whose text on the subject (1914) goes back to Döbereiner and other precursors.

Not only Czechs and Croats, but also other nationalities lived in polyethnic Austria-Hungary, maintaining their language, traditions and many centuries of their own cultural activities, like Hungarians. Since the *Ausgleich* from 1867, between the Emperor and the Hungarian government, Hungarian became the official language in schools, and Karoly Than (1834-1908) was designated chemistry professor at Budapest University. Than was the author of the most popular chemistry textbook in Hungary, *Elements of Experimental Chemistry* (1898), in which he presented Mendeleev's classification and systematisation.[43]

At the same time, in Serbia, a Slavic country *de facto* independent since 1867, with a University in Belgrade (1905), there was modest chemical activity. Frequently repeated information about a first non-Russian textbook on a Periodic System written by Serbian chemist Sima Lozanic (1846-1935) in 1874 (*Chemistry as Viewed by Modern Theories*) is incorrect. Lozanic included Mendeleev's System only in the second edition of his book (1897).[44]

Like Serbia, Bulgaria, another Slavic nation *de facto* independent since 1876 (Treaty of San Stefano) had modest scientific activity. A recent essay by Borislav Toshev suggests that all Bulgarian publications on Mendeleev are hagiographic, with the only exception being professor Dimitar Balarev's (1885-1964) *Significance of the Periodic System*, 1950).[45] Balarev himself designed a three-dimensional form of the Periodic Table.[46]

It is difficult to state precisely which Latin-American country first received the periodic system. Latin American historiography rarely refers to science, and when it does, it pays close attention to institutional history, or biographical data. Equally difficult to obtain information on Latin American contributions to the periodic system. It is however easy to ascertain that from the 1940s interest in the periodic table of the elements has spiked. It's great potential as a teaching tool was the main driving factor, as can be seen in Ceccon and Berner's monograph.[47]

The first record of the periodic system in Latin America is probably due to Álvaro Joaquim de Oliveira (1840-1922), professor at the Rio de Janeiro Polytechnic School. In his textbook *Apontamentos de Química* (1883) he critically examines the table under the influence of positivist dogmas.[48] Oliveira was one of the founders of the Brazilian Positivist Society (1876), but his views and interpretation of Mendeleev's work met strong opposition from his peers,[49] prompting another leading Brazilian positivist, Raimundo Teixeira Mendes (1855-1927), to publish an alternative textbook, *La Philosophie Chimique* (1898).[50]

There were different versions of the periodic table in use by Brazilian teachers. We mention, because of its originality, a contribution presented in 1949 by Alcindo Flores Cabral (1907-1983), professor of chemistry at the School of Agriculture in Pelotas. Cabral's spiral classification, elegant in its symmetry and use of colours, made use of what he called the 'differentiating electron'.[51] Another formulation of the table (1950) worth mentioning was made by professor Werner Gustav Krauledat (1908-1990), from Rio de Janeiro State University.

In Spanish speaking Latin America, a very successful table was designed in 1952 (and revised in 1962) by Gil Chaverri Rodrigues (1921-2005), a physicist and chemist from Costa Rica. His table follows a logical sequence derived from the sequence of atomic numbers and has done well in presenting lanthanides and actinides without disrupting the sequence of elements.[52] Like Cabral, Chaverri lectured at an agricultural school, which showed a widespread interest in periodic classifications.

Another successful table was that of Peruvian chemist Oswaldo Baca Mendoza (1908-1962), from Cuzco University, *Generic Laws of the Chemical Elements. A New Periodic System* (1953), inspired by the theories of his Spanish teacher A. del Campo y Cerdán.[53] Julio António Gutierrez (b. 1955) continued Mendoza's work (*Sistema Periódico Armônico and Leyes Genéticas de los Elementos*, 2004) on the 'quantification' of Mendeleev's table. Spaniard António García-Banús (1888-1955), creator of the great mural table in Barcelona, immigrated in 1938 to Colombia (1938) and lectured at the Bogotá National University, where he got involved with the periodic system.

In Uruguay, a chemical institute was created at the Faculty of Medicine in Montevideo (1908), where studies on periodicity largely focused on using the table as a teaching tool. During the decades of 1930 and 1940, there were some original ideas about the best position for the actinides in the table, and during the seventies, there were discussions about a new spiral design of the periodic system, but without a successful outcome.[54]

Western science found its way to Japan through Dutch textbooks used in "Dutch Studies": before the Meiji period, the Netherlands were the only western nation to have consistent contact with Japan. The first Japanese chemistry textbook, *Seimi Kaiso*, was written by Utagawa Yoan (1798-1846) around 1830 and included parts from Lavoisier's treatise.[55] Robert William Atkinson (1850-1929), an English chemist, the first western chemistry teacher in Japan, was interested in periodic classification but preferred Lothar Meyer's table. Naokishi Matsui (1857-1911), a professor in Tokyo, was the first to mention Mendeleev in a paper (1882), and Toyokichi Takamatsu (1852-1931) was probably the first to mention it in a textbook. Research on the subject was also done by Kikunae Ikeda (1864-1936) and Masataka Ogawa (1865-1930), the former from a theoretical point of view, and the latter in an empirical context.[56]

Of notable interest was the difficult introduction of the periodic table in Turkey. Two problems contributed to making this task complicated: an absolute lack of modern chemistry texts and the use of Arabic symbols for letters and numbers – Arabic texts are written from right to left, which turns writing formulas, equations and reactions even more difficult. Despite these difficulties, Vasil Naum (1856-1915) included Mendeleev's system in his book *Medical Chemistry*, with names of elements and numbers in Arabic characters (the official language of the Ottoman Empire). In 1914, the Turkish government decided to modernise its higher education system, and from 1915 to 1918 a group of German chemists lectured in Constantinople, headed by Fritz Arndt (1885-1969) – Gustav Fester (1886-1975) and Kurt Hoesch (1882-1932) were the other members of the mission. After facilities and equipment, Arndt's priority was the production of textbooks in Turkish language (Arndt was fluent in Turkish), and in his *First Medical Experiments* (1917) we find the second Turkish periodic table, with Latin characters used for the elements and their symbols, but with the text itself remaining in Arabic, read from right to left.[57]

In the United States, we distinguish between the reception of Mendeleev's system and the reception of several other classifications, some of them proposed by American chemists, a situation similar to that observed in Great-Britain and France. In 1854, Harvard professor Josiah Parsons Cooke (1827-1894) presented before the American Academy of Arts and Sciences in Boston a lecture *Numeric Relations between Atomic Weights and some Ideas about Classification of Elements*, considered by Edgar Fahs Smith (1854-1928) as the first serious attempt in studying this subject (1914).[58] Gustavus Hinrichs (1836-1923) published his textbook in 1874, but instead of Mendeleev's system he included his own spiral classification (worked out in 1867), not even mentioning Mendeleev's formulation.[59] Lewis Reeves Gibbes (1820-1896) published in 1886 a *Synoptical Table of Chemical Elements*, using an 'inverted' procedure with respect to Mendeleev's, arranging a great number of chemical proprieties and deriving from them a periodicity of atomic weights.[60] Stephen Brush could not find a single American textbook discussing Mendeleev's ideas until Lecoq's discovery of gallium in 1875. In 1877, Ira Remsen (1846-1927), from Johns Hopkins University, published his *Principles of Theoretical Chemistry*, the first text in the United States to mention Mendeleev.[61]

THE TABLE AS A RESEARCH TOOL

Mendeleev`s Periodic Table contains 'blanks' (though he was not the first to postulate their existence); all periodic tables presented after Mendeleev's also contained 'blanks'. The desire to replace such blanks with new discoveries strongly motivated chemical research.

The increasing number of elements discovered since 1800 (thanks to improved analytical techniques), the degree of uncertainty associated with many physical properties (such as atomic weights), the dispute on what properties to use as criteria of periodisation, and the inability to forecast how many elements remained to be discovered, all illustrate how the study of the 'blanks' became a powerful centraliser of experiments and discoveries. In one way or another, research activity revolved around the question: How many elements are there, and how can we best order them?

Let us detail two recent events in the history of chemistry related to 'blanks' in the periodic table: the troubled hunt for mysterious Element 43 (technetium, masurium), and the controversial discovery (1923) of hafnium, Element 72. It was precisely the discovery of three of the elements foreseen by Mendeleev (three 'blanks') which promoted the acceptance of Mendeleev's system: (eka-aluminium or gallium by Lecoq de Boisbaudran in 1875, ekaboron or scandium by Nilson in 1879, and ekasilicon or germanium by Winkler in 1886).

The epistemological status of these discoveries is still a matter of contention among philosophers of chemistry. Mendeleev considered the existence of nine unknown elements (including gallium, scandium and germanium), as well as the need to correct the atomic weights of five elements (including beryllium, tellurium and uranium). And as put by Mendeleev himself, "the confirmation of a law is possible only by deducing consequences from it, and by justifying those consequences by experimental proof."[62] But as highlighted by Scerri, the number of verified predictions equals the number of predictions which turned out to be false, so not a good score for the confirmation of the law of periodicity.[63] However, despite fewer than optimal numbers, Mendeleev's table had a predictive ability which was lacking in alternative formulations, such as the tables by Odling, Newlands, and Lothar Meyer, hence Mendeleev's eventual widespread acceptance.

How can the periodic table guide research? A simple example: by the position of the 'gaps' predicted by Mendeleev in the Table, one can predict in which minerals these new elements should be sought. In the 10th series, Group VII, from his second table (1872), Mendeleev predicted the existence of two elements still unknown below manganese, that would have atomic masses 100 and 190, respectively. He named them ekamanganese and dwi-manganese; eka- and dwi- are Sanskrit prefixes, meaning 'first' and 'second'. Mendeleev was a friend of German Indologist and Sanskrit scholar Otto von Böhtlingk (1815-1904), his colleague in St. Petersburg, which may explain his use of Sanskrit (Mendeleev did not know the language). Speculations on a possible analogy between the periodicity of the elements and the phonemes of Sanskrit are fantasies.

Elements with atomic masses 100 and 190 were really discovered: technetium (atomic Number 43) and rhenium (atomic number 75). For over two centuries chemical literature accumulated innumerable cases of spurious, never confirmed discoveries, i.e. 'discoveries' of already known elements or of mixtures of elements.[64] Unguided research rarely led to new discoveries. But the discoveries mentioned above were achieved by using the positions of the missing elements in Mendeleev's table as a guide. The most striking example of such a 'guided' discovery is the discovery of hafnium (1923) by Gyorgy de Hévesy (1885-1966) and Dirk Coster (1889-1950). Hafnium was Mendeleev's ekazirconium and was effectively obtained from zirconium silicate ($ZrSO_4$) extracted from the mineral alvite. Mendeleev's prediction was in this case strengthened by Bohr's theoretical arguments, and by the discovery of the new metal by mineralogist Victor Goldschmidt (1888-1947) in 1925.

The association between prediction and discovery is not obvious in the case of elements 43 and 75. Although Walther Noddack (1893-1960), Ida Tacke (1896-1978) and Otto Berg (1873-1939) published an article "Die Manganelemente" (1925), rhenium was actually discovered in the minerals molybdenite (MoS_2, today the most important source of rhenium), columbite [$(Fe,Mn)(Nb,Ta)O_6$] and gadolinite, and in platinum minerals.[65] Masurium, the supposed element 43, was never obtained from natural sources (there is a recent controversy on this issue), but allegedly identified spectroscopically in molybdenite. Properties of technetium and rhenium are more similar to molybdenum (element 42) than to manganese, but there are diagonal relations in the periodic table.

Chemists, historians and philosophers of science questioned the predictive capacity of the periodic table. Lothar Meyer doubted the possibility of making predictions based on classification. After the formulation (1913) by Henry Moseley (1887-1915) of what would be known as 'Moseley's Law', some have questioned whether these predictions had heuristic status since Mendeleev's times, or if it was Moseley's Law that was responsible for any heuristic value ascribed to the periodic system. Moseley predicted the existence of only 14 rare earths, one of them still unknown (element 61), and of six elements to be discovered – six 'blanks', in the periodic system (elements with atomic numbers 43, 61, 72, 75, 85 and 87). The 'criticism', while reasonable, seems exaggerated. One can justifiably say that Moseley's law and the discoveries that followed from it added to the stock of empirical data that ultimately offers support to the prior discovery of elemental periodicity.

The periodic table has also seen many uses in non-strictly chemical research. It is employed in fields such as mineralogy, geology and geochemistry.[66] The table itself benefited from the search for new minerals and still unknown elements in these minerals. Before ionic rays were known, isomorphism and so-called isomorphic substitutions were important for the 'periodisation' in mineralogy. This can be seen in the table by Vladimir Vernadsky (1863-1945), of the University of Moscow, considered one of the 'fathers' of geochemistry. The introduction of magnitudes such as atomic mass, atomic number and ionic radius allowed Norwegian mineralogist Victor Goldschmidt (1888-1947) to establish the substitutions in mineral series, such as the feldspars (Goldschmidt's rule).

PERIODICITY AND SOME PHILOSOPHICAL CONSIDERATIONS

In 1869, Mendeleev's Periodic Table, the model of all tables to come, appeared. Mendeleev's representation is not only the prototype, so often modified, of the record of all subsequent tables, but its own theoretical basis (the periodic law) – is the basis for all later tables. Mendeleev's classification should not be regarded, however, as the crowning of precursor classifications – the Russian chemist's table is grounded, *malgré lui*, on philosophical assumptions. Mendeleev initially did not consider philosophy important for the formation of chemists, but during his professional life, especially after the Congress of Karlsruhe (1860), he became himself a philosopher of chemistry.

His intellectual positions are original and difficult to fit into some philosophical school. But it is generally accepted that later in life, as an old man, Mendeleev would accept something like *Kantian* epistemology: the belief that humankind, even when well-equipped with the tools of science, was unable to comprehend the "thing-in-itself", i.e. substances as mind-independent entities. In fact, he would say that substances can only ever be studied by "their properties or by their relations to our organs of sense and to other substances and bodies" although he clearly accepted substances' independent existence "for there is something in its nature which is self-existent."[67]

Such a view was also dear to Goethe, namely, that experience is, to an important extent subjective – every scientist experiences phenomena in a way that is only his/her, not being able to see through the eyes of someone else. It is according to this Kantian framework that Mendeleev considers himself to be a realist (although it must be said that there is a less prominent interpretation of *Kantian* ontology which places the German philosopher closer to idealism). According to Vucinich:

> *To Mendeleev being a realist meant denying the ontological unity of the universe and rejecting revolution as a source of natural and social change. It also meant recognising not only the powers of science but also its limitations. But above all, it meant adopting a philosophical outlook untrammelled by metaphysics.*[68]

So, despite being a self-declared realist of some sort, positivists, nihilists and Marxists alike all attempted, in vain, to exhibit Mendeleev's ideas were in agreement with their intellectual frameworks (and political agendas) and count him as one of their own.

Several of the periodical classifications presented during the nineteenth-century show relations with philosophy, relations only sometimes explicit. But it was Mendeleev's periodic system that most aroused the attention of philosophers of science, not forgetting the 'philosophy of science' implicit in the work of Mendeleev himself – which for some is empirical, for others theoretical, or even empirical/theoretical). Also, his table is sometimes considered just a classification based on experimental data, and sometimes a representation of a law or theory.

It is necessary to separate the theoretical bases of chemical periodicity together with experimental data from the experimental data of the philosophical aspects involved in the periodic law and the resulting table. A supposed dialectical materialism that would permeate Mendeleev's science is a fiction by Friedrich Engels (1820-1895), for whom the periodic classification was a victory of dialectical materialism, an unconscious application of Hegel's law of transformation (though Marx explicitly states that his dialectic differs and opposes that of Hegel) concerning the transformation of quantity into quality. Engels's analysis of 1890 was made in the absence of Mendeleev himself, who never accepted this interpretation by Engels and Marx, or even Heraclitus's principle of transformation as a universal principle.

For Mendeleev, and in accordance with leading ideas from his time, "the elements are constituents of nature, essentially unique, *permanently fixed* and genetically discrete, irreducible to a primary matter."[69] Richard Feynman (1918-1988) would later say about something seeming permanently fixed: "To our eyes, our crude eyes, nothing is changing, but if we could see it a billion times magnified, we could see that from its own point of view it is always changing: molecules are leaving the surface, molecules are coming back."[70]

Mendeleev, after the discussions at the Karlsruhe Congress, approaches the issue later raised by Feynman with surprising insight, solving the problem inherent in atoms and molecules in three stages; at the macroscopic level, at the microscopic level, and in the relationship between the macroscopic and the microscopic. On the macroscopic level, it is necessary to distinguish in current chemical language between 'body' and 'substance'; at the microscopic level, to distinguish between 'atom' and 'molecule'; and finally, to establish a relationship between the two levels." He expands on this:

> *It is evident that water does not contain gaseous oxygen or oxygen in the form of ozone; it contains a substance capable of forming oxygen, ozone and water... It is necessary to distinguish the concept of a simple body from that of an element. A simple body substance, as we already know, is a substance, which taken individually, cannot be altered chemically by any means produced up until now or be formed through the transformation of any other kinds of bodies. An element, on other hand, is an abstract concept; it is the material that is contained in a simple body and that can, without any change in weight, be converted into all the bodies that can be obtained from this simple body. A similar definition of an element and the same argument for the need to distinguish clearly between an element and simple body were later presented in the first part of Principles."*[71]

An immediate perception by the senses refers to macroscopic phenomena, it is a perception of the transformations that occur in 'bodies'. But 'bodies', necessary to understand the transformations that occur, refer to the idea of 'substance' (= element). As Gaston Bachelard (1884-1962) would later say, the experiment never puts us in contact with the 'substance', but without the notion of 'substance' it is impossible to understand experiments (which refer to 'bodies'). It proceeds at the microscopic level, differentiating atom from molecule:

> *We call a 'molecule' the quantity of 'substance' that reacts with other molecules, and which occupies in the vapor state volume equal to two weights of hydrogen [...] 'atoms' are the smallest quantities of chemical masses indivisible from the elements, which form the molecules of simple and compound bodies.*[72]

For more than 60 years our high school teachers, capturing the essence of Mendeleev's argument, taught students that 'atom' is the smallest part of an element that conserves its properties, and 'molecule' is the smallest amount of a substance that retains its properties. In a similar fashion, 'element' is the set of all atoms of the same atomic number (atomic weight, in the time of Mendeleev): the simple substances coal, graphite and diamond are formed by atoms of the element carbon. Mendeleev's simple but ingenious innovation related macroscopic and microscopic levels:

> *A simple body is something material endowed with physical properties and capable of chemical reactions. The term 'simple body' corresponds to the idea of 'molecule' ... The name 'element' should be reserved for the particles which form the simple and compound bodies, and which determine how they behave from the point of physical and chemical view.*[73]

Fritz Paneth (1887-1958), one of the few chemists to philosophise, rationalised these concepts along with ontological and epistemological considerations. The word 'element' refers to the idea of 'atom'. The element, the *Grundstoff*, belongs to the transcendental world and is not observable. The simple substance, *einfacher Stoff*, is observable because it belongs to the world of 'primitive' or 'naive' realism. The *Grundstoffe* are, therefore, the entities that fill the 'squares' of the periodic table. Still on this subject, American chemist Benjamin Harrow (1888-1970) offered much earlier (1930) a very simple, perhaps too simple, anthropomorphic explanation:

> *This periodic Law is really more complicated than our exposition would lead the reader to believe; but for our purpose [diffusion of scientific knowledge] all complications can here be discarded. For us the important lesson that the periodic law teaches is that since there are family relationships among, since there are brothers and sisters, there must be fathers and mothers, from which we conclude that there must be a 'something' in the universe simpler and still more fundamental than the elements – a 'something' out of which the elements themselves are built.*

This 'something', recent studies have shown, is the proton and the electron, the positive and the negative particles of electricity. All atoms are made up of protons and electrons. The atoms of any element, such as gold, are practically alike, but an atom of gold is different from an atom of chlorine. On the other hand, the protons and electrons, so far as we can tell, are the same, whether they are found in an atom of gold, in an atom of chlorine, or in any atom of the 92 elements.[74]

Harrow certainly knew Moseley's law: there is no direct evidence of this, but reference to anthropomorphic "brothers" and "mothers" must have been inspired by the radioactive decay series. Mendeleev himself explained Harrow's 'something' in 1869 when he referred to carbon, diamond and coal. In the following quote, we can identify Paneth's classification of *Grundstoff* and *einfacher Stoff*:

> *It does not matter how the properties may change, something remains unchanged, and when these elements form compounds, this something acquires a material value and establishes the properties of the element containing compounds. With respect to this, we know only one property characteristic of each element, the atomic weight. The magnitude of the atomic weight, according to the very essence of matter, is a number unrelated to the degree of division of simple bodies but related to the material part common to the simple body and its compounds. The atomic weight does not refer to coal or diamond, but to carbon.*[75]

Finally, it may prove useful to verify if the concept of the element has remained unchanged over the years, or whether it has undergone some sort of 'reconceptualization'. Going to back to Lavoisier, we can see that the French chemist introduced a pragmatic concept of element: a substance which cannot be further subdivided by any chemical means. This pragmatic, empirical and operational approach to the definition of 'element' can be traced back to Condillac and even to Locke, and it can be singled out as one of the probable causes of Lavoisier's inability in elaborating a philosophy of chemistry.

The alternative to the pragmatic approach can be found in classic metaphysics: the element is a 'substance' (from the Greek *ousia* = being). *Substantia* (Latin) is that which 'grounds' things like attributes or properties. Substances, in generic philosophical terms, can therefore, be said to be the fundamental entities of reality. According to this definition, if atoms are the basic things from which all else is constructed, then atoms are (or are like) substances. There is an obvious realist interpretation of reality here, substances – the basic building blocks of reality – are real, and so are all instantiated properties.[76]

Philosophical schools such as logical positivism or pragmatism (i.e. those which consider metaphysics a simple matter of convention) would deny the reality of substances. For the antirealist there can be no fact of the matter about the foundation of reality, so substances, atoms, elements, or any candidate to what can be ontologically basic, lose their objective status. It must also be said that one can coherently think of a substance in different terms. It can be said to be a kind of entity, like an object. And an object can perhaps be thought of as a bundle of properties, in which case 'object' is not basic, or simple. The same reasoning could be applied to an atom or even element.

Mendeleev's views, according to Martin Labarca and Alfio Zamboni, seem to somehow combine pragmatism with a metaphysical approach to substance, what they call a dual sense.[77] Elements are foundational, abstract and real, but deprived of properties. 'Operational' elements are 'simple' substances (like atoms) which possess properties. One could think of such a hybrid approach used by Mendeleev – in contrast to other classifications – as vulnerable to challenges originating from Soddy's definition of isotope. But Paneth, in the 1930s, sustained that isotopy does not modify chemical properties (hydrogen being the exception), so no revision of the chemical periodic table would be necessary. Each new isotope would be a new 'simple substance', and not a new abstract element. Paneth's arguments convinced the IUPAC to substitute the atomic mass as characteristic of each element by the atomic number (1923), a property of the abstract (real) element.

But with the discovery of the neutron (Chadwick, 1932) some adaptations were indeed necessary: for each element, there is an upper and lower limit of the number of neutrons, and of atomic mass, to ensure the atom's stability. An up-to-date representation of periodicity would be based not just on the atomic number, but also on the number of neutrons. Labarca and Zamboni propose to reconceptualise the element as: "a certain class of entity constituted by a 'fundamental substance' [metaphysical concept] which exhibits two representative properties, the atomic number and the limits for the atomic mass, with contingent proprieties varying case-by-case."[78] The primary criterion for the classification of the elements, they propose, would be the number of neutrons, whereas the second criterion would be the electronic distribution – and not the atomic number. Nevertheless, even under such a reconceptualisation, the periodic system maintains most of Mendeleev's conception.

THE PERIODIC TABLE AND AESTHETICS

Georges Urbain (1872–1938), a chemist interested in so many arts and involved in filling the "blanks" or "voids" left by Mendeleev in his table, said in one of his non-chemical works: "from an intellectual point of view, the sage and the creative artist are twin brothers."[79]

It is also often the case that scientists regard the products of their work (theories, models, proofs) as holding aesthetic value. But the precise nature of the relationship between science and aesthetics is difficult to grasp, and often involves confusion of categories. As an example, one could refer to a rather cryptic quote from the engineer who turned physicist and philosopher, Abraham Moles (1920-1992):

> *In the act of creation, the scientist does not differ from the artist: in principle, there is no difference between artistic creation and scientific creation, they work with different materials of the Universe […] creation is an act of spirituality, which, using all 'dimensions' of spirituality, all its planes of freedom and phenomenological apprehension, cannot be limited to a logical Universe, to a ludic Universe of gratuity, but must include all aspects of spiritual freedom, […] there is only one unique intellectual creation.*[80]

It is one thing to say there can be beauty in the products of scientific investigation, or in the tools used to represent scientific knowledge (such as the periodic table), quite another to say there is beauty in the 'act' of creation. Intermingling aesthetics with spirituality does not do Moles any favours either. Furthermore, in science, there is often talk of discovery, instead of creation, so where and when scientific creation occurs must be specified.

Several aspects of science may hold aesthetic value. It is possible that aesthetic considerations play a role in theory choice – for example, in a situation of empirical underdetermination of theories: when having to choose between empirically equivalent rivals, one could appeal to aesthetic properties of one theory to favour it over the other. Or, it could be said that valuing simplicity as a heuristic guide is yet another instance of science intermingling with aesthetics.

More importantly, as singled out by Ivanova, "beauty is also often taken to stand in a special epistemic link to truth. Many scientists argue that a beautiful theory is more likely to be true."[81] To assign an epistemic role to aesthetics is difficult. Can we ever justify confidence in the truth of a theory as arising from its beauty? Any aesthetic judgement is secondary to empirical adequacy, which remains to this day the main criterion theory acceptance.

Furthermore, it seems unlikely that beauty can ever be a predictor of scientific success. One could easily challenge the association between aesthetics and scientific progress (or truth, or empirical adequacy) and claim it to be arbitrary and misleading. One could do so by pointing out cases of 'beautiful' theories that turned out to be false (such as *Newtonian* mechanics), while highlighting the success of theories which lack any aesthetic appeal. As Ulianov Montano points out, aesthetic values such as simplicity and unity are not [usually] instantiated by highly successful theories.[82]

However, if one considers not truth but understanding to be the aim of science, then it may be easier to assign an epistemic role to aesthetics. For Henri Poincaré (1854-1912) aesthetic values, Ivanova reminds us, reduced in the case of science to simplicity and unity, work as "regulative ideals to be followed because they are linked to the ultimate aim of science, namely, gaining an understanding of the relations that hold among the phenomena." Therefore, aesthetic value gains an epistemic role because it shows how, given a certain theory, "apparently disconnected phenomena are unified under a simple framework."[83]

We may now return to the case of the periodic table. While its acceptance is clearly owed to its success in predicting the discovery of a few elements, our appreciation of it as an object possessing important aesthetic value can be said to be the result of its excellent capacity to unify phenomena under a simple framework, therefore facilitating our understanding of, among other things, periodicity.

It falls outside the scope of this essay to address the question of whether aesthetic judgements in chemistry or science in general, may have objective validity. We wish to highlight, however, that there is consensus among the scientific community that the periodic table exhibits aesthetic properties that are widely regarded as desirable, such as unity and simplicity. This helps explain why different representations of the table exist outside chemistry or academia.

So, let us now focus on less abstract digressions, and briefly survey the periodic table's existence outside chemistry books. It can be found in works of art around the world, ranging from gigantic murals or monuments to postal stamps.

In fact, the first homage of the Periodic Table on a postal stamp was issued by the Spanish mail in 2007 (centenary of Mendeleev's death). Created by inorganic chemist, Javier Garcia-Martinez (Alicante University), it was designed to transmit a "modern and positive image of chemistry" and "to catch the attention of stamp users and collectors alike with a colourful and highly geometric design." Garcia-Martínez was inspired by Dutch painter Piet Mondrian (1872-1944), whose abstract expressionism, geometric expression, and judicious use of colours help detail the 'voids' in the table.[84] On the verse of the stamp, there are mural tables and printed tables in laboratories and classrooms.

Over the years, some representations of the periodic table acquired notoriety or made the news – like the one recently discovered at St. Andrews University, printed in Vienna (1885) and brought to Scotland by Thomas Purdie (1843-1916). The oldest preserved printed table (1876) can be found in the Museum of the University of St. Petersburg. The historically most interesting case of mural tables is the large mural (2,2 x 2,7m) existing in an auditorium in the old building of the University of Barcelona (Taula de García-Banús), painted in 1934 by commission of professor Antonio Garcia-Banús (1888-1955). Historians later discovered that it was a reproduction of the table conceived in 1926 by Bonn professor Andreas von Antropoff (1878-1956), a popular table at the time,[85] but abandoned in 1945 because of Antropoff's ideological positions. Some historians refer to *Bauhaus* and *de Stijl* influences in Antropoff's table. Recently rediscovered by Philip Stewart (b. 1939), the table was carefully restored in 2008 by professor Claudi Mans i Teixidó.[86] Mans would say this is a unique case in the history of chemistry: a republican and socialist professor adopted a table created by a national-socialist professor, which was restored during a fully democratic government, after surviving Franco's dictatorship. J. Marshall suggests Antropoff's table was situated halfway between Mendeleev's classic short table and Alfred Werner's (1866-1919) "long" table from 1905, and that the resulting practicality was responsible for the popularity of Antropoff's table, even in the United States.[87]

It would probably be best if ideologies never intervened in the progress of science. But ideologies often accompanied Mendeleev's career: his prestige in tsarist Russia was enormous, *malgré lui* a national hero of the Soviet Union, although he did not see himself as socialist and despite his criticism of popular demonstrations after failure of the 1905 Revolution. Mendeleev, in Brooks' opinion, was always loyal to the tsarist regime, although there were frequent disagreements between the scientist and lower-ranked bureaucrats.[88]

Another classic table, very popular in the 1920s and 30s, was the one designed by American chemist Henry David Hubbard (1870-1943), from 1901 to 1938 secretary of the *United States National Bureau of Standards*. Hubbard modified Mendeleev's table (1924), giving it a more compact form, suitable for use in class. It has been updated several times, 12 editions until 1936, 18 until 1963, sponsored by *Sargent & Welch*, Buffalo, manufacturers of teaching material. Hubbard's was the most widely used periodic wall table in American schools. It was also well received in Brazil during the 1930s, the so-called "Hubbard's Brazilian Table" from the former *Escola Nacional de Engenharia* (now the Polytechnic School of the Federal University of Rio de Janeiro), a table 'rediscovered' by Sir Martyn Poliakoff, of Nottingham University. Hubbard's Brazilian Table includes dated symbols, like Cb (columbium ^{41}, instead of niobium), Ma (masurium ^{43}), Il (illinium ^{61}), Ab (alabamine ^{85}), and Vi (virginium ^{87}), among other curiosities, none of which were recognized discoveries.[89] In an era of atavistic nationalism, Hubbard's table clearly illustrates the reluctance to abandon elements 'discovered' in the United States, even though these were not recognised by the international chemical community and would later have to be removed from the table.

In past centuries chemists had different, often subjective, views on the structure of matter, which reflected on their teaching of chemistry. The same can be said of chemistry teachers and their subjective views on how best to present the periodic table. In some cases this personal exploration of the table by teachers was incredibly creative, and quoting Bertomeu-Sanchez (*et al*):

> *The most creative books were not necessarily the great treatises written by creative academic chemists. Obscure chemistry teachers, who were not necessarily active in scientific research, attempted innovative and ambitious systems of elements in order to satisfy both didactic and scientific constraints. Textbook writing remained a creative activity. By creative, we do not necessarily imply innovation or great discovery. They were creative in a more modest way as they expressed original and ambitious interpretations of the foundations of chemistry.*[90]

This idea is exemplified by one of the few Brazilian contributors to represent the periodic system, Alcindo Flores Cabral (1907-1982), professor at the School of Agriculture Eliseu Maciel (nowadays part of the Federal University of Pelotas), in 1946. Examining a mysterious mural at the entrance of the chemistry building in Pelotas, professor Eder Lenardão rediscovered his table (2001).[91]

In the case of a few talented chemists the necessity to write more engagingly and creatively – often inspired by episodes from their personal and professional lives – was responsible for the production not just of textbooks, but high-quality, transcendent or poetic literary pieces. Two examples deserve special attention: "Il Sistema Periodico" by Primo Levi (1919-1987), published in 1975, and the biographical "Uncle Tungsten – Memories of a Chemical Boyhood" (2001) by neurologist Oliver Sacks (1933-2015). For Sacks:

> *The Periodic Table is incredibly beautiful, the most beautiful thing I had ever seen. I could never adequately analyze what I meant here by beautiful – simplicity? Coherence? Rhythm? Inevitability? Or perhaps it was its symmetry, the comprehensiveness of every element firmly locked into its place, with no gaps, no exceptions, everything implying everything else.*[92]

The elements in Primo Levi's "Il Sistema Periodico" become symbols and metaphors for the various phases of the author's life, so that a summation of elements becomes his life story or a memoir. On such metaphorical usage Luigi Dei (b. 1956) concluded that "we can say that the properties of the elements often reflect the properties of life itself: volatile, inert, lustrous, precious, poisonous, brittle, explosive..."[93]

In the chapter dedicated to iron, Levi thus refers to the Periodic Table:

> *That the nobility of Man, acquired in a hundred centuries of trial and errors, lay in making himself the conqueror of matter, and that I had enrolled in chemistry because I wanted to remain faithful to this nobility. That conquering matter is to understand it, and understanding matter is necessary to understanding the universe and ourselves: and that therefore Mendeleev's Periodic Table, which just during those last weeks we were laboriously learning to unravel, was poetry, loftier and more solemn than all the poetry we had swallowed down in liceo, and come to think of it, it even rhymed! That if one looked for the bridge, the missing link…*[94]

Most of such literary pieces portray the periodic system in a positive light. This need not always be so. In the poem "The Periodic Table of Elements", Australian poet Bruce Greenhalgh shows his disenchantment with the table:

> *…that it listed more/and less/than earth, wind, fire and water, [but 118 elements are] arranged by atomic number/ in an obscure scheme/of electrons and abbreviations, [without any] reflect/on sodium/or potassium/or Byzantium [in reference to Yeats's poem], no flair, no mystery, no poetry, nothing for me", [poet and periodic table] have gone our separate ways.*[95]

Chilean poet Nicanor Parra (1914-2018), professor of theoretical physics in Santiago, has a similar, if more ironic, take on the table. In his long poem "Los Profesores" ("The Teachers"), he speaks of "teachers turning us mad/with questions which do not matter" – including the periodic table.

One may be tempted to explain why, given the success of the table in systematizing existing knowledge and predicting new elements, a chemist would react negatively to it. One could speculate that the table, for some people, may fall victim to its own success. It would be very difficult for a chemist to attempt any different form of systematisation today, which some would see as a limitation to creativity. The table also indicates what possible new chemical discoveries may be like, which may lessen our sense of amazement when progress is indeed achieved.

Finally, some chemical elements, isolated or classified by the table, inspired musical compositions as well. Edgar Varèse (1883-1965) honoured platinum with a piece for flute solo (1936), "Density 21.5" (the density of the metal), and the composer and theorist Andrew Stiller (b. 1946) composed in 1988 "A Periodic Table of the Elements" for 14 wind and percussion instruments.[96]

This brief survey of the table's presence in non-chemical or academic contexts goes to show that some scientific achievements, when consolidated through a universally accepted form of representation, have the tendency, or at least the potential, to become iconic – in the sense defined at the beginning of this essay. More on this in the next section.

THE PERIODIC TABLE AND POP CULTURE

The periodic table is the object of this essay, so let us define less rigorously what after all is 'popular culture'. Also, the definition of "science fiction" differs from author to author; let us adopt here the definition given by Darko Suvin (b. 1930): "... a literary genre or verbal construct whose necessary and sufficient conditions are presence and interaction of estrangement and cognition, and whose main device is an imaginative framework alternative to the author's empirical environment."[97]

Science Fiction does not necessarily deal with the actual Periodic Table, but often invents (sometimes even foresees) fantastic and fanciful imaginary elements in an environment artificially constructed, but still plausible and credible. Hans Dominik (1872-1945), engineer, in his time famous as author of many science fiction stories and novels conceived in *Atomgewicht 500*, published in 1934, artificial elements with very high atomic weights.

At the time he wrote it uranium had the highest atomic weight, 238. Dominik's scientific views are no longer valid, but the author's utopian vision with respect to the future of nuclear chemistry is worthy of note. Some lines from the book: "The most important! You know what I mean. Atomic weight? Two hundred and forty-two! Four unities more than the atomic weight of uranium. Congratulations, Slawter! You were the first to obtain a substance non-existent on Earth and in terrestrial conditions"[98]. Transuranic and transfermic elements exceed this weight; the heaviest known element to date is oganesson (Og, atomic number 118 - first synthesised in 2002 at the Joint Institute for Nuclear Research in Dubna, Russia, by Russian and American scientists), with an atomic weight of 294.

With the probable completion of the ninth series of the table, we will surpass the value 300 ... will these imaginary elements one day become reality? Suze Kundu wrote in N*ature*: "scientists and non-scientists alike have long been dreaming of elements with mighty properties. Perhaps the fictional materials they have conjured up are not as far from reality as it may at first seem."[99] In face of "Atomic Number 500" and the ongoing study (a reality) of the Periodic Table, may we expect an upper limit for this "expanded" Periodic Table? Or a lower limit? What will this limit be? Sima Lozanic speculated about a limit already in 1906. Niels Bohr (1885-1962) in 1922 expanded electronic configuration to element 118, but in 1924 he concluded theoretically that it would be difficult to surpass atomic number 137.[100] Beyond the "island of stability" around atomic masses 290 – 300, perhaps atomic number 128 will be the limit, or, for Albert Khazan (b. 1934), this figure would be 155.[101] Pekka Pyykkö (b. 1941) and Burkhard Fricke, on the basis of mathematical calculations, suggest a limit of Z = 172 (suggesting a noble gas)[102], and for Walter Greiner (1935-2016) there is no limit for the Periodic Table.

On the chemical properties of aluminium (an element already known but still unused at the time), Charles Dickens (1812-1870) wrote in 1856:

> *Within the course of the last two years [...] a treasure has been divined, unearthed and brought to light [...] what do you think of a metal as white as silver, as unalterable as gold, as tough as iron, which is malleable, ductile, and with the singular quality of being lighter than glass? Such a metal does exist and that in considerable quantities on the surface of the globe.*[103]

Dickens' 'treasure' element did become reality. Another contemporary of Dickens, English chemist and industrialist John Carrington Sellars (1840-1916), in an attempt to popularise chemistry and find connections with Christianity, published in 1873 a curious and rather long poem titled *Chemistianity*, "an oratorical verse, in poetic measure, on each known chemical element [...] in the universe."[104] Each of the 63 then-known elements received symbolic names. Dickens's wonder metal aluminium, for instance, was called 'Ktyon', and about it Sellars says: "Aluminium, the Bright Star of Metals,/ The principal metal in common clay/In extremely light, bright, and silver-like/It does not oxidise in exposure to Air..."[105] Sellars described in 'oratorical verse' the properties of the element. According to van der Krogt, Sellar's book (today very rare and collectable) was well-received at the time of publication.[106]

On the other hand, there is a perceptible trend in more recent fictional writing in which plausibly imagined chemical knowledge gives way to fantastic, far-fetched chemical worlds – as can be seen in superhero comics (Captain America, Wolverine), or in Tolkien's fantasy books, and even in Janet Kuypers' poetry: "I wracked my brain, 'wait a minute,/I know osmium, it's the densest metal/in the Periodic Table. But Diburnium?"[107]

J. Ober and T. Krebs include amongst their favourite fictional elements the *mithril* of the Hobbit, by J. R. Tolkien (1892-1973), the *dilithium* from the universe of Star Trek, and the *vibranium* of Captain America's shield.[108] *Mithril*, made by dwarves, resembles silver, but it is lighter and stronger than steel. *Dilithium*, a mineral found on different planets of the Star Trek universe, regulates the reaction between matter and antimatter. *Vibranium*, originating from Wakanda (Africa) exhibits a powerful capacity to absorb, store, and release vast amounts of kinetic energy. One cannot help but wonder whether reality will meet fiction at some point, and whether we will be able to say of a new element something similar to what Dickens said of aluminium.

Still, in the genre of popular culture, the musician, comedian and Harvard professor of mathematics Tom Lehrer (b. 1928) authored a song containing all the elements of the periodic table. The song was based on comic opera "The Pirates of Penzance" (*aka* "The Slave of Duty"), by Sir Arthur Sullivan (1842-1900).

In the case of cinema, probably one of the most efficient vehicles of mass communication, there has been little interest in the periodic table and its creator, Mendeleev. He has not been the subject of any movies, figuring only in documentaries such as "The Mystery of Matter" (2014). This is in sharp contrast to the cinema's interest in the lives and works of many notable scientists, such as Pasteur, Marie Curie, Ehrlich, Paracelsus, Copernicus, and even Julius Robert Mayer.

FINAL REMARKS

On November 2nd, 2017, the 39th General Conference of *UNESCO* in Paris proclaimed 2019 the *International Year of the Periodic Table*. This is, of course, a result of the table's iconicity and universal appeal. Such recognition does not mean that the table itself, or even the discovery of periodicity, are the most important innovations in the history of chemistry. One could think of Dalton's quantitative atomic theory, or Lavoisier's oxygen theory, as better candidates for most important breakthrough moments. Yet, most are quick to recognise the table as chemistry's most important icon.

Michael Mingos (b. 1946), from Oxford University, resumes the real possibilities of the Periodic Table:

> *The Periodic Table is neither a biblical tablet of rules nor a monolithic Rosetta Stone, which provides accurate translations of chemical trends and properties. It does, however, offer a flexible two-dimensional mnemonic for recalling the important characteristics of the 118 known elements and the structure of their constituent atoms. [...] It thereby provides a way of thinking for chemists which also reflects the individual's unique history and personality.*[109]

The table has undoubtedly been the most successful tool for the popularisation of chemistry and, by extension, scientific knowledge and practice. This cannot be explained just as a response to the discovery of periodicity. But perhaps it can be explained by the table's success in both, accommodating and systematizing existing knowledge (theories and data) and predicting new discoveries. As is always the case in science, empirical adequacy was the primary reason for the table's worldwide adoption as the best representation of what is known about the elements, atoms and their structure. But there were also other reasons for its positive reception in different countries.

Finally, we hope to have shown that it is the dual nature of the table – its capacity to enclose the totality of chemical and physical knowledge about the elements, and its usefulness as a research and teaching tool – that give it iconicity. And such iconicity is revealed by the table's appeal in domains outside of chemistry, such as the arts. By quickly surveying such domains, it shall be clear that the table's role as a main vehicle of scientific communication to the broad general public remains unchanged.

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