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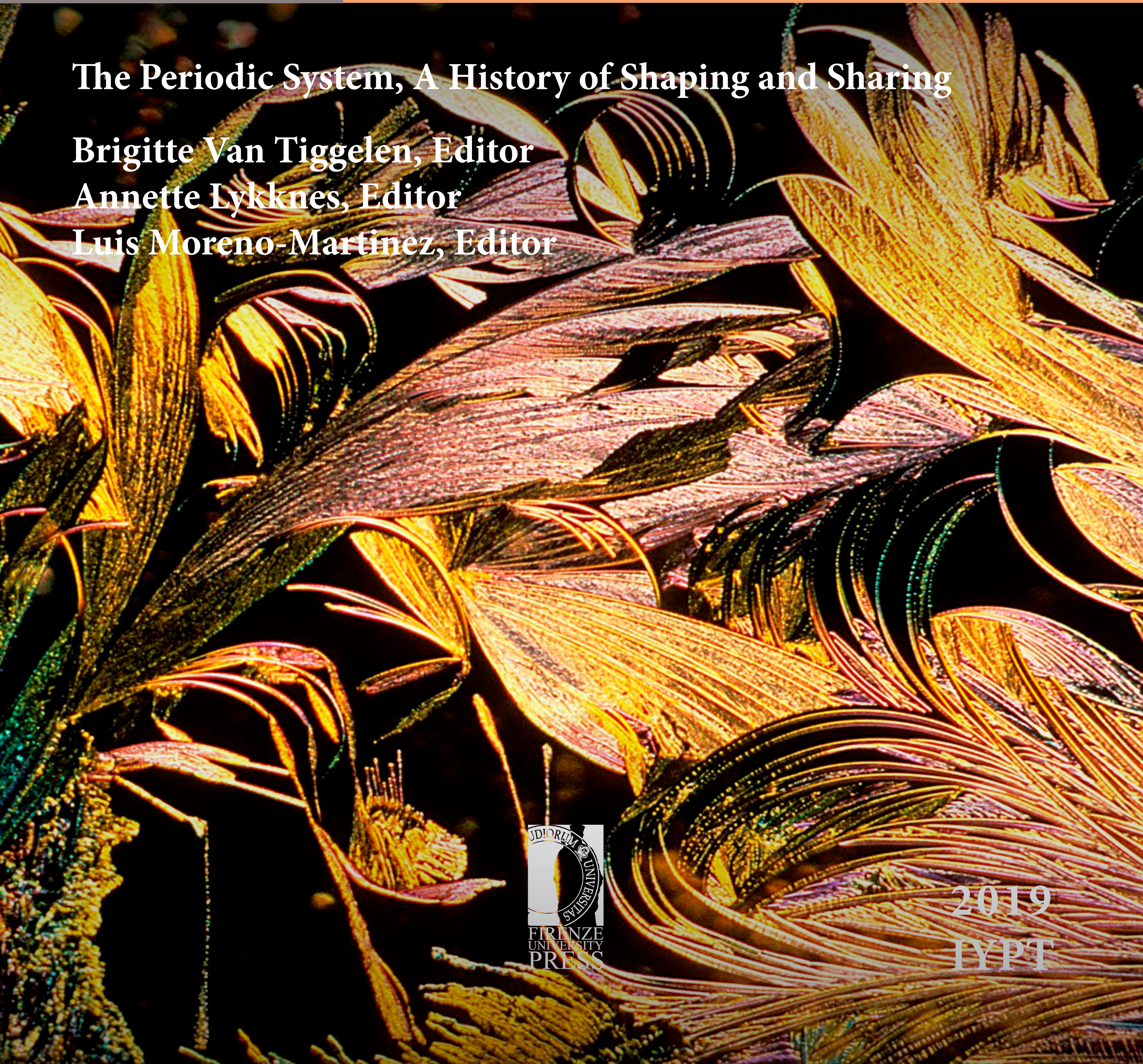

The Periodic System, A History of Shaping and Sharing

Brigitte Van Tiggelen, Editor
Annette Lykknes, Editor
Luis Moreno-Martinez, Editor

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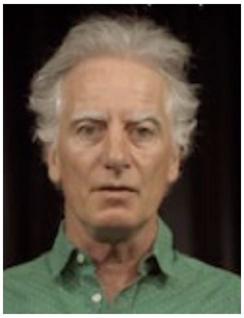

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Preface

It is a great honour for me to write these few lines of preface to the special issues of *Substantia* dedicated to the 150th anniversary of the Periodic Table by Dmitrij Mendeleev. In 2019 there are other important anniversaries besides that of the periodic table. One of these is the centenary of Primo Levi's birth. I believe these two anniversaries are strictly related, in fact *The Periodic Table* by Levi has been considered by the *Royal Institution of Great Britain* as the "best book of science ever written". It would be sufficient to recall an impressive excerpt from "Iron", a tale of the *The Periodic Table*, to acknowledge the uniqueness of this literary work:

> "*We began studying physics together, and Sandro was surprised when I tried to explain to him some of the ideas that at that time I was confusedly cultivating. That the nobility of Man, acquired in a hundred centuries of trial and error, 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 understand the universe and ourselves: and that therefore Mendeleev's Periodic Table [...] was poetry ...*".

When we designed the project related to these special issues, we had in mind Levi's work and in particular his wonderful tales that belong to *The Periodic Table*. I like to recall this homage to a chemist-writer-witness to introduce the six topics that are associated to the special volumes of *Substantia*.

As President of the University of Florence which is the owner of the publisher *Firenze University Press*, I am truly grateful to the Editors – Marc Henry, Vincenzo Balzani, Seth Rasmussen, Luigi Campanella, Mary Virginia Orna with Marco Fontani, and Brigitte Van Tiggelen with Annette Lykknes and Luis Moreno-Martinez – for accepting the invitation made by the Editor-in-Chief Pierandrea Lo Nostro and for the extraordinary work for the preparation of these special issues. Of course the choice of the six subjects was not accidental: we tried to identify some features of the chemistry realm, related for several reasons to the periodic table. They are strikingly associated to the great challenges for our future: these are water, sustainability, energy, open chemistry, the history and the educational perspectives of the periodic table.

During its long path of progress and civilisation mankind has strongly modified nature to make our planet more comfortable, but at present we must be very careful with some dramatic changes that are occurring in our Earth. Science and technology, and chemistry primarily, can help mankind to solve most of the environmental and energy problems that emerge, to build a radically different approach from that that has prevailed in the last two centuries. It is a fantastic challenge, since for the first time we can consider nature not as a system to simply exploit, but a perfect ally for improving life conditions in the whole planet. Chemistry has already engaged and won a similar challenge when, understanding the pollution problems generated by a chaotic and rapid development, succeeded in setting up a new branch, green chemistry, that turned upside down several research topics. Now is the time to develop sustainable chemistry: the occurring events demand that chemists propose new routes and innovative approaches. In the last two centuries we have transformed immense amounts of matter from nature into waste without thinking that we were using non renewable energy sources. We have been acting as our natural resources were unlimited, but knowing that they are instead limited. Now we are realizing that it is not possible to continue along this road. Our planet and our atmosphere are made of finite materials and their consumption during the last two centuries has been impressive. Some elements that are crucial for current and future industrial countries are known to be present on Earth crust in very small amounts and their recycling from waste cannot be a choice anymore, but it is rather an obligation.

Climate is another big problem associated to the terrific changes occurring in some equilibria, both as a consequence of the violent industrial development and energy consumption. We need, and we will always need more and more, an immense amount of energy. The only solution to secure wellness to future generations is the conversion to renewable energy sources. In this view, food and water, due to the strong increment in the demographic indices, could become the true emergencies for billions of individuals. Looking at the picture I tried to draw in this short preface it becomes more clear why we selected those topics for our special issues.

I am optimistic, and I have the strong confidence that chemistry, that studies matter and its transformations, will give mankind the picklock to overcome those challenges.

We will definitely need insightful minds, creativity, knowledge and wisdom.

Luigi Dei
President of the University of Florence

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Editorial

The Periodic System, a History of Shaping and Sharing

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By now, everyone knows that 2019 has been dedicated to the International Year of the Periodic Table of the chemical elements (IYPT) by UNESCO. At the very least, this is true for the chemical community and science teachers and popularizers at large. On many occasions during this year, historical accounts have been provided by specialists and profane alike. The year 2019 was chosen precisely because it corresponds to the 150th anniversary of the first publication of a classification of the then known elements by Dmitrii Ivanovitch Mendeleev (transcribed from the Russian as Dmítriy Ivánovich Mendeléyev), a classification he ended up calling a periodic system when publishing it. He devised the system while he was working on a textbook of chemistry – the famous *Principles of Chemistry* (two volumes, 1868–1870) –, but immediately recognized the importance of what he had just sketched and published a separate one-sheet comprising the first "periodic table" with the title *An Attempt at a system of elements based on their atomic weights and chemical similarities* on March 6, 1869 (or 17 February in the Julian calendar as written on the sheet).[1]

Two features of what we have just outlined call for our attention. First, Mendeleev spoke and wrote about a periodic system (and later a periodic law) and not about a periodic *table*. Indeed Mendeleev's system is often referred to as a *classification* of the elements, and in many cases the periodic system was indeed first received as a classification by many of Mendeleev's contemporaries and successors. This is however not how Mendeleev viewed it. Second, the system emerged in a teaching context, even though Mendeleev published it separately from his textbook and continued publishing on it as

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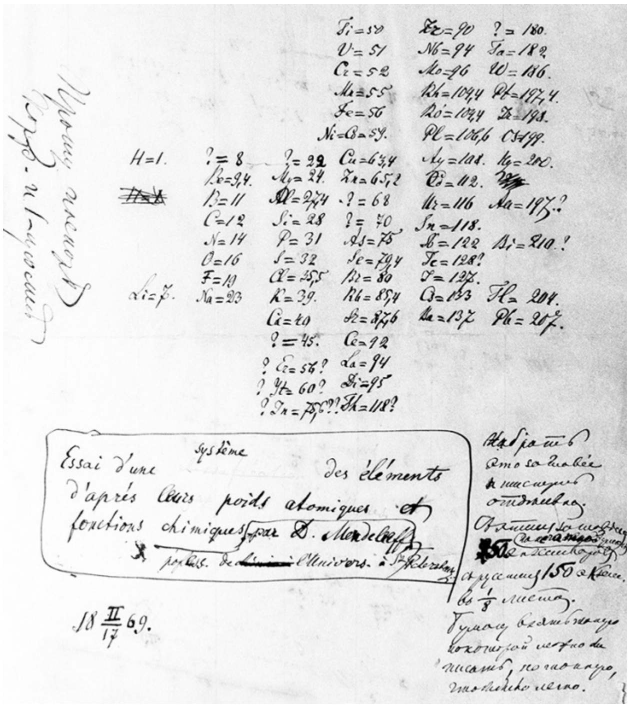
[1] Mendeleev rushed the publication of that separate sheet all the while he asked his colleague Nikolai Alexandrovich Menshutkin to read his paper to the Russian Chemical Society on 18 March 1869 (6 March Julian calendar). It was published as a few months after as "Sootnoshenie svoistv s atom s atomnym vesom elementov" ("The relations between the properties of the elements and their atomic weights"). Zhurnal Russkogo Khmicheskogo Obshchestva (Journal of the Russian Chemical Society). 1 (1869) 2/360-77.



Essai d'une système des éléments
d'après leurs poids atomiques et
fonctions chimiques par D. Mendeleeff

18 II/17 69.

Figure. 1. The hand-written copy of the "Attempt" that would be published under the title "Attempt at a system of elements based on their atomic weights and chemical similarity" in both Russian and French, and kept at the Mendeleev Museum and Archives, Saint Petersburg State University, Saint Petersburg, Russia.

a research topic in itself, in parallel with the successive editions of his Principles of Chemistry.[2] To this day, the pedagogical use of the periodic system is still preeminent, as it is hard to imagine a lecture hall or a textbook in chemistry (or science) that would not feature a representation of the periodic system.

Let us first deal with the issue of nomenclature. This special issue uses the periodic *system* rather than *table*, which is a deliberate choice. There are thousands of periodic tables, according to Mark Leach who keeps a comprehensive database of periodic tables. His website provides a large variety of representations of the periodic system, most of them in two dimensions.[3] They come in many shapes, inner organizations and colors, and have evolved alongside new understandings of matter and the inner structure of atoms over the course of 150 years. Mendeleev himself designed and published several versions, demonstrating that what lied at the core of his thought was not the periodic *table*, even though it was presented in that form, but a *system* from which he inferred his periodic *law*. This is very clear from the title of his March 1869 publication mentioned and illustrated above. He perceived it as a natural law, which could be used to deduce the existence of elements and foresee their properties, not just describe existing knowledge. His trust in this law was such that it enabled him to predict correctly three elements that were discovered within less than 20 years of his initial statement. But his conviction also led him to failed predictions and errors of appreciation in the wake of new discoveries such as the noble gases or the phenomenon of radioactivity. To Mendeleev, if the system derived from the periodic law did not have space for an element, then this element could simply not exist. This is how he reacted when the news about the discovery of argon was announced before accepting a whole new group, the noble gases.[4]

While the distinction between table, system, classification or law might seem more of theoretical interest than anything else, these different conceptions of periodicity in relation to classifying chemical elements will be discussed in some of the contributions to this issue. That such distinctions are relevant and important will be demonstrated in the contributions dedicated to the response to the periodic system. Indeed, the appropriation process of the iconic tool that the periodic system is for chemistry, and its different shapes since its initial publication, do explicitly refer to a spectrum of conceptual objects, ranging from a mere classification to a system to a law of nature, including tables and charts that adorn textbooks or classrooms. Depending on which object is used or referred to, the reception is different and belongs to a different context of use.

This leads us to the second point. As mentioned earlier the teaching context was crucial from the start. It is within the context of teaching that the system emerged as a new tool, and it is also in this context that the appropriation process really took place. For a long time, historical accounts of the development of this seminal idea and the scientific icon have been limited to the traditional succession of chapters devoted to the questions of forerunners, co-discoverers (including the delicate question of priority), successful predictions, rearrangements according to atomic numbers instead of the atomic weights, and alongside atomic, subatomic and quantum interpretations. The discovery of new elements is often discussed as well, as is the question of the bounda-

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[2] Van Spronsen, J. W. (1969). The Periodic System of Chemical Elements: A History of the First Hundred Years (Elsevier, Amsterdam, London and New York, NY; Scerri, E. R. (2007). The Periodic Table: Its Story and its Significance (Oxford University Press, Oxford) and Gordin, M. D. (2004). A Well-Ordered Thing: Dmitrii Mendeleev and the Shadow of the Periodic Table (Basic Books, New York, NY).

[3] https://www.meta-synthesis.com/webbook/35_pt/pt_database.php?Button=All

[4] See for instance: Giunta, C. (2001). Argon and the Periodic System: the Piece that would not fit. Foundations of Chemistry. 3. 105-128.

ries between chemistry and physics. For instance, both Van Spronsen and Scerri mentioned above use that organisation in their table of contents. Such traditional narratives, consciously or not, stress Mendeleev's genius, as if he were a prophet, able to devise a classification/system while atoms were still not accepted entities for chemists. As a result, the success of the periodic system often appears as a natural consequence of it being "correct".

When taking a closer look though, it appears that in many countries and institutions, periodic tables appeared rather late – which is hard to grasp given the position the system holds in today's chemistry. The question of "being correct" has a different meaning in teaching; teachers adopt what is helpful and efficient. Thus explaining the dissemination of the periodic system/table/classification in chemical education is crucial to understand its success and how it has become the icon we all recognize today.

A few years ago, a collective work edited by Masanori Kaji, Helge Kragh and Gabor Pallo was devoted to the first responses to the periodic system demonstrating the diversity of appropriation processes across the world, by offering case studies for several countries, some of which had not been studied before.[5] This built on a contribution by Stephen Brush which was influential even though limited to the mention of the periodic system or the mere inclusion of a table in textbooks, and had already pointed at some delay for the acceptance of Mendeleev's and Meyer's initial ideas.[6]

In this special issue, we have deliberately left aside the questions of priority, the discussion about predictions, and adaptations or rearrangements of the system to focus on *the process of how the periodic system became a shared universal tool for chemistry and science*. We envision this process as dynamic, and active, and we claim that this process was exactly so right from the very beginning when Mendeleev, Meyer and others published and discussed the periodic system and the periodic law. In fact, the periodic system published by Mendeleev in March 1869 is *not* the one we use today, as it was shaped in the following ten years by a succession of additions, changes and improvements that were the result of ongoing discussions with the community and constant interactions with teaching practice, as much as the outcome of a few men's solitary train of thoughts. The process continued all over the last 150 years. In the same way, when the periodic system eventually was adopted as a teaching device, this came most of the time as a result of a process of appropriation during which teachers, chemists and students shaped their own understanding and sometimes invented their own version. This is precisely why there are (and will be) so many periodic tables around: for a concept to become universal it has to be plastic enough to accommodate personal appropriation. Interestingly history becomes a part of how this tool is incorporated and legitimized in the textbooks and teaching practice. Even in science texts that leave very little place to the historical development of the chemical sciences, the discovery of the periodic system (or, quite often the periodic *table*) is mentioned as well as its discoverer(s). In a weird way this mention often smoothens or ignores the appropriation process, in a manner that negates the historical evidence and defaces the nature of science.

The history of shaping and sharing of the periodic system is approached in this special issue in three acts.

The first three contributions illustrate how the periodic system emerges and is shaped through the context of teaching chemistry. The contribution "Julius Lothar (von) Meyer (1830-1895) and the Periodic System" by Gisela Boeck provides insight into the development of Lothar Meyer's thought on a periodic system of the elements while he was devising the successive editions of his chemistry textbook from 1864 onwards. The wide variety of responses to the periodic system in Portugal analyzed by Isabel Malaquias and João A. B. P. Oliveira in the "Shaping the Periodic Classification in Portugal through (text)books and charts" provides a good example of how reception is linked to the different contexts of use. "The St Andrews Periodic Table Wallchart and its Use in Teaching" by Alan Aitken and M. Pilar Gil shows how a precious wall chart acquired in 1888 was used, getting us one step closer to the fine grain process of appropriation of the periodic system which is often hard to track.

The following two contributions analyze the way the history of the periodic system is presented in textbooks and how this kind of history shapes not only the central place of the periodic system in the teaching but also conveys something about the way chemistry developed. In "The Periodic System and the Nature of Science: The History of the Periodic System in Spanish and Norwegian Secondary School Textbooks", Luis Moreno Martinez and Annette Lykknes underline how the brief historical presentation of the periodic system in many textbooks affects the underlying teaching of the nature of chemistry and its history. Gebrekidan Mebrahtu Tesfamariam and Mengesha Ayene make the same assessment for Ethiopian chemistry textbooks for the sec-

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[5] Kaji, M., Kragh, H. and Palló, G., eds. (2015). Early Responses to the Periodic System (Oxford University Press, Oxford).

[6] Brush, S. (1996). The reception of Mendeleev's periodic law in America and Britain. Isis, 87(4). 595–628.

ondary schools as they pose the question "Are History Aspects Related to the Periodic Table Considered in Ethiopian Secondary School Chemistry Textbooks?".

The periodic system is alive and well, and its versatility and continuing evolution represents a challenge to the present and future sharing of this universal tool of chemistry, a challenge which lies at the core of the last three contributions. The attempts and so far limited success at standardization by the International Union of Pure and Applied Chemistry are described in "Order From Confusion: International Chemical Standardization and the Elements, 1947-1990" by Ann Robinson. This variety has its advantages. For instance, Alfio Zambon shows in his contribution "Periodicity Trees as a Secondary Criterion of Periodic Classification: Its Implications for Science Teaching and Communication" how a specific design, the periodicity tree he has devised, opens the way to a more chemical approach to the teaching of the periodic system. Along the same line, in "Compounds Bring Back Chemistry to the System of Chemical Elements", Guillermo Restrepo reconstructs the 1869 system on the basis of computer analysis of chemical knowledge, and the use of contemporary databases yield other systems or groupings of elements classification according to their similarities. These provide a less physically laden approach to the periodic system that is nowadays usually explained in quantum mechanical, or even relativistic terms, ignoring the chemistry behind the making of the periodic system 150 years ago.

The result of a history of shaping and sharing, the periodic system will continue to evolve and its plasticity will no doubt continue to serve as one of its core values. As Professor Emeritus Pekka Pyykkö (University of Helsinki) expressed it during several talks along the IYPT: "It is a human right to make your own Periodic Table. Don't let anyone take that right from you".[7]

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[7] These views were expressed a.o. during P. Pyykkö's Lecture at the Mendeleev-150 conference in Saint Petersburg, Russia, and confirmed to the authors through a private communication, October 14, 2019.

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Julius Lothar (von) Meyer (1830-1895) and the Periodic System

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Abstract. The logo of the "International Year of the Periodic Table of Chemical Elements" (IYPT) shows only Dmitri I. Mendeleev (1834-1907) and none of the other scholars who were closely related with the discovery of the classification of elements. As early as 1864 the German physical chemist Lothar Meyer used a table to explain the "peculiar regularities" that were found among the atomic weights; by the end of that decade he had considered more elements and improved the system. Among other discoverers of the periodicity, Meyer and his colleague Karl Seubert (1851-1942) determined and recalculated atomic weights. This essay depicts the biography of Lothar Meyer and evaluates his contributions to the development of a classification system for chemical elements in several steps, to the periodic arrangement of elements. Finally, Meyer's opinion of the use of the periodic tables in teaching and organizing the material in courses on inorganic chemistry is presented.

Keywords. Julius Lothar (von) Meyer, systems of elements, periodic table, use in teaching process

INTRODUCTION

It was 150 years ago – on 17 February 1869 (Julian calendar) or 1 March 1869 (Gregorian calendar) – that Dmitri Ivanovič Mendeleev (1834-1907) arranged a two-dimensional grid of the elements. For this reason, the United Nations General Assembly and UNESCO proclaimed 2019 as the "International Year of the Periodic Table of Chemical Elements" (IYPT). The IYPT logo shows Mendeleev's portrait. But in the 1860s there were also other scholars who were thinking about a classification of elements. Among these Meyer stands out as the most known contender to Mendeleev. His endeavor was actually also in connection with writing a textbook like Mendeleev. This paper is dedicated to the contributions of Meyer to the periodic system. It presents his biography as well as his work in connection with the classification of elements, before providing a brief analysis of Meyer's train of thought on periodicity and the role the periodic system can play in chemistry teaching. Through this example, we aim to illustrate that while it does not diminish Mendeleev's accomplishments, it does frame these accomplishments in a wider historical context where many similar pursuits were undertaken by the fellow chemists of his time.[1]

LOTHAR MEYER – HIS BIOGRAPHY

Julius Lothar Meyer (Fig. 1) was born in Varel, Germany on 19 August 1830, in the current district of Friesland in Lower Saxony.[2] The *gymnasium* in Varel bears his name today. Lothar's father, Heinrich Friedrich August Jacob Meyer (1783-1850), was a physician. He and his wife, Anna Sophie Wilhelmine Biermann (1800-1853), had at least eight children, most of whom died young. Only three of Lothar's siblings reached adulthood, Oskar August Emil Meyer (1834-1909), who became a professor of physics in Breslau and was well-known for his work on viscosity, Eugen Theodor Meyer (1836-1890), who became a farmer, and Selma Corinna Helmine Meyer (1839-1928).

Initially, Lothar was tutored at home. From 1841 until his confirmation he attended a citizens school (*Höhere Bürgerschule*), but his school education was interrupted due to poor health, particularly strong headaches. Lothar Meyer worked in a gardening nursery, regained his health, and from 1847 he was able to continue his education at the *Old Gymnasium* in Oldenburg. In 1851 he passed his school leaving examination, the *Abitur*. He decided to study medicine and to become a physician like his father, who had died in the meantime.

On 8 May 1851, Lothar Meyer enrolled at the University of Zurich, where he attended lectures in medical subjects, but also in chemistry, physics, mineralogy, geology, botany and zoology, until the end of the winter term 1852/53. He was especially interested in Carl Ludwig's (1816-1895) instruction in physiology – perhaps this led to his interest in gas exchange of the blood?

Around Easter 1853 Meyer traveled to Würzburg, and in February 1854 he completed his Doctor of Medicine with a thesis paper on the pigment cells of frogs. A year later he moved to Heidelberg to work with the famous Robert Bunsen (1811-1899). Although he was enrolled for medicine, he was more interested in chemistry. He investigated the behavior of gases in the blood, trying to determine how much oxygen, nitrogen, and carbon dioxide are in arterial blood and to establish regularities for the gas exchange. These results were summarized in the paper *The gases of the blood* in 1857, which he submitted to the faculty of medicine as a second doctoral thesis.[3] It is unclear as to why he felt the need to complete a second dissertation, following his medical degree. Even though his first paper on the frog offered poor results, there is no evidence that the faculty granted his degree coupled with an obligation for a second paper. It is also not possible to examine the archived documents in Würzburg, as most were destroyed during World War II.[4] It is possible that Meyer felt obliged to do this because he was aware of the poor reception of his first paper.

Figure 1. Lothar Meyer. Scan from K. Seubert, *Ber. Dtsch. Chem. Ges.* **1896**, *28*, 1109–1146, here p. 1110.

Later, in Heidelberg, Lothar Meyer met other scientists, including Friedrich Beilstein (1838-1906), Henry Roscoe (1833-1915), Hans Landolt (1831-1910) and August Kekulé (1829-1896). Meyer remembered that Kekulé presented the type-theory of Charles Gerhardt (1816-1856) and Alexander Williamson (1824-1904) to the other young chemists, even though Bunsen was not interested in these new ideas.[5]

Lothar Meyer went to Königsberg (today Kaliningrad in Russia) with his brother, Oskar August Emil, and Landolt in the winter term 1856/57 to expand his knowledge of physics. This exposed him to the lectures of Franz Ernst Neumann (1798-1895) about electromagnetism and the wave theory of light. He also continued his physiological research in the laboratory of Gustav Werther (1815-1869), he was interested in the effect of carbon monoxide on blood. These results were published in a paper which was submitted to the Faculty of Philosophy in Breslau to earn the degree Dr. phil. Meyer showed that carbon monoxide is attracted to blood by chemical forces. This means that the blood cannot transport oxygen. He was not able to discover which substance attracts the carbon monoxide. This phase of his education exposed Meyer to analytical and physiological problems; he was educated in mathematical physics and learned about new theories in chemistry. The time in Königsberg was critical for Meyer's turn to physical approaches to chemistry. Franz Ernst Neumann is regarded as the founder of theoretical physics as a university discipline in Germany. He connected the use of precise measuring devices with mathematical approaches and the use of error calculation.[6] These principles were adopted by Meyer.

For his habilitation degree, the qualification as *Privatdozent,* Meyer worked on the development of chemical theories ranging from Claude-Louis Berthollet (1748-1822) to Jöns Jacob Berzelius (1779-1848).

From Easter 1859 onwards, Lothar Meyer supervised the chemical laboratory of the Institute of Physiology at the University of Breslau (today Wrocław in Poland). He gave lectures about plant and animal chemistry, photo chemistry, gas and volumetric analysis, and he offered refresher courses on organic and inorganic chemistry.[7]

In September 1860 the first International conference of Chemistry took place in Karlsruhe. It was organized by Kekulé together with Karl Weltzien (1813-1870) and Charles Adolphe Wurtz (1817-1884). The goal was the clarification of the atomistic system: what is an atom, what is a molecule, but also to decide the basis for determining atomic weights. In a sparkling speech Stanislao Cannizzaro (1826-1910) demanded recognition and a consequent application of the theory of Amadeo Avogadro (1776-1856). Cannizzaro also distributed prints of his *Sunto di un corso di filosofia chimica* (Short course of theoretical chemistry).[8]

Meyer and Mendeleev, who also attended the conference, were struck by this proposal that opened new perspectives. And Meyer – trained both in organic and physical chemistry – started to work on molecular theory. He wrote a paper on chemical statics which he first wanted to publish in *Poggendorff´s Annalen der Physik*.[9] He mentioned his intention to publish it in letters to Kekulé und Hermann Kolbe (1818-1884),[10] but it seems that he later used this material for his textbook, *Die modernen Theorien der Chemie und ihre Bedeutung für die chemische Statik* (Modern theories of chemistry and its importance for the chemical statics). In the foreword to the second edition, written in August 1872, Lothar Meyer says that he had started with the manuscript ten years earlier.[11] A letter addressed to his brother corroborates this timing.[12] The book was finally published in July 1864; the second edition was issued in 1872, the following editions in 1876, 1883, and 1884. The book became more and more comprehensive, the fifth edition reaching 626 pages.

There was no chance for Meyer to pursue an academic career in Breslau, so he took a position at the forest academy in Neustadt-Eberswalde, where he had many teaching tasks in the fields of mineralogy, chemistry, physics, and sometimes even botany. This left him little time for scientific work. At first he had to establish a "considerably cute laboratory from miserable cottage".[13] And he complained that he could not find research students, the students of the forest academy were only interested in finishing the chemistry classes.[14] So this position posed not only issues of time – he did not have his own students to work with. In 1867 he was appointed to be professor of inorganic science at the forest academy, but in 1868 he left the academy and became a professor of chemistry and the director of the chemical laboratory at the Polytechnikum in Karlsruhe. There he found better working conditions, teaching only chemistry, and he had his own students for scientific work.

From 1868 to 1875 Meyer worked in Karlsruhe; he turned a professorship in Königsberg down. But his health problems had surfaced again. During the winter term 1874/75 he was released from his teaching duties, which were then assigned to August Michaelis (1847-1916).

1876, Lothar Meyer received a full professorship in Tübingen as the successor of Rudolph Fittig (1835-1910). His financial situation improved, but the most important benefit was that he had finally become a full university professor, as the polytechnic institutions had no rights to award doctorates. Meyer was offered a considerably well-equipped laboratory in Tübingen's Wilhelmstraße 9 (part of which is still there). Meyer and his family lived on the upper floor and he refurbished some of the laboratory rooms for his research interests, improving the technical equipment.[15] In Tübingen Meyer worked together with his colleague Karl Seubert on the redetermination of atomic weights. The results were published in a book in 1883. Later Seubert was the first biographer to write about Meyer and was responsible for publishing or republishing his most important papers.[16]

Meyer's good working and research conditions in Tübingen, his integration in the social life of this town and his state of health were reasons for turning down professorships in Leipzig (1887) and Breslau (1889). He received several awards, including the Davy medal given to him and Mendeleev on 2 November 1882, recognizing their research on the classification of elements. In

1883 Lothar Meyer became an honorary member of the Chemical Society London; in 1887 he joined the Physikalischer Verein (Physical society) in Frankfurt/Main; in 1889 the Manchester Literary and Philosophical Society. A year prior to this, in 1888, Meyer had been appointed corresponding member of the Mathematics and Physics section of the Prussian Academy of Science and in 1891 of the Academy of Science St. Petersburg. In 1892 Lothar Meyer was knighted with the decoration of the Honorable Cross of the Royal House of Württemberg.

At the start of the 1894/95 academic year, Lothar von Meyer was elected rector of the University Tübingen: shortly after the term, on 11 April 1895, he died. His grave is in the *Stadtfriedhof* cemetery in Tübingen.

LOTHAR MEYER AND THE CLASSIFICATION OF ELEMENTS

Lothar Meyer left his mark on multiple fields of chemistry, but this paper discusses only his activities in connection with the classification of chemical elements.

The question of classification systems in chemistry came about as a consequence of the large amount of new knowledge about chemical compounds and elements at the turn from the 18th to the 19th century – especially in connection with the revival of atomic theory and the possibility to determine relative atomic weights, but also with the discovery of many new elements. The atomic weights opened the path to a classification based not only on qualitative properties but also on quantitative data.[17] This was connected with attempts for a deeper understanding of the nature of elements and atoms and it was one of the scientific interests of Meyer after his turn from physiological to problems of theoretical chemistry. Meyer also wanted to show the interrelation between hypothesis and theories based on them.[18]

Lothar Meyer's considerations about the nature of the elements were connected inter alia with ideas of William Prout (1785-1850) and Johann Wolfgang Döbereiner (1780-1849).

Early in the century, the physician Prout had observed that atomic weights are whole multiples of the atomic weight of hydrogen, and later proposed that hydrogen should be the primeval matter (greek: prote hyle). The experimental possibilities for determining atomic weights had since then been improved, in consequence, it could be demonstrated already before 1850 that most atomic weights are not integers. But despite the issues with Prout's hypothesis, many scholars continued to debate these ideas throughout the 19th century and beyond. For instance, it has been suggested that Ernest Rutherford (1871-1937) introduced the term proton in 1920 not only for etymological reasons (greek *proton* = the first), but also in commemoration of William Prout.[19] As Meyer mentions in the first paragraph of *Moderne Theorien*[20], he thought that matter consists of discrete particles, the atoms. He posited that it is unclear if these are really indivisible. Later Meyer followed the idea that atoms consist of smaller aggregates.

Meyer was also influenced by the theory of *triads*, as first described in 1816[21] by Johann Wolfgang Döbereiner, professor of chemistry in Jena and well-known for his pneumatic gas lighter, the *Döbereiner Feuerzeug*. He also tried to classify around 30 elements based on their chemical analogy, such as Ca, Ba, Sr, or Cl, Br, I, or Li, Na, K in the alkali group. He compared their atomic weights and found that the atomic weights of the middle elements of each of the series of three elements were roughly the mean value of the other two. These groups of three elements were later called *triads*.[22] In his 4th edition of 1883, Meyer established that Döbereiner's work was propagated by Leopold Gmelin in his *Handbuch der Chemie*.[23] Meyer was curious about these numerical relations and in his book *Moderne Theorien* he discusses "the peculiar regularities"[24] that were found between atomic weights by Döbereiner and later by many other scholars. Meyer used the notion of there being an arithmetic relationship between atomic weights. He suspected that these relationships were responsible for the idea that atoms are an aggregate of smaller units. This explanation was adopted from the homologous series in organic chemistry, which are characterized by the repeated addition of constant fragments.

In the first edition of *Moderne Theorien* Meyer arranged fifty elements into three tables with the aim to underline the mathematical relations between the atomic weights. The first included twenty-eight elements, which were grouped consequently with respect to their increasing atomic weights and valency. He described the relations as "six well-characterized groups of elements"[25] (Fig. 2).

Meyer combined elements with the same valency and similar chemical properties. The atomic weight of the elements increases in each row from left to the right. A regular change of valency can be established – but Meyer did not use the word periodicity in his text. The table also includes the differences of atomic weights of elements which were paired in the column. Meyer underlined the regularity for the differences in the atomic weights. In the first rows one finds as difference nearly 16, later nearly 46 and then 87-90 which is more or less the double value of 46.[26] The integration of these numerical values demonstrates again Meyer's interest in finding a similarity to the homologous series. And it is

	Valency 4		Valency 3		Valency 2		Valency 1		Valency 1		Valency 2	
		-		-		-		-	Li	= 7,03	(Be	= 9,3?)
difference =		-		-		-		-		16,02		(14,7)
	C	= 12,0	N	= 14,04	O	= 16,00	Fl	= 19,0	Na	= 23,05	Mg	= 24,0
difference =		16,5		16,96		16,07		16,46		16,08		16,0
	Si	= 28,5	P	= 31,0	S	= 32,07	Cl	= 35,46	K	= 39,13	Ca	= 40,0
difference =	89,1/2	= 44,55		44,0		46,7		44,51		46,3		47,6
	-		As	= 75,0	Se	= 78,8	Br	= 79,97	Rb	= 85,4	Sr	= 87,6
difference =	89,1/2	= 44,55		45,6		49,5		46,8		47,6		49,5
	Sn	= 117,6	Sb	= 120,6	Te	= 128,3	J	= 126,8	Cs	= 133,0	Ba	= 137,1
difference =	89,4	= 2 · 44,7	87,4	= 2 · 43,7		-		-	(71	= 2 · 35,5)		-
	Pb	= 207,0	Bi	= 208,0		-		-	(Tl	= 204 ?)		-

Figure 2. Meyer's table of "well-characterized groups of elements". Adapted from L. Meyer, *Die modernen Theorien der Chemie und ihre Bedeutung für die chemische Statik,* Maruschke & Berendt, Breslau, **1864**, p. 137.

noteworthy that Meyer uses values with one or two decimal points.

It should be mentioned that the increase of atomic weight from row to row has two exceptions. Although one can clearly see that tellurium has a higher atomic weight than iodine, Meyer arranged Te prior to I, which corresponds with the valency. The second exception in the order of increasing atomic weights is thallium which Meyer placed after Bi in the group of the alkaline metals with valency one. He mentioned that the difference of the atomic weights between Ca and Tl differs extremely from 2x46 and assumed a wrong determination in the case of Tl. Question marks in the table indicate Meyer's doubts concerning the correctness of some of these atomic weights.

This table also contains gaps, marked with dashes. One example of such a gap concerns the precautionary prediction of the atomic weight. The element following silicon in the group of elements with valency four should have an atomic weight 44.55 higher than silicon (28.5), namely 73,05. But Meyer did not discuss this prediction like later Mendeleev.

The difference 46 of atomic weights and the valency were also the basis for the two other tables of elements published by Meyer in 1864 (Fig. 3 and 4). Meyer did not give an explanation why he did not place the following 22 elements in one table. We can only see that the first (Fig. 3) belongs to elements with valency four and six, the second (Fig. 4) to valency two, four and mixed. Later Meyer explained that he contemplated combining all tables in one but he was concerned with the uncertainties and potential mistakes in atomic weights.[27]

In Fig. 4 Meyer placed Mn and Fe on the same spot because of the similarity of the atomic weights. In the consequence he formulated two differences – the difference in the atomic weights Ru-Mn, and Ru-Fe.

	Valency 4		Valency 6	
	Ti	= 48	Mo	= 92
difference =		42		45
	Zr	= 90	Vd	= 137
difference =		47,6		47
	Ta	= 137,6	W	= 184

Figure 3. Groups of six elements with the difference of nearly 46 of atomic weights and the valency four and six. Adapted from L. Meyer, *Die modernen Theorien der Chemie und ihre Bedeutung für die chemische Statik,* Maruschke & Berendt, Breslau, **1864**, p. 138.

Today, the elements of the table in Fig. 2 are known as the main group of elements, those of the tables in Fig. 3 and 4 are the transition elements. Meyer finished his explanations by asserting that there is no doubt about a certain law (*bestimmte Gesetzmäßigkeit*) in the numerical values of the atomic weights. He reasoned that discrepancies are linked with incorrectness of atomic weights. He wrote:

> *We can assume that some of the discrepancies result to some extent from the incorrect determination of atomic weights. But this is not valid for all. It is not fair – as is done often – to correct or to change the empirically estimated atomic weights until the experiment has delivered more exactly determined values.*[28]

By 1866 at the latest, Meyer had started to examine the atomic weights with the claim of more correctness. When he arrived in Karlsruhe to take his teaching duties, he had no time for this task; it was only in Tübingen where he could continue this research program, together with Seubert.

During his time in Eberswalde, Meyer was already working on the second edition of *Moderne Theorien*. It

	Valency 4		Valency 4		Valency 4		Valency 2			
	Mn	= 55,1	Ni	= 58,7	Co	= 58,7	Zn	= 65,0	Cu	= 63,5
	Fe	= 56,0								
difference =		49,2 48,3		45,6		47,3		46,9		44,4
	Ru	= 104,3	Rh	= 104,3	Pd	= 106,0	Cd	= 111,9	Ag	= 107,94
difference =	92,8	= 2·46,4	92,8	= 2·46,4	93,0	= 2·46,5	88,3	= 2·44,2	88,8	= 2·44,4
	Pt	= 197,1	I (Ir)	= 197,1	Os	= 199,0	Hg	= 200,2	Au	= 196,7

Figure 4. Groups of six elements with the difference of nearly 46 of atomic weights and the valency two, four and mixed. Adapted from L. Meyer, *Die modernen Theorien der Chemie und ihre Bedeutung für die chemische Statik,* Maruschke & Berendt, Breslau, **1864**, p. 138.

may be assumed that it is to this aim that he drafted a new, more extensive table with 52 elements in 1868. But this system was not published in a timely manner. It was not until 1895 that Seubert published it on two pages along with several important papers about the historical development of the periodic system.[29]

We assume it was Seubert who used not one, but two pages to print the table in a better, readable format (see Fig. 5). He explained that it is necessary to combine the two pages in such a manner that C and N, P and Si, Sb and Sn, Bi and Pb became neighbors.[30] Only under this condition Meyer‘s table would be faithfully reproduced. Otherwise the table was just too long to be printed in a book page.

In this version Meyer also included aluminum and chromium, which had not been presented in 1864. He allotted chromium its own column, but aluminum presented him with problems. Seubert noted that Meyer first placed Al in the fourth column, then moved it to the third column, and finally decided to go with his first decision.[31] It is more astonishing that aluminum does not fit in the order of increasing atomic weights. It would fit better in the third row, prior to Si. But most elements are placed in rows with regularly increasing atomic weight – from left to right and top down. However, if one checks the table carefully one can find some more irregularities concerning the increasing atomic weight. If molybdenum were placed next to zirconium and vanadium next to tantalum there would be less irregularity. It is unclear whether Seubert transferred the data correctly. The original version of the table could not be found. But if one assumes that the new table is a combination of the first three (Fig. 2, 3 and 4), one can see table 2 (Fig. 3) has been moved to columns 14 and 15.[32] In this table Mo followed Ti, Vd followed Zr, and W followed Ta. Thus it is unlikely that Seubert made a mistake.

The new table has 16 columns, the last of which is empty. Hydrogen is not considered. The reason was Meyer‘s belief in a special role of hydrogen comparable to Prout‘s theory. The already accepted elements of boron, indium, niobium, thorium, uranium, and some rare earths metals are also excluded. If we compare these multiple columns with modern representations of the periodic system, we can find some matches concerning the main group of elements (columns 8 to 13 or the first table from 1864). The table in Fig. 5 also displays an empty space for the element following silicon (see in column 8), as it was the case in the first 1864 table (Fig. 2). These constant differences were viewed by Meyer as proof of the complexity of the atoms, as being constituted as aggregates of smaller units, and he used this constancy in the difference to suggest an element after silicon. While Mendeleev went further boldly, also successfully predicting chemical properties for what he called “eka-silicon” (germanium), Meyer stopped short and did not elaborate on his prediction.

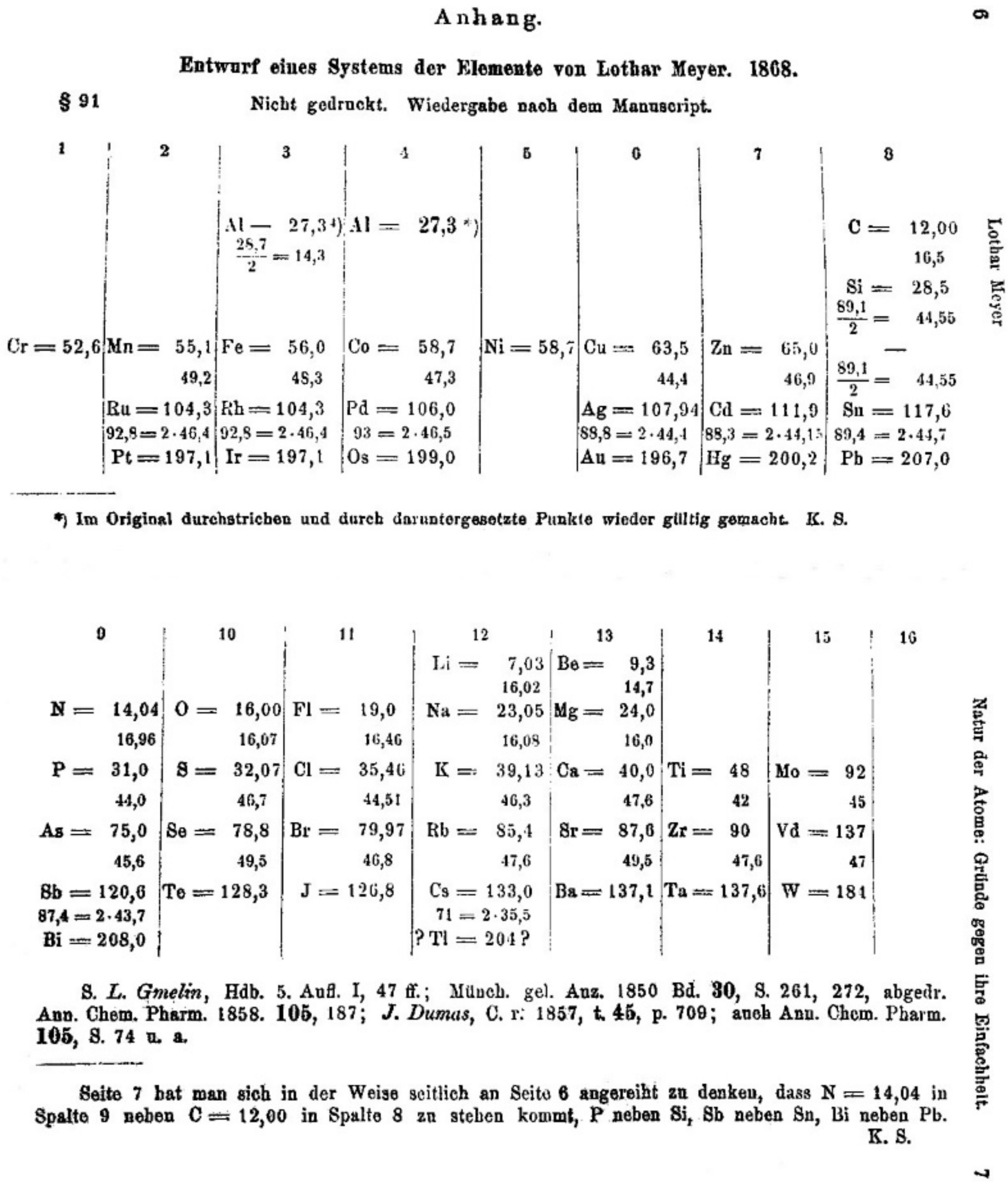
Meyer didn’t keep that draft as he gave the original document to his successor in Eberswalde. This was the mineralogist and geologist Adolf Remelé (1839-1915), who reported indeed that Meyer had left the hand-written draft to him:

> *When I came in July 1868 as his successor for chemistry, physics and mineralogy I got the inventory which belonged to the teaching post. But he also gave me the self-written arrangement of elements by increasing atomic weights which was a more comprehensive and completed scheme of that from 1864 and established that he will publish it soon.*[33]

It is unclear why Remelé did not return this draft to Meyer in the years of the priority dispute, or why Meyer did not ask for it. Remelé showed it to Meyer only in 1893; a copy was most likely sent to Seubert in 1895.[34]

Long before Seubert’s publication of Meyer’s draft in 1895, Meyer finished a paper about the nature of chemical elements as a function of their atomic weights in 1869 and published it in March 1870.[35] It contains a table with 55 elements (Fig. 6). Hydrogen is again not considered with respect to its "exceptional position"[36]. Other elements with uncertainties of their atomic weights were excluded by Meyer. It seems that for Meyer it was very important to use reliable data. In Mendeleev's 1869 paper 63 elements were regarded, uncertainties in the atomic weight were simply marked. In contrast to Mendeleev who published atomic weights as integers or one decimal point at most, Meyer systematically used weights with one or two decimals in his publications.

The table in Fig. 6 portrays how Meyer ordered the elements strictly according to increasing atomic weights, following the first column top down, then repeating this in the second column, etc. He highlighted some uncertainties such as Te and Os with question marks. What is new is that the column does not combine elements with similar properties – these are found in one row. In total there are nine columns and 16 rows (the second row has three dashes). Perhaps Meyer was influenced by Mendeleev's first table and changed the rows and columns? Meyer also mentioned the constant differences of the atomic weights: From column I to column II, and from II to III, etc. Later Meyer changed rows and columns again.



Anhang. 6

Lothar Meyer

Entwurf eines Systems der Elemente von Lothar Meyer. 1868.

§ 91 Nicht gedruckt. Wiedergabe nach dem Manuscript.

1	2	3	4	5	6	7	8
		Al — 27,3*)	Al = 27,3 *)				C = 12,00
		$\frac{28,7}{2}$ = 14,3					16,5
							Si = 28,5
							$\frac{89,1}{2}$ = 44,55
Cr = 52,6	Mn = 55,1	Fe = 56,0	Co = 58,7	Ni = 58,7	Cu = 63,5	Zn = 65,0	—
	49,2	48,3	47,3		44,4	46,9	$\frac{89,1}{2}$ = 44,55
	Ru = 104,3	Rh = 104,3	Pd = 106,0		Ag = 107,94	Cd = 111,9	Sn = 117,6
	92,8 = 2·46,4	92,8 = 2·46,4	93 = 2·46,5		88,8 = 2·44,4	88,3 = 2·44,15	89,4 = 2·44,7
	Pt = 197,1	Ir = 197,1	Os = 199,0		Au = 196,7	Hg = 200,2	Pb = 207,0

---

*) Im Original durchstrichen und durch daruntergesetzte Punkte wieder gültig gemacht. K. S.

Natur der Atome: Gründe gegen ihre Einfachheit.

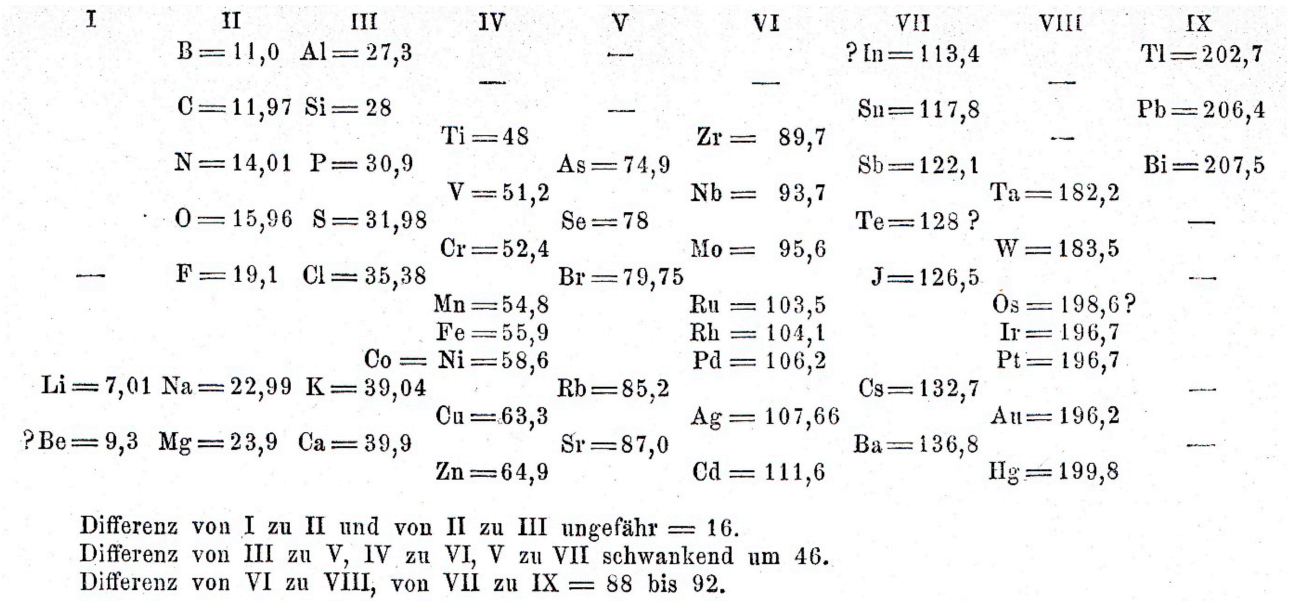
9	10	11	12	13	14	15	16
			Li = 7,03	Be = 9,3			
			16,02	14,7			
N = 14,04	O = 16,00	Fl = 19,0	Na = 23,05	Mg = 24,0			
16,96	16,07	16,46	16,08	16,0			
P = 31,0	S = 32,07	Cl = 35,46	K = 39,13	Ca = 40,0	Ti = 48	Mo = 92	
44,0	46,7	44,51	46,3	47,6	42	45	
As = 75,0	Se = 78,8	Br = 79,97	Rb = 85,4	Sr = 87,6	Zr = 90	Vd = 137	
45,6	49,5	46,8	47,6	49,5	47,6	47	
Sb = 120,6	Te = 128,3	J = 126,8	Cs = 133,0	Ba = 137,1	Ta = 137,6	W = 181	
87,4 = 2·43,7			71 = 2·35,5				
Bi = 208,0			? Tl = 204 ?				

S. *L. Gmelin*, Hdb. 5. Aufl. I, 47 ff.; Münch. gel. Anz. 1850 Bd. **30**, S. 261, 272, abgedr. Ann. Chem. Pharm. 1858. **105**, 187; *J. Dumas*, C. r. 1857, t. **45**, p. 709; auch Ann. Chem. Pharm. **105**, S. 74 u. a.

Seite 7 hat man sich in der Weise seitlich an Seite 6 angereiht zu denken, dass N = 14,04 in Spalte 9 neben C = 12,00 in Spalte 8 zu stehen kommt, P neben Si, Sb neben Sn, Bi neben Pb.
K. S.

7

Figure 5. Meyer's unpublished draft of an elements' system. Scan from K. Seubert, *Das natürliche System der chemischen Elemente,* 2nd edition, Engelmann, Leipzig, **1913**, pp. 6-7.



I	II	III	IV	V	VI	VII	VIII	IX
	B = 11,0	Al = 27,3		—		? In = 113,4		Tl = 202,7
			—		—		—	
	C = 11,97	Si = 28		—		Sn = 117,8		Pb = 206,4
			Ti = 48		Zr = 89,7		—	
	N = 14,01	P = 30,9		As = 74,9		Sb = 122,1		Bi = 207,5
			V = 51,2		Nb = 93,7		Ta = 182,2	
	O = 15,96	S = 31,98		Se = 78		Te = 128 ?		—
			Cr = 52,4		Mo = 95,6		W = 183,5	
—	F = 19,1	Cl = 35,38		Br = 79,75		J = 126,5		—
			Mn = 54,8		Ru = 103,5		Os = 198,6?	
			Fe = 55,9		Rh = 104,1		Ir = 196,7	
		Co =	Ni = 58,6		Pd = 106,2		Pt = 196,7	
Li = 7,01	Na = 22,99	K = 39,04		Rb = 85,2		Cs = 132,7		—
			Cu = 63,3		Ag = 107,66		Au = 196,2	
? Be = 9,3	Mg = 23,9	Ca = 39,9		Sr = 87,0		Ba = 136,8		—
			Zn = 64,9		Cd = 111,6		Hg = 199,8	

Differenz von I zu II und von II zu III ungefähr = 16.
Differenz von III zu V, IV zu VI, V zu VII schwankend um 46.
Differenz von VI zu VIII, von VII zu IX = 88 bis 92.

Figure 6. Meyer's classification of elements from 1870. Scan from K. Seubert, *Das natürliche System der chemischen Elemente.* 2nd edition, Engelmann, Leipzig, **1913,** p.11.

As noted above, this table contains dashes. It seems that these are place holders for those elements with uncertain atomic weights or for elements yet unknown. He wrote:

> *These elements [with uncertain atomic weights G.B.] will later at least partly occupy these gaps which are still in the table. Other gaps will be filled by elements which will be discovered in future; prospective discoveries will possibly move one or the other element from its place and substitute it by another one, which fits better.*[37]

In this 1870 publication, Meyer also used the newly determined atomic weights and for the first time mentioned a periodic function of the atomic weight:

> *The same or similar properties recur when the atomic weight increased for a certain size, at first 16, later 46 and finally 88 to 92 units.*[38]

From 1864 on, Meyer had arranged the elements with respect to chemical properties, such as valency, and thus expressed periodicity but this was implicit. To explain the concept of periodicity more clearly, he used the relation between the atomic volume and the atomic weight. Meyer calculated the atomic volume as the quotient of the atomic weight and the density of the elements in the solid state, except for chlorine for which he used the liquid state. The graphic presentation shows the periodicity clearly – it is actually more striking than the tables (Fig. 7).

Like Mendeleev, Meyer predicted the discovery of new elements but he did not describe any properties. Meyer was impressed by periodicity but explicitly mentioned that it was still not clear what the reasons for the periodic change might be:

> *These and similar regularities cannot be a simple coincidence but we must recognize that the empiric way to the establishment is not the key to the recognition of its internal primary link. But it seems that a starting point is found for the study of the constitution of the hitherto undecomposable atoms, it is a guideline for future examinations of elements.*[39]

In the meantime Mendeleev had published his natural system of elements, copies of which were sent to other chemists in Russia and several other countries. By the end of 1869 the correspondent of the *Berichte der Deutschen Chemischen Gesellschaft* (Reports from the German Chemical Society) Viktor von Richter (1841-1891) had reported on the interesting relationship in the system of elements that Mendeleev had developed.[40] A short review of Mendeleev's system was also published in the *Zeitschrift für Chemie* (Journal of Chemistry) in Germany.[41]

Meyer was acquainted with Mendeleev's paper and wrote in his own 1870 paper that "the hereinafter published table is in the main identical with that of Mendelejeff".[42] Subsequently many readers and also Mendeleev understood this phrase as an admission that Meyer did

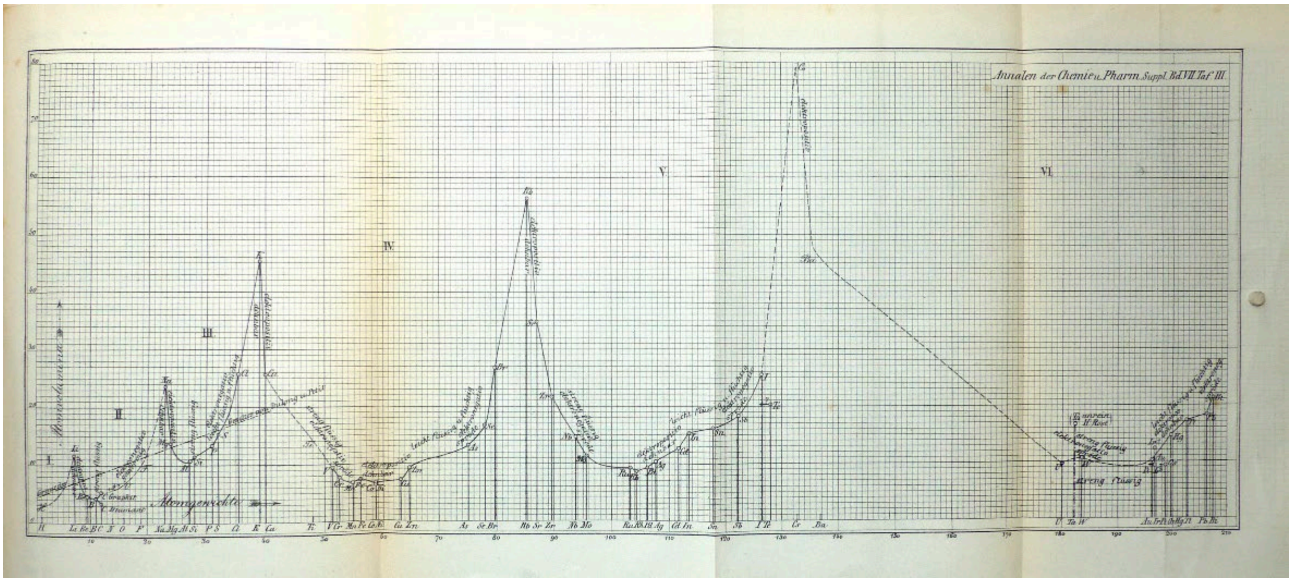


Figure 7. Presentation of the graph which shows the periodic relation between atomic volume and atom weight. Scan from L. Meyer, *Annalen der Chemie und Pharmacie*. VII. Supplementband **1871**, 354-364.

not publish his own ideas, but elaborated on Mendeleev's. Mendeleev answered with two publications in 1871.[43] But subsequently both Meyer and Mendeleev focused mainly on other scientific problems. Meyer did however publish several papers after 1878 on the determination of atomic weights. The priority dispute began again in 1879, but we shall not discuss it further here.[44]

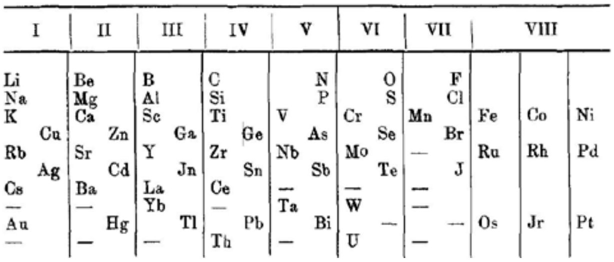
THE PERIODIC SYSTEM AND THE COURSE OF INORGANIC CHEMISTRY

We will now turn to the question of how Lothar Meyer valued the periodic system as a didactic tool. He was interested in questions like the organization of school and university instruction[45], but also in the issue of how to integrate the periodic system into the study of inorganic chemistry. Meyer reported on this topic in Berlin two years before his death; this lecture was published later.[46]

In this paper he used the table type presented in Fig. 8. It shows that Meyer returned to his first ordering: he combined elements with similar chemical properties in one column and not in one row. One can also establish that he separated most of the transition elements from the rest. Meyer introduced this distinction already in the second edition of the *Moderne Theorien*.[47] In that edition one finds also for the first time tables starting with the alkali metals. Meyer explained the reason: those elements display the maximum atomic volume for each row.[48]

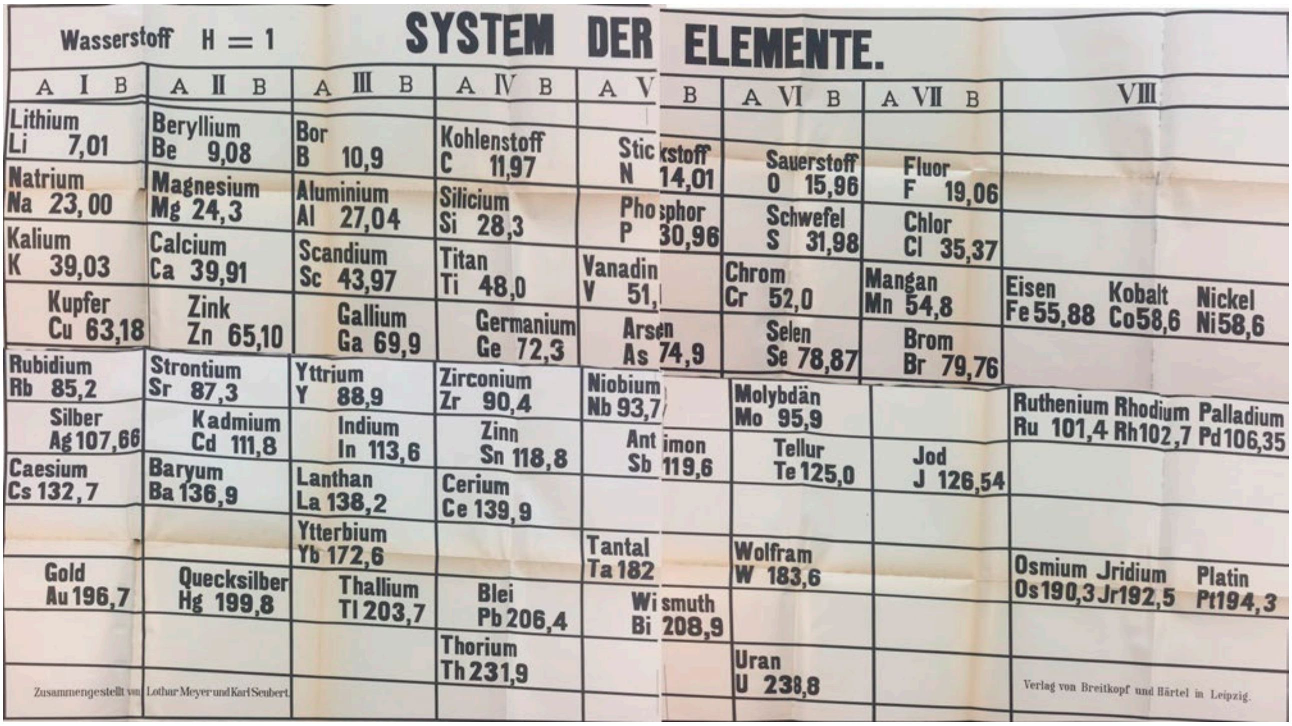
Sometimes Meyer used in his papers presentations of the system which reminds of the spiraled form used by Alexandre-Emile Béguyer de Chancourtois (1819-1886).[49] Such a representation type was also used for a printed chart (Fig. 9).[50]

It can be assumed that this format is similar to the one he used in the lecture hall in Tübingen. Meyer noted that he understood his contribution to the periodic system as a modification of the Döbereiner system and not as a new qualitative step. He called his system neither a new theory nor a new law. He emphasized that the system would be well-suited to giving students an overview. Meyer also pointed out that during the last twenty years this system had only received minimal attention in textbooks, where it received a brief mention or cursory explanation. Only a small number of textbooks used it as a fundamental part of the arrangement for the teach-



I		II		III		IV		V		VI		VII		VIII		
Li		Be		B		C			N		O		F			
Na		Mg		Al		Si			P		S		Cl			
K		Ca		Sc		Ti		V		Cr		Mn		Fe	Co	Ni
	Cu		Zn		Ga		Ge		As		Se		Br			
Rb		Sr		Y		Zr		Nb		Mo		—		Ru	Rh	Pd
	Ag		Cd		Jn		Sn		Sb		Te		J			
Cs		Ba		La		Ce		—		—		—				
—		—		Yb		—		Ta		W		—				
	Au		Hg		Tl		Pb		Bi		—		—	Os	Jr	Pt
—		—		—		Th		—		U		—				

Figure 8. One of the last presentations of Meyer's arrangement of elements in 1893. Scan from L. Meyer, *Ber. Dtsch. Chem. Ges.* **1893**, *26*, 1230–1250, here 1232.



Wasserstoff H = 1

SYSTEM DER ELEMENTE.

A I B	A II B	A III B	A IV B	A V B	A VI B	A VII B	VIII
Lithium Li 7,01	Beryllium Be 9,08	Bor B 10,9	Kohlenstoff C 11,97	Stickstoff N 14,01	Sauerstoff O 15,96	Fluor F 19,06	
Natrium Na 23,00	Magnesium Mg 24,3	Aluminium Al 27,04	Silicium Si 28,3	Phosphor P 30,96	Schwefel S 31,98	Chlor Cl 35,37	
Kalium K 39,03	Calcium Ca 39,91	Scandium Sc 43,97	Titan Ti 48,0	Vanadin V 51,	Chrom Cr 52,0	Mangan Mn 54,8	Eisen Kobalt Nickel Fe 55,88 Co 58,6 Ni 58,6
Kupfer Cu 63,18	Zink Zn 65,10	Gallium Ga 69,9	Germanium Ge 72,3	Arsen As 74,9	Selen Se 78,87	Brom Br 79,76	
Rubidium Rb 85,2	Strontium Sr 87,3	Yttrium Y 88,9	Zirconium Zr 90,4	Niobium Nb 93,7	Molybdän Mo 95,9		Ruthenium Rhodium Palladium Ru 101,4 Rh 102,7 Pd 106,35
Silber Ag 107,66	Kadmium Cd 111,8	Indium In 113,6	Zinn Sn 118,8	Antimon Sb 119,6	Tellur Te 125,0	Jod J 126,54	
Caesium Cs 132,7	Baryum Ba 136,9	Lanthan La 138,2	Cerium Ce 139,9				
		Ytterbium Yb 172,6		Tantal Ta 182	Wolfram W 183,6		Osmium Jridium Platin Os 190,3 Jr 192,5 Pt 194,3
Gold Au 196,7	Quecksilber Hg 199,8	Thallium Tl 203,7	Blei Pb 206,4	Wismuth Bi 208,9			
			Thorium Th 231,9		Uran U 238,8		

Zusammengestellt von Lothar Meyer und Karl Seubert.

Verlag von Breitkopf und Härtel in Leipzig.

Figure 9. Meyer's system of elements as chart. Combination of four individually printed unbounded parts. Scan from L. Meyer, K. Seubert, *Das natürliche System der Elemente. Nach den zuverlässigsten Atomgewichtswerthen zusammengestellt*. 2^{nd} edition, Breitkopf&Härtel, Leipzig, **1896**.

ing content.[51] He established that the course of organic chemistry, with its type-theory and the homologous series, is better systematized than inorganic chemistry. For example, several ways can be used for an overview of the metals. The use of the periodic system must be prepared. If someone is unacquainted with the system he will need explicit instruction, as the system was not self-explanatory. Meyer noted that he had modified his own course several times and emphasized that in any case it is necessary to start with simple substances.

In teaching, Meyer started with a short introduction about the relation between chemistry and physics He regretted that the type theory in organic chemistry had not found yet an equivalent in inorganic chemistry. Then he turned to some aspects of history of chemistry like alchemy or the phlogiston theory. He mentioned Johan Baptista van Helmont (1580-1640), Antoine Laurent de Lavoisier (1743-1794) and Bunsen and combined his historical approach with the introduction of elements and compounds which are connected with those savants. Later he introduced the atomic weights and discussed the compounds. Then he was able to explain the periodic system. Meyer mentions using a large chart to illustrate the system in the lecture hall, as well as a model using a rotating cylinder.

He started with hydrogen as the foundation for the atomic weights, then he dealt with group VII (compare figure 8). He delayed working with group I, as it seemed too complicated for the students. Meyer finished his paper by expressing his wish that readers would try this course and perhaps find a better way of arranging the material on the basis of the periodic system.

CONCLUSION

Today the periodic system has its atom-theoretical explanation. Its representation as a table can be found in nearly every chemical cabinet. The subject matter in courses of inorganic chemistry is organized on the basis of the groups of the periodic system. However, Lothar Meyer's contribution to this system is often forgotten and mainly Mendeleev's is appreciated. After Meyer's death Mendeleev often emphasized the importance of his predictions and their confirmation. For most people this was easy to understand. Meyer's accurateness in determining atomic weights and his reflections on the nature of atoms were not so easily understandable.

This paper presented Lothar Meyer's biography and key achievements in the field of classification of the elements. It demonstrates that Meyer tried to find an explanation to Döbereiner´s triads and that he started to determine and to recalculate the atomic weights of elements as a result of irregularities in his classifications. Meyer was very cautious concerning predictions of new elements, as his main interest was the understanding the nature of atoms. He also was interested in using the periodic table for instruction in inorganic chemistry.

By analyzing the successive reworkings of his classification, and the discovery of periodicity as much as the absence of archives allows, it is possible to follow the train of Meyer's thoughts in this endeavor. This demonstrates that the Karlsruhe conference was key, as was the case for Mendeleev, but also underlines differences between the two pursuits. A convinced atomist, Meyer also paid much attention to valency and other atomic properties such as the atomic radii. In his recollections, it is also clear that Meyer saw his work as a continuation of prior developments such as Döbereiner. He did not predicted new elements explicitly, but he was more successful in placing most elements in the right order. Mendeleev ordered all known elements, but with more mistakes than Meyer. On the other side he predicted not only the elements but described their properties. Mendeleev always insisted on his proposal as being a breakthrough. As this paper illustrates, the finding and development of the periodic system was more than one man's feat.

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25. Ibid, p.136.
26. Ibid, p. 138.
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28. Zum Theil allerdings können diese Abweichungen mit Fug und Recht angesehen werden als hervorgebracht durch unrichtig bestimmte Werthe der Atomgewichte. Bei allen dürfte indess dies kaum der Fall sein; und ganz sicherlich ist man nicht berechtigt, wie das nur zu oft geschehen ist, um eine vermeintlichen Gesetzmäßigkeit willen die empirisch gefundenen Atomgewichte willkürlich zu corrigieren und zu verändern, ehe das Experiment genauer bestimmte Werthe an ihre Stelle gesetzt hat. Source 24, p. 139 (all translations by the author).
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33. Als ich im Juli 1868 als sein Nachfolger im Lehramt der Chemie, Physik und Mineralogie die ihm unterstellten Inventarien übernahm, übergab er mir mit dem Bemerken, er denke die Sache doch bald zu veröffentlichen, eine eigenhändig geschriebene Anordnung der Elemente nach den Atomgrößen, welche eine wesentliche Ergänzung und Vervollkommnung seines vorerwähnten Schemas von 1864 darstellt. A. Remelé, *Zeitschrift für Forst- und Jagdwesen* **1895**, *27*, 721-724.
34. The archive has only a letter with the announcement but not the copy itself. Archiv der Berlin-Brandenburgischen Akademie, Autographensammlung, Chemikerbriefe, Briefwechsel Seubert-Remelé, Nr. 94.
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36. Source 29, p. 12.
37. Diese Elemente werden voraussichtlich später, z. Th. wenigstens, die Lücken ausfüllen, welche sich in der Tabelle jetzt noch finden. Andere Lücken werden möglicherweise durch später zu entdeckende Elemente ausgefüllt werden; vielleicht auch wird durch künftige Entdeckungen das eine oder andere Element aus seiner Stelle verdrängt und durch ein besser hinein passendes ersetzt werden. Ibid, p. 12.
38. Dieselben oder ähnliche Eigenschaften kehren wieder, wenn das Atomgewicht um eine gewisse Grösse, die zunächst 16, dann etwa 46 und schließlich 88 bis 92 Einheiten beträgt, gewachsen ist. Ibid, p. 13.
39. Wenn diese und ähnliche Regelmässigkeiten unmöglich reines Spiel des Zufalls sein können, so müssen wir uns andererseits gestehen, dass wir mit der empirischen Ermittlung derselben noch keineswegs den Schlüssel zur Erkenntnis ihres inneren ursächlichen Zusammenhangs gefunden haben. Aber es scheint wenigstens ein Ausgangspunkt gewonnen zu sein für die Erforschung der Constitution der bis jetzt unzerlegten Atome, eine Richtschnur für fernere vergleichende Untersuchung der Elemente. Ibid, p.16.
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Shaping the Periodic Classification in Portugal Through (Text)books and Charts

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Abstract. In the current paper, we present an investigation carried out to map the reception and use of Mendeleev's periodic classification in the Portuguese education system, from 1850 to 1975 while being confronted with other classifications. We present protagonists and documents to demonstrate the attention that the topic received. The research involved the identification of textbooks, programs and graphic presentations used in higher and secondary education levels within this time frame. During the 1880s, Mendeleev's classification appears in higher-level (text)books and programs. Secondary school textbooks however remained faithful to earlier classifications for some more decades, with the exception of the first occurrence found in a textbook for advanced high school in 1906. It does not seem that the periodic system was integrated in the official secondary programs before 1938. The oldest use of periodic charts seems to be from after 1891 at the University of Coimbra, the oldest surviving one dating back to the second quarter of the twentieth century. The periodic table wall charts seem to have entered the secondary classroom in Portugal by the 1960s. This survey of the use of the periodic system in Portugal demonstrates how the different contexts of reception have shaped its introduction in the educational system of what we now regard as the indispensable tool for chemistry. While there was relatively little scientific debate on the periodic law and system, as far as it was found, Mendeleev's classification was appropriated at different speed and stages through textbooks and charts, responding to different pedagogical needs and usage.

Keywords. Periodic classification, Mendeleev, Portugal, textbooks, charts.

1. INTRODUCTION

The publication of the periodic system in 1869 by Dmitri Mendeleev (1834-1907) triggered its widespread circulation and appropriation of the proposed classification of chemical elements in different countries, a subject dealt with in the book *Early Responses to the Periodic System* (2015). Since its beginning, the periodic system was meant to serve both as a support for the conceptual understanding of the periodicity and similitude of the properties of the elements known at the time, and as a pedagogical tool for chemistry students. The current paper stems from one of the chapters of the aforementioned book – "Echoes from the reception of the Periodic Classification in

Portugal"[1] and attempts to go beyond the period already studied, following up on the mention, presence and discussion of the periodic system and classification in books, textbooks, programs, and charts in secondary and higher education, in the period between 1850 and 1975.

The paper begins with the account of an early response in a booklet printed in 1880 dealing with atomic theory and the periodic law of Mendeleev, published at the fringe of a higher education institution, the Porto Polytechnic Academy. After a brief description of the Portuguese higher education system, the next section deals with professors, programs and/or textbooks in the three Portuguese higher education institutions: the Lisbon Polytechnic School, the Porto Polytechnic Academy, and the University of Coimbra where the first mentions of use appear from 1880 onwards. One of the earliest references is the topic of "Mendeleev's law" given as a subject of a dissertation at the Faculty of Natural Philosophy in Coimbra.

Before the periodic system, textbooks and teachers were using other classifications. In a separate section, the impact of the pre-Mendeleev and Mendeleev's classification at university and secondary school level is thus examined and analyzed through different textbooks in use until 1975.

Finally, we traced back what is probably the first use of a Mendeleev periodic chart in a Portuguese university classroom context, linked to the adoption of the periodic system as a pedagogical tool at the University of Coimbra, and what seems to be the oldest surviving Portuguese wall chart, hanging today in the Science Museum, also in Coimbra.

We conclude on the diversity of response, related to each context, and how these various contexts shaped the variety of reception of the periodic classification in Portugal.

2. FIRST RESPONSE TO MENDELEEV'S PROPOSAL: THE UNITY OF MATTER AT THE MARGINS OF ACADEMIA

The first Portuguese publication explicitly mentioning the periodic law dates back to 1880, but to fully understand the context in which it appeared it is necessary to briefly describe a book dated 1876 but only published in 1879, in Porto. *A theoria dos átomos e os limites da sciencia* (The theory of atoms and the limits of science), authored by António Luiz Ferreira Girão (1823-1876) does not make any references to Mendeleev or any other periodic classification for that matter, but sets the scene for the conceptual context in which it will be discussed a year after.[2] Relying mostly on philosophical arguments, Ferreira Girão developed different considerations on the question of the ultimate atom and the creation of matter, surveying the whole of the historical background from Greek times to the most recent developments.[3] Ferreira Girão pursued his historical examples, showing that the idea of considering the simple bodies as compounds was very old, but when alchemy stepped down, it took away with it the underlying belief in the unity of matter. Coeval discoveries and hypotheses (e.g. those of cyanogen and ammonium radicals, and facts relating to isomerism) brought the unity of matter to the fore again, although these theoretical speculations had not been experimentally confirmed. Indeed, even though William Prout's (1785-1850) ideas on the unity of matter seemed to be refuted after Jean-Servais Stas' (1813-1891) accurate determinations of several atomic weights at mid-century, this did not deter the author. According to him, one is in fact led to pursue the direct analysis to see if it is possible to go further and beyond the chemical atoms such as hydrogen, iron or copper, on the basis of evidence relating to the body's free fall, optical phenomena, the dissociation of gases at high temperatures, and the spectral analysis of celestial bodies.

Ferreira Girão presents examples of well-known experiments by different authors, systematizes them, and discusses a certain number of objections to the unity of matter and the existence of prime atoms, convinced that Marcellin Berthelot (1827-1907)'s objections are not sufficiently strong to destroy the hypothesis of the simplicity of matter. The only admissible conclusion in his eyes is that the chemist's atoms are already the result of arrangements of prime atoms. In this way, the existence of prime atoms, and the unity of matter, seems to be beyond doubt to the author. He concludes that, "if reason and experiment lead us to infer that chemical atoms cannot be the last expression of the divisibility of matter, it does not follow that we know what the nature and properties of the first principles are."[4]

While Ferreira Girão cites neither Mendeleev nor the periodic classification, he raises the question on how the huge number of different minerals to be found in the Earth's crust, could be formed by only sixty-five elementary or simple bodies.[5]

The quest was soon taken up by a student, D. Agostinho de Sousa (unknown dates) who published a small booklet in 1880 in which he presents Mendeleev's ideas: *La loi périodique–de M. Mendéléjeff en ce qui concerne le problème de l'unité de la matière et la théorie de l'atomicité*.[6] Little is known about the author and the circumstances: the author introduces himself in the title page as a student at the Porto Polytechnic Academy (and in the text as a student of Ferreira Girão). His use of the title "D." indicates that he was a clergyman but it remains unclear why he uses the French language, which seems to target an undefined foreign audience. The fifty-two pages work consists of an introduction and two chapters, and considers that chemistry is on the verge of a revolution. The first one is entitled *La loi périodique et la question de l'unité de la matière*, and the second chapter, *La théorie de l'atomicité et M. Mendéléjeff*. The author frames the discussion in the field of the unity of matter and atomicity[7] and refers to various recent foreign publications on that topic.

To start with, the author states the tendency of chemistry, physics, and astronomy to establish the unity of matter, despite the brilliant opposition of chemists like Stas and Berthelot. The spectral analysis of nebulae demonstrated, in his opinion, the generation of simple bodies from hydrogen. Further, the author believes, the periodic classification gives an unexpected support to Prout's theory even though Mendeleev would not agree with that conclusion. Agostinho de Sousa proceeds saying that Mendeleev's endeavour is supported by the previous proposals of classification by Jean-Baptiste Dumas (1800-1884), Jean Charles Galissard de Marignac (1817-1894), and Julius Lothar Meyer (1830-1895). Admitting imperfections, he sees them as inherent to a subject both complex and difficult. Agostinho de Sousa prefers to look at it as a whole and in this respect, he is convinced that the periodic law is a broad synthesis, a rational history of simple bodies, but principally a powerful affirmation of the unity of matter. Dumas[8,9] had established the natural families of simple bodies, but he did not know the link connecting one group to another, what Mendeleev made appear. He filled the gap, noting that the difference between the atomic weights of two neighboring bodies does not surpass an average of two or three units, and where this interval is greater, there are gaps to be filled by later discoveries, as recently confirmed with *gallium* (1875) and *scandium* (1879). Facing all this, Agostinho de Sousa considers that Mendeleev came to the aid of Prout's thesis, and to the support of his own opinion on the unity of matter.[10] In that way, and in his opinion, Mendeleev has shaken the theory of atomicity by recognizing that hydrogen, chlorine, and oxygen cannot serve as a standard for measuring the atomicity of elements. Moving on to Berthelot, Agostinho de Sousa states that only when chemistry will relate its laws to those of pure mechanics and the physical sciences, then it will raise itself to the level of the positive physical sciences and, concurrently, will contribute to reaching the unity of the universal law of movements and natural forces. It is thus no coincidence that the insistence of this booklet is not so much on the classification or the system than on the periodic law, which has to be seen as a law of nature, as coincidentally Mendeleev himself hoped it to be.

3. THE CONTEXT OF PORTUGUESE HIGHER ACADEMIC EDUCATION IN CHEMISTRY

This application of the periodic law was published at the margins of the institutions where chemistry was taught. To situate the other mentions of Mendeleev's work in the academic setting, it is important to understand the Portuguese context of higher academic education in chemistry. The institutionalization of chemistry as an independent scientific discipline in Portugal occurred with the 1772 reform of the University of Coimbra which was by then the only institution for higher education in Portugal. The reform of 1844 initiated an innovative approach in the study of chemistry, which introduced three new courses (Analise e Philosophia Chymica, Chymica Inorganica and Chymica Organica) in the chemistry curriculum, following similar developments abroad. By 1851, the Coimbra professor Joaquim Augusto Simões de Carvalho (1822–1902) objected about the use of French textbooks in the study of chemistry. He published a modern textbook *Lições de Philosophia Chimica* (Lessons of chemical philosophy) that included in the chemical lessons recent research achievements and defended greater "attention to the day-today communications in scientific journals and newsletters than to more complete and extensive manuals" should be given.[11]

After the end of the Portuguese civil war (1834), the country flourished politically and economically. Naturally, those developments influenced on the reform of the curricula of the university. In the case of chemistry, some of its professors went abroad to be updated with the modern experimental techniques, and at the same time, some foreign staff were hired, such as Bernhard Christian Gottfried Tollens (1841-1918).

Focusing on this period, the Portuguese historian of chemistry Amorim da Costa (1939-) considered that although the teaching of chemistry at the university was not outdated, there was no connection whatsoever between experimental teaching and the research underway. The insufficient governmental financial support and the insignificant links to a weak industrial milieu were the two main reasons for that state of affairs.[12] From the 1830s, there was a particular emphasis on teaching emerging from those efforts a secondary school system. One of the aims was the scientific and technical preparation of younger middle-class students intended to serve a modernized Portuguese society. As was the case abroad, all the education reforms were meant to broaden the preparation of the younger generation taking into account, namely the progresses in science and technology. At the secondary level, several disciplines were introduced, in particular the first scientific and technical elements of mathematics, physics, chemistry, natural history, political economy, public administration, and commerce were taught.[13] Later in the century, industrial and agricultural curricula were restructured, both of which were becoming more practical.

By the middle of the century, two institutions stood out: the Polytechnic School in Lisbon, and the Porto Polytechnic Academy, both founded in 1837. The creation of these Polytechnic institutions aimed at developing the industrial sciences. Their goals were to prepare students for the practice of agriculture, industry and commerce and for the first two, chemistry was considered of utmost importance. A specific diploma was also created for chemists establishing their license to manufacture and handle chemical products.[14]

The setting up of the Porto Municipal Chemical Laboratory (1884/87) with António Joaquim Ferreira da Silva (1853–1923), needs to be emphasized as it updated the practical and theoretical chemistry teaching. A similar situation occurred at the Lisbon Polytechnic School, where, during its first years, the teaching of chemistry was mainly expository and speculative, and whose organization and main features did not differ much from the chemistry teaching at the University of Coimbra in the same period. Nevertheless, the Polytechnic had “younger and much more motivated and possibly better-prepared professors,” including Agostinho Lourenço (1822–1893), António Augusto de Aguiar (1838–1887), José Júlio Rodrigues (1843–1893), Roberto Duarte Silva (1837–1889), and Achilles Machado (1896–1932), who updated their laboratories, and published textbooks.[15]

3.1. Porto Polytechnic Academy

In 1876, Ferreira da Silva succeeded Ferreira Girão at the Porto Polytechnic Academy, developed a reputable career and took chemistry to a higher level both at the Academy and at the Municipal Laboratory, where there was significant teaching of practical chemistry. Among the recommended textbooks was Ferreira da Silva’s *Tratado de Chimica Elementar* (Treatise of Elementary Chemistry).[16] In the second edition (1895) the author states that the structure of mineral chemistry was largely similar to that in the first edition (1884), but some more recent topics were included, and some doctrines of general chemistry were enlarged, namely those concerning the periodic law of elements.

From the first edition, we know that the textbook was intended to prepare the students taking the chemistry course at Porto Polytechnic Academy and that it was written in a simple way, to help ease the learning of the basics of chemistry.

When referring to the atomic theory, Ferreira da Silva points out that “the atomic theory in chemistry is independent of the general theories usually admitted on the constitution of matter. But the exposition method followed in the elementary books, even the more popular ones, hides rather than presents this truth, as admitted by the leader of this doctrine in France, Mr. Wurtz, and even more clearly expressed by another savant of the same school, P. Schutzenberger, professor at the College of France.”[17] According to Ferreira da Silva, the position of these two eminent French chemists could explain why it was difficult to introduce the atomic theory in the secondary level.

Next, Ferreira da Silva mentions that he aims to introduce the atomic theory without relying on the controversial hypothesis about the constitution of matter, and doing so it remains possible to compare it with the theory of equivalents. Concerning the atomicity, he concludes that it is a valuable concept when purged of the hypothesis that plagues it.

In the second edition (1895), Mendeleev’s periodic classification is presented in six pages, beginning with the “Relations between the elements properties and their atomic weight.” Keeping hydrogen as a separate element, the author compares the properties (physical and chemical) of the elements along the different rows of the table, noting that there is a regularity and similitude of the properties. Moreover, when the rows are aligned the set of elements in each column formed is very similar to the so-called natural families. He quotes Mendeleev’s law as “the properties of the simple bodies, the constitution and properties of their combinations are periodic functions of their atomic weights,”[18] presents the periodic table, reaffirms that the periodic law is expressed in the similitude of the physical properties (not just the chemical ones), namely the specific weight, the atomic volume, fusibility, tenacity, malleability, volatility, specific heat, and heat and electrical conductibility, and concludes just showing a Lothar Meyer’s curve taken from *Les théories modernes de la chimie*,[19] translated in French from the original 5th edition.

In a last paragraph, Ferreira da Silva states his position concerning the periodic classification:

> *Some reservations should be maintained regarding Mendeleev's classification of the place occupied by some metals, like gold, which usually acts as trivalent and not as monovalent. But as it is organized, it represents a great and happy attempt. It enabled this author to foresee the existence and the properties of some new elements, which were missing in the table; three of these bodies were discovered: gallium (Mendeleev's ekaluminium), germanium (ekasilicium), and scandium (ekaboron). It also enabled the atomic weights of many little known elements to be corrected, weights which were confirmed by new experimental determinations (uranium, cerium, etc.)."[20] Looking inside the third edition of his Tratado de Chimica Elementar (1903), Ferreira da Silva points out to some continuing difficulties with the periodic classification, namely as regards the noble gases, concluding: "For this reason, the principle that underpins Mendeleev's classification does not seem to be a natural law.[21]*

3.2. Lisbon Polytechnic School

Considering now what was going on at the Lisbon Polytechnic School, in 1850, we find Júlio Máximo Oliveira Pimentel (1809-1884) as the professor of chemistry and in his book *Lições de Chymica Geral* (General Chemistry Lessons),[22] he considers the ten natural families of the elements as many contemporary textbook authors did, when providing an overview of the chemistry of the known elements (Table 1). This way of organizing teaching continued until a younger teacher entered the scene.

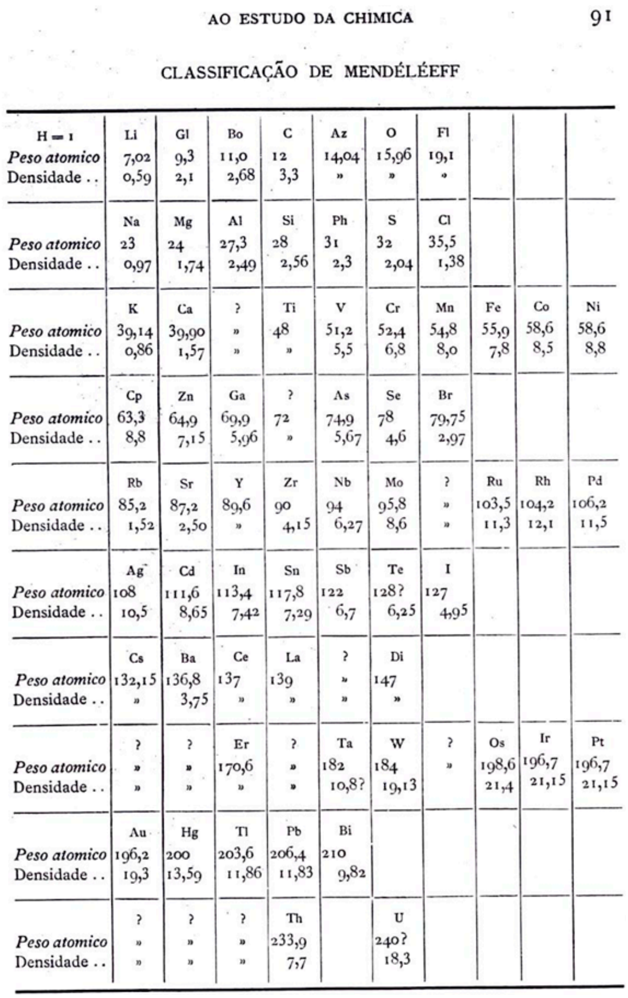
Eduardo Burnay (1853–1924), substitute professor of chemistry at Lisbon Polytechnic School in 1888, became full professor in 1893 and very early in his teaching career he produced a set of extended summaries of some of his lectures – *Introducção Theorica ao Estudo da Chimica* (Theoretical Introduction to the Study of Chemistry) (1888).[26] He starts considering that bodies can be either simple or compound which goes back to Lavoisier and even before, noting that the simple bodies have been classified either in natural families or on various other bases: the electrochemical character, the atomic weight, the atomicity and the natural physicochemical properties. Then he presents Mendeleev's classification in two-pages with a table of elements where density and atomic weight are provided (Figure 1).

He highlights what he calls the typical period (the first one, containing Li, Gl, Bo,[27] C, Az,[28] O, Fl[29]), the small periods (where density attains a maximum that sometimes is the first term, and then decreases), and the great periods (where density increases progressively) with examples; he then mentions the vertical sequences as the true natural chemical families.[30] He asserts that this taxonomic display of the elements offers a certain plausibility, although possessing some imperfections and exceptions. The gaps that appear should correspond to yet unknown bodies, as was demonstrated with the case of *gallium* (the *ékaluminium* Mendeleev forecasted) discovered by Lecoq de Boisbaudran. He refers to several metals: *decipium,[31] philipium,[32] mosandrum,[33] iterbium, scandium, holmium, thulium, samarium, davyum[34]* and *norwegium,[35]* the existence of which is only suspected at the time.[36]

The next full professor of chemistry (1896) at the Lisbon Polytechnic School was Achilles Machado (1862–

Table 1. Authors' table of the ten natural families as they are described in J. M. O. Pimentel's book (ref. 22).

1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
F	O	N	C	Na	Mg	Al	Fe	Cd	Ag
Cl	S	P	B	K	Ca	Gl (glucinium[23])	Mn	Cu	Pt
Br	Se	As	Si	Li	Sr	Zr	Co	Sn	Au
I	Te	Sb	Ti	AzH_3 (ammonia)	Ba	Th	Ni	Mo	Pd
			Ta		Pb	Y	Cr	W	Rh
							Zn	Nb	Ir
								Pp (pelopium[24])	Os
								Il (ilmenium[25])	Ru
								V	
								U	
								Bi	
								Hg	



AO ESTUDO DA CHIMICA 91

CLASSIFICAÇÃO DE MENDÉLÉEFF

H = 1	Li	Gl	Bo	C	Az	O	Fl			
Peso atomico	7,02	9,3	11,0	12	14,04	15,96	19,1			
Densidade . .	0,59	2,1	2,68	3,3	»	»	»			
	Na	Mg	Al	Si	Ph	S	Cl			
Peso atomico	23	24	27,3	28	31	32	35,5			
Densidade . .	0,97	1,74	2,49	2,56	2,3	2,04	1,38			
	K	Ca	?	Ti	V	Cr	Mn	Fe	Co	Ni
Peso atomico	39,14	39,90	»	48	51,2	52,4	54,8	55,9	58,6	58,6
Densidade . .	0,86	1,57	»	»	5,5	6,8	8,0	7,8	8,5	8,8
	Cp	Zn	Ga	?	As	Se	Br			
Peso atomico	63,3	64,9	69,9	72	74,9	78	79,75			
Densidade . .	8,8	7,15	5,96	»	5,67	4,6	2,97			
	Rb	Sr	Y	Zr	Nb	Mo	?	Ru	Rh	Pd
Peso atomico	85,2	87,2	89,6	90	94	95,8	»	103,5	104,2	106,2
Densidade . .	1,52	2,50	»	4,15	6,27	8,6	»	11,3	12,1	11,5
	Ag	Cd	In	Sn	Sb	Te	I			
Peso atomico	108	111,6	113,4	117,8	122	128?	127			
Densidade . .	10,5	8,65	7,42	7,29	6,7	6,25	4,95			
	Cs	Ba	Ce	La	?	Di				
Peso atomico	132,15	136,8	137	139	»	147				
Densidade . .	»	3,75	»	»	»	»				
	?	?	Er	?	Ta	W	?	Os	Ir	Pt
Peso atomico	»	»	170,6	»	182	184	»	198,6	196,7	196,7
Densidade . .	»	»	»	»	10,8?	19,13		21,4	21,15	21,15
	Au	Hg	Tl	Pb	Bi					
Peso atomico	196,2	200	203,6	206,4	210					
Densidade . .	19,3	13,59	11,86	11,83	9,82					
	?	?	?	Th		U				
Peso atomico	»	»	»	233,9		240?				
Densidade . .	»	»	»	7,7		18,3				

Figure 1. Classification of Mendeleev, printed in Eduardo Burnay's book (ref. 26, p. 91).

1940). In 1897, he published a comprehensive teaching program based on his notes on chemistry – *Apontamentos de chimica: 6ª cadeira (Chimica Mineral)* [da Escola Politecnica], with greater focus on modern theoretical notions than had previously been the case, and including Mendeleev's classification.[37] Besides publishing for his students at the Polytechnic, he had co-authored a textbook five years earlier with his brother Virgílio Machado (1859-1927), - *Chimica Geral e Análise Chimica* (General Chemistry and Chemical Analysis) (1892),[38] which was used in both the Polytechnic and the Industrial School in Lisbon. In it, they briefly explained Mendeleev's classification.[39] Achilles also published several official textbooks for secondary levels.

Between 1930 and 1960, professor António Pereira Forjaz (1893-1972), later director of the Lisbon Polytechnic School, published more than fifty chemistry books. In two of them only (1937, 1940),[40,41] the fundamentals of the periodic classification of Mendeleev are shown.

3.3. University of Coimbra

Despite the importance both Polytechnic Schools had in the academic Portuguese milieu, we cannot forget what was happening at the University of Coimbra, then the unique university in function. Both Ferreira Girão and Ferreira Silva were alumni of the University of Coimbra.

Dated February 13th, 1886, we find that the Faculty Congregation decided that the first graduated from the Faculty of Natural Philosophy should have "the Mendeleev's law" as topic of his dissertation. As far as it was possible to follow this was the first time such a subject appears registered in the Congregation *Acta*.[42]

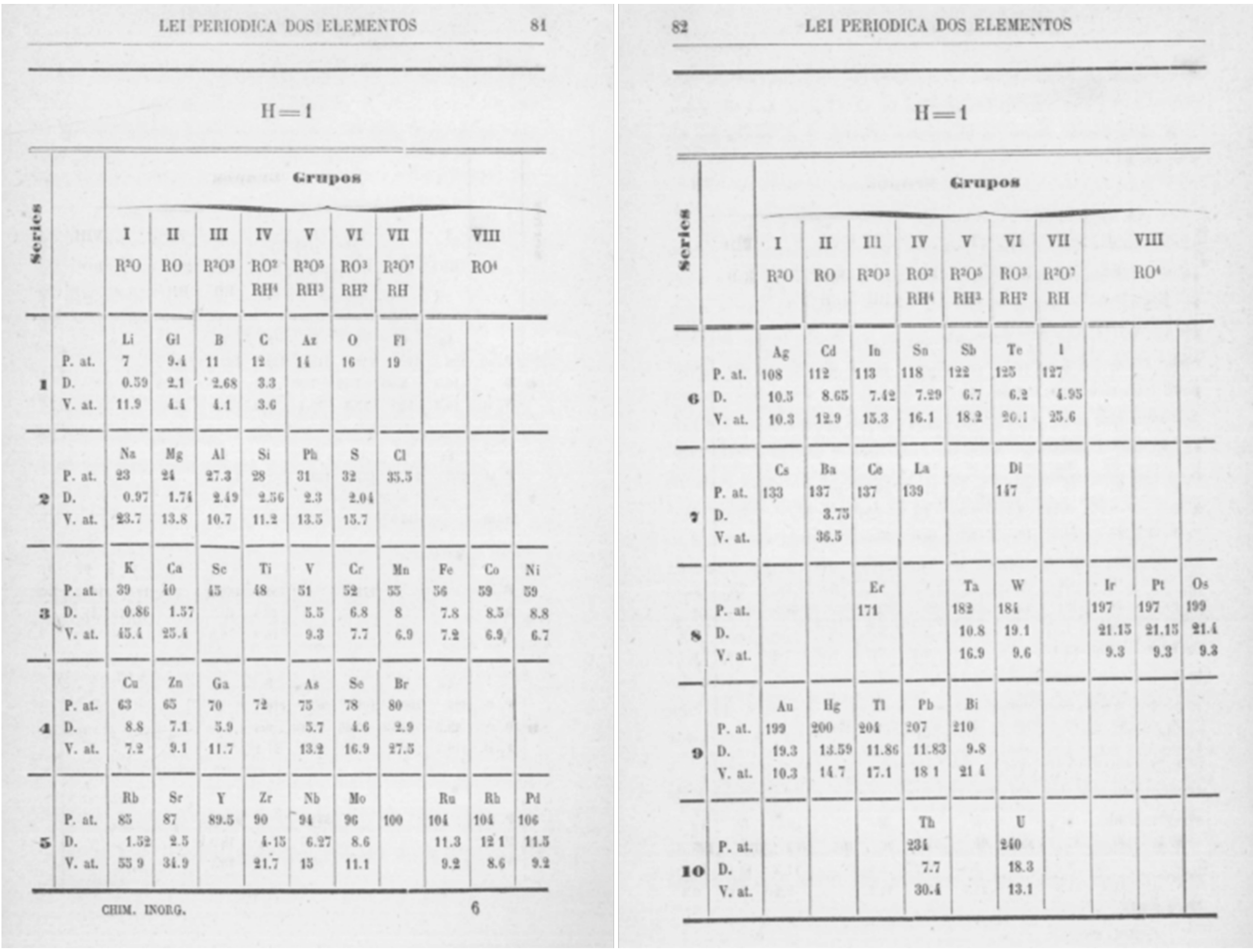
However, the access to a rare textbook - *Lições de Chimica Inorganica* (Lessons of Inorganic Chemistry), by Francisco Augusto Corrêa Barata (1847-1900), published in 1880, of which only two incomplete copies are known, sheds light on what was happening with the chemistry lessons at the university. Barata was professor of chemistry in 1880,[43] and in his book explicitly mentions Mendeleev and his periodic law, in the following terms:

> *The highest combination forms of an element with hydrogen and with oxygen, or with equivalent elements, are a periodic function of the atomic weight, being so determined by it. This law regulates the limiting forms, making restrictions to the diversity of possible forms; and establishes a dependence among those forms, and so between atomicity and its atomic weight.*
> *Considering its importance, we are going to present it in a separated chapter.*[44]

Next, the author presents what we believe to be the first periodic table ever published in a Portuguese university textbook. There, three properties are mentioned: atomic weight (P.at.), density (D) and atomic volume (V. at.).

A few years later, Francisco José Sousa Gomes (1860-1911), professor of chemistry, wrote a *Nota sobre o ensino da Chimica na Universidade de Coimbra* (Note on the teaching of chemistry at the University of Coimbra),[45] presented to the Hispano-Portuguese-American Pedagogical Congress, and published in 1892.

Beginning with a contextualization of the origins of chemistry as an independent academic discipline in Portugal, he quickly comes, in his *Note,* to recount his own last three years of teaching experience. The insufficient training in experimentation in secondary school education led him to make some decisions relating to his own teaching. Instead of lengthy explanations of fundamental



LEI PERIODICA DOS ELEMENTOS 81

H=1

Grupos

Series		I R^2O	II RO	III R^2O^3	IV RO^2 RH^4	V R^2O^5 RH^3	VI RO^3 RH^2	VII R^2O^7 RH	VIII RO^4		
1		Li	Gl	B	C	Az	O	Fl			
	P. at.	7	9.4	11	12	14	16	19			
	D.	0.59	2.1	2.68	3.3						
	V. at.	11.9	4.4	4.1	3.6						
2		Na	Mg	Al	Si	Ph	S	Cl			
	P. at.	23	24	27.3	28	31	32	35.5			
	D.	0.97	1.74	2.49	2.56	2.3	2.04				
	V. at.	23.7	13.8	10.7	11.2	13.5	15.7				
3		K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni
	P. at.	39	40	45	48	51	52	55	56	59	59
	D.	0.86	1.57			5.5	6.8	8	7.8	8.5	8.8
	V. at.	45.4	25.4			9.3	7.7	6.9	7.2	6.9	6.7
4		Cu	Zn	Ga		As	Se	Br			
	P. at.	63	65	70	72	75	78	80			
	D.	8.8	7.1	5.9		5.7	4.6	2.9			
	V. at.	7.2	9.1	11.7		13.2	16.9	27.5			
5		Rb	Sr	Y	Zr	Nb	Mo		Ru	Rh	Pd
	P. at.	85	87	89.5	90	94	96	100	104	104	106
	D.	1.52	2.5		4.15	6.27	8.6		11.3	12 1	11.5
	V. at.	55 9	34.9		21.7	15	11.1		9.2	8.6	9.2

CHIM. INORG. 6

82 LEI PERIODICA DOS ELEMENTOS

H=1

Grupos

Series		I R^2O	II RO	III R^2O^3	IV RO^2 RH^4	V R^2O^5 RH^3	VI RO^3 RH^2	VII R^2O^7 RH	VIII RO^4		
6		Ag	Cd	In	Sn	Sb	Te	I			
	P. at.	108	112	113	118	122	125	127			
	D.	10.5	8.65	7.42	7.29	6.7	6.2	4.95			
	V. at.	10.3	12.9	15.3	16.1	18.2	20.1	25.6			
7		Cs	Ba	Ce	La		Di				
	P. at.	133	137	137	139		147				
	D.		3.75								
	V. at.		36.5								
8				Er		Ta	W		Ir	Pt	Os
	P. at.			171		182	184		197	197	199
	D.					10.8	19.1		21.15	21.15	21.4
	V. at.					16.9	9.6		9.3	9.3	9.3
9		Au	Hg	Tl	Pb	Bi					
	P. at.	199	200	204	207	210					
	D.	19.3	13.59	11.86	11.83	9.8					
	V. at.	10.3	14.7	17.1	18 1	21 4					
10					Th		U				
	P. at.				234		240				
	D.				7.7		18.3				
	V. at.				30.4		13.1				

Figure 2. Possibly the first periodic table published in a Portuguese university textbook. Francisco Augusto Corrêa Barata's book, 1880 (ref. 44, pp. 81-82).

laws, he decided to favor the use of chemical notation, equations and formulas and based it on a table of atomic weight.

In that frame, Mendeleev's periodic classification played an important role. Sousa Gomes clearly mentions his adoption of Mendeleev's periodic classification, and presents his reasons: it enables the summarized presentation of several properties, reactions, and processes of preparation, that are repeated in each group and are therefore bridgeable in a general schema.

From his *Note*, we learn that the classification had been adopted from the time he entered as professor of mineral chemistry (academic year 1888-1889) and that he used a German translation (1891) of Mendeleev's textbook as a guide in his teaching.[46] Later in 1895, he published his book *Lições de Chimica I* where there was a first part concerning chemical philosophy and a second part dealing with the properties of elements and compounds organized according the Mendeleev's periodic classification. In assessing its use, Sousa Gomes considers that students learn all the related facts more easily when using Mendeleev's classification in contrast to when they were taught descriptive chemistry in a disconnected manner based on the old arbitrary classifications.

Another concern of Sousa Gomes was the implementation of a student-centered learning methodology, contrary to what was usual, and according to the method nicknamed heurism proposed by the British chemist Harry Edwards Armstrong, professor at the Central Technical College of London, who introduced it in 1884.[47]

The pedagogical use of the periodic classification and other previous classifications of the elements will be further described in the next section devoted to (text) books aimed to the secondary (basic and upper) and college levels.

Table 2. Thénard's & Régnault's classification for metals in six sections (authors' table).

1st	2nd	3rd	4th	5th	6th
Li	Mg	Fe	Sn	As	Hg
Na	Al	Zn	Sb	Cu	Ag
K	Mn	Ni	W	Pb	Au
Sr	Gl	Co	Mo	Te	Pt
Ca	Zr	Cr	Os	Bi	Pd
	Y	V	Ta		Rh
	Th	Cd	Ti		Ir
	Ce	U	Nb		Ru
	La		Il		
	Di		Pp		
	Er				
	Tb				

4. CLASSIFICATIONS IN (TEXT)BOOKS

4.1. Introduction

In the previous sections, the impact of Mendeleev's classification on the higher education schools in Portugal was examined, and is here presented in a condensed manner in Table 4, while also systematizing the appearance of the different pre-Mendeleev's classifications of the elements in Portuguese (text)books for the different levels.

The Portuguese secondary school system, included the teaching of science subjects, and developed consistently from the mid-nineteenth century, with an increasing number of schools around the country, beyond Coimbra, Lisbon, and Porto. Chemistry, along with physics, was taught during the last five years of secondary school.

In the two final years of the secondary level that will be referred to as the upper secondary, the subjects were dealt with more detail than before. When reading textbooks from that time, one realizes that the methodological advice was to teach practical knowledge, and the laws already established. In this section, we will focus on the classifications used for elements.

4.2. Metals and metalloids

In all textbooks intended for basic secondary schools (Table 3), the simple classification in metals and metalloids was the only one used in the period spanning from 1850 to 1967.

In 1854, João Ignacio Ferreira Lapa (1823-1892) published a book for the basic secondary courses with the classification of the elements as either metals or metalloids, being more specific about metals following Louis Jacques Thénard (1777-1857)'s and Henri Victor Regnault (1810-1878)'s classification (Table 2).[48] According to this classification, the metals are divided in six groups, depending on the following properties: affinity to the oxygen of the air, ability to decompose water, decomposition of their oxides by heat, and ability to decompose water when mixed with an acid.

One of the official textbooks used in 1893, for upper secondary schools, was from Francisco Ribeiro Nobre (1858-19??). After some preliminary considerations on chemistry, affinity, classification and nomenclature, and chemical theories, the author moves to metals, metalloids, and their compounds, ending up with organic chemistry.[49] Basically, the structure of secondary school textbooks had not evolved since Ferreira Lapa.

The official secondary school program (1895), concerning chemistry, recommended the examination of the bodies, experimentation, the use of equipment, and the inspection of appropriate pictures, using a clear and simple language.[50]

Along with the official textbooks, some booklets (64-pages each) of a well-known popular collection, the - *Bibliotheca do Povo e das Escholas* (People and Schools Library) - were published showing explicitly that they were in accordance with the official programs, to be used either in Portugal or in Brazil. This collection started in 1881 and stayed alive for more than thirty years. For the four books devoted to chemistry, only three deal with classification of the elements, but neither of them includes the periodic system. In *Introdução às Sciencias Physico-Naturaes* (Introduction to the Physico-Natural Sciences) (1881),[51] the author, João Cesário de Lacerda (1841-1903) classifies the elements into metals and metalloids in a single page of the chapter on the first notions of chemistry. In *Principios Geraes de Chimica* (General Principles of Chemistry) (1881),[52] only one page is devoted to the classification of metals and metalloids, distributed in five groups according to the atomicity of the elements. In *Chimica Inorganica* (Inorganic Chemistry) (1st ed. 1882, 5th ed. 1907), José Maria Greenfield de Mello (1848-1905), besides classifying the elements in metals and metalloids, elaborates about "The atomic theory and its adversaries." He points out that as the collection was aimed for the public, he had to simplify the presentation, deciding to follow the notation and nomenclature based on the reasoning of the atomic theory, even though not all renowned chemists had yet unanimously accepted that hypothesis.[53]

In three cases, a more specific classification for both metalloids and metals, according to the atomicity, was

Table 3. Classification of elements in Portuguese textbooks from 1850 to 1967.

Metals	Teaching level	Metalloids		Metals	
Júlio Máximo de Oliveira Pimentel[54] (1850)	Polytechnic (Lisbon)[55]	10 natural families			
		Atomicity	Dumas	Thénard & Regnault	"Natural"
João Ignacio Ferreira Lapa[56] (1854)	Basic Secondary	No	No	Yes	No
Antonio Xavier Corrêa Barreto[57] (1874)	Upper Secondary	Yes	No	Yes	Yes
Miguel Arcanjo Marques Lobo[58] (1875)	Upper Secondary	Yes	Yes	Yes	Yes
João Cesário de Lacerda[59] (1881)	Basic Secondary	No	No	No	No
João M. Greenfield de Mello[60] (1881)	Basic Secondary	No	No	No	No
Adriano Augusto de Pina Vidal & Carlos Augusto Morais d'Almeida[61] (1883)	Upper Secondary	Yes	No	Yes	Yes
Antonio Xavier Corrêa Barreto,[62] (1883)	Upper Secondary	Yes	No	No	Yes
Antonio Joaquim Ferreira da Silva[63] (1884)	Polytechnic (Porto)	Yes	Yes	Yes	Yes
Virgílio Machado & Achilles Machado[64] (1892)	Industrial School	Yes	Yes	Yes	Yes
Eduardo Burnay[65] (1888)	Polytechnic (Lisbon)	Yes	No	No	Yes
Francisco Ribeiro Nobre[66] (1893)	Basic Secondary	Yes	No	No	Yes
Francisco Sousa Gomez[67] (1903)	Basic Secondary	Yes	No	No	Yes
Achilles Machado[68] (1906)	Basic Secondary	No	No	No	No
Achilles Machado[69] (1906)	Basic Secondary	No	No	No	No
Achilles Machado[70] (1906)	Basic Secondary	No	No	No	No
João Greenfield de Mello[71] (1907)	Basic Secondary	No	No	No	No
Francisco de Sousa Gomes[72] (1907)	Upper Secondary	Yes	No	No	Yes
L. Troost,[73] translated by Ramiz Galvão (1910) from 29th ed.	University[74] (Coimbra)	Yes	No	Yes	No
Alexander Smith[75], translated by Sousa Gomes (1911)	University (Coimbra)	No	No	No	No
Francisco de Sousa Gomes & Antonio Joaquim Ferreira da Silva[76] (1914)	Basic Secondary	Yes	No	No	Yes
Biblioteca de Instrução Profissional[77] (1924)	Basic Secondary	No	No	No	No
Francisco R. Nobre[78] (1933)	Basic Secondary	Yes	Yes	Yes	Yes
Riley da Motta & Rómulo de Carvalho[79] (1950)	Basic Secondary	No	No	No	No
José A. Teixeira[80] (1967)	Basic Secondary	Yes	No	No	Yes

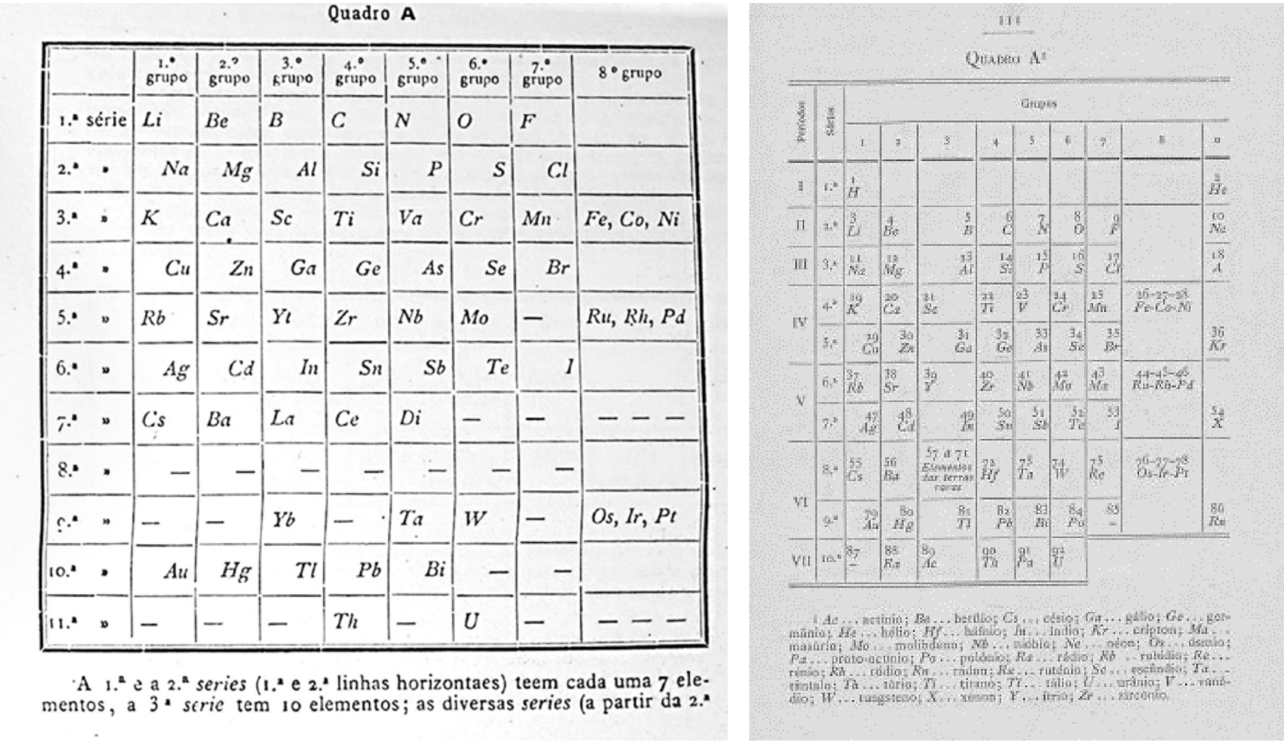
used, called "natural" classification in the case of metals. In two cases, metals were classified according to Thénard's & Régnault's.

However, focusing on textbooks recommended for upper secondary schools, industrial school, and higher education, there we find that they used the distinctive categories for metals and metalloids at least until 1933 (Table 3). All but one use the atomicity and/or Dumas classification for metalloids and Thénard's & Regnault's and/or the "natural" classification for the metals.

4.3. Mendeleev´s classification

The periodic classification only appears officially in 1948 as a topic to be taught in the secondary school programs.[81] This does not mean, however, that the subject was unknown at this level in the preceding decades. Frequently, in those years, some university/polytechnic professors were involved in the production of textbooks and sometimes gave classes either in the secondary or in the industrial schools. Achilles Machado was one such example. His books were used either as the unique official textbook, or with others, for secondary level and for several decades (Table 4). As far as it is known, the first periodic table for upper secondary school was included in one of Achilles Machado's textbooks, published in 1906, as a supplementary reading material.[82] It contained two items—"Relations between the properties of different elements and their atomic weights, Mendeleev's classification" and "Applications of the periodic law", discussed in eight pages (Figure 3).

A bigger emphasis on the periodic classification occurs in 1975, but the textbook by Sena Esteves, in 1946, is certainly the most informative one, considering the level to which it was proposed. As far as we could find, it is the only one that includes a folding and very



Quadro A

	1.º grupo	2.º grupo	3.º grupo	4.º grupo	5.º grupo	6.º grupo	7.º grupo	8.º grupo
1.ª série	Li	Be	B	C	N	O	F	
2.ª »	Na	Mg	Al	Si	P	S	Cl	
3.ª »	K	Ca	Sc	Ti	Va	Cr	Mn	Fe, Co, Ni
4.ª »	Cu	Zn	Ga	Ge	As	Se	Br	
5.ª »	Rb	Sr	Yt	Zr	Nb	Mo	—	Ru, Rh, Pd
6.ª »	Ag	Cd	In	Sn	Sb	Te	I	
7.ª »	Cs	Ba	La	Ce	Di	—	—	— — —
8.ª »	—	—	—	—	—	—	—	
9.ª »	—	—	Yb	—	Ta	W	—	Os, Ir, Pt
10.ª »	Au	Hg	Tl	Pb	Bi	—	—	
11.ª »	—	—	—	Th	—	U	—	— — —

A 1.ª e a 2.ª *series* (1.ª e 2.ª linhas horizontaes) teem cada uma 7 elementos, a 3.ª *serie* tem 10 elementos; as diversas *series* (a partir da 2.ª

111

Quadro A¹

Períodos	Séries	Grupos								
		1	2	3	4	5	6	7	8	0
I	1.ª	1 H								2 He
II	2.ª	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F		10 Ne
III	3.ª	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl		18 A
IV	4.ª	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26-27-28 Fe-Co-Ni	
	5.ª	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br		36 Kr
V	6.ª	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Ma	44-45-46 Ru-Rh-Pd	
	7.ª	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I		54 X
VI	8.ª	55 Cs	56 Ba	57 a 71 Elementos das terras raras	72 Hf	73 Ta	74 W	75 Re	76-77-78 Os-Ir-Pt	
	9.ª	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 —		86 Rn
VII	10.ª	87 —	88 Ra	89 Ac	90 Th	91 Pa	92 U			

¹ *Ac* … actínio; *Be* … berílio; *Cs* … césio; *Ga* … gálio; *Ge* … germânio; *He* … hélio; *Hf* … háfnio; *In* … índio; *Kr* … crípton; *Ma* … masúrio; *Mo* … molibdeno; *Nb* … nióbio; *Ne* … néon; *Os* … ósmio; *Pa* … proto-actínio; *Po* … polónio; *Ra* … rádio; *Rb* … rubídio; *Re* … rénio; *Rh* … ródio; *Rn* … radon; *Ru* … ruténio; *Sc* … escândio; *Ta* … tântalo; *Th* … tório; *Ti* … titânio; *Tl* … tálio; *U* … urânio; *V* … vanádio; *W* … tungsteno; *X* … xénon; *Y* … ítrio; *Zr* … zircónio.

Figure 3. Two presentations of the periodic classification in textbooks from the same author, the first in 1906 from Achilles Machado, *op. cit*, (ref. 87, pp. 95-98) and the second in 1938, in Achilles Machado, *op. cit.* (ref. 91, pp. 108-121).

complete periodic table for student's use, which we will analyze here later (Figures 4a and 4b).

With more detail, it is interesting to look at the evolutionary arrangement of the elements in the periodic classifications presented. Table 4 shows the list of these books according to the number of pages dedicated to the subject/total number of pages of the book, number of series or periods (rows) and groups (columns), and the presence of Lothar Meyer's curve (plot of the atomic volume versus atomic weight).

Of the thirty-nine books examined, which span from 1850 to 1975, fifteen were published during the nineteenth century. Some were addressed to people with no formal education, others for teaching at the secondary level, and finally the rest for polytechnic and university level. Concerning the classification of the elements there are clearly two options: the classification into metals and metalloids is present in twenty five books, five for university/Polytechnic, but only two dating from the first decade of the twentieth century, and Mendeleev′s is mentioned in fifteen books, none of them for the Basic Secondary. It should be emphasized that three of the books, published between 1888 and 1910, present both classifications.

5. PERIODIC SYSTEM CHARTS

We cannot imagine a chemistry room without a periodic table, and more recently the habit is that students have their own periodic chart on top of their chemistry textbooks. This section describes the charts found for the chronological period under investigation. At the University of Coimbra, from 1872 onwards, the Chemical Analysis course was taught independently from the Organic Chemistry course and, by law of 1890, it became mandatory to be taught at a practical level. The teaching room of the laboratory building had two wall charts: one with the names and symbols of the elements, along with some properties, such as "atomic weights, equivalents, specific heats, densities, molecular composition, etc."; the other one the scheme of Mendeleev's periodic law" (69 elements).[100] Although we could not find these charts, we think they were probably similar to those published in the German edition of Mendeleev's book (1891),[101] (Figure 4) as the professor in charge since 1888, Francisco Sousa Gomes, used this book in his lectures. As other clues are missing, we do not know if the tables were reproduced or translated into Portuguese.

Table 4. Mentions of Mendeleev's classification in the Portuguese textbooks analysed from 1880 (first mention found) to 1975.

Book	Teaching level	Number of pages	Lothar Meyer's curve	Periods	Groups
Francisco Corrêa Barata[83] (1880)	University (Coimbra)	c.20/96 known	Yes (description)	10 series	8
Virgílio Machado & Achilles Machado[84] (1892)	Polytechnic (Lisbon)	2/666 1/640	No	8	7
Eduardo Burnay[85] (1888)	Polytechnic (Lisbon)	2/115	--	10	7
Francisco Sousa Gomes (1895)[86]	University (Coimbra)	40/590	Yes	12 series	8
Achilles Machado[87] (1906)	Upper Secondary	8/c.250	No	11 series	8
L. Troost,[88] translated by Ramiz Galvão (1910) from 29th ed.	University (Coimbra)	2/428	No	10 series	8
Achilles Machado[89] (1916)	Upper Secondary	9/276	Yes	11 series	8
Pereira Forjaz, Ferreira de Mira & Kurt Jacobson (1937)[90]	University (Lisbon)	3/235	No	7	8+1 (Group zero)
Achilles Machado[91] (1938)	Upper Secondary	14/151	Yes	7	8+1 (Group zero)
Pereira Forjaz (1940)[92]	University (Lisbon)	3/110	No	-	7
Carlos de Azevedo Coutinho Braga[93] (1944)	University (Porto)	0,5/111	No	7	8
Sena Esteves[94] (1946)	Upper Secondary	13/ 271	Yes (extended after Ce by Nernst)	7	8
Rómulo de Carvalho[95] (1950)	Upper Secondary	9/359	Yes	12 series	8+1 (Group zero)
Alice Maia Magalhães & Túlio Lopes Tomás[96] (1961)	Upper Secondary	1/344	No	-	8
Helena Côncio de Sousa[97] (1973)	Upper Secondary	8/90	Yes	-	-
José A. Teixeira e Adriana Sousa Nunes[98] (1973)	Basic Secondary	4/236	No	7	8
Helena Côncio de Sousa[99] (1975)	Upper Secondary	34/159	Yes	7	8+1 (Group zero)

Another periodic chart that is now displayed at the Science Museum of the University of Coimbra is probably the oldest surviving one used in the university teaching in Portugal (Figure 5). It is in Portuguese, listing 92 elements, from which two of them were not yet discovered (85 *astatine* and 87 *francium*). To the best of our knowledge, the details of its production are unknown. Concerning its date, it seems to span from 1926 to 1937. It should be mentioned that we found a picture of this table referring the date of 1931, but without any supporting evidence either in the text or in the bibliography.[102]

The layout consists of seven periods, eight groups plus a zero group for the noble gases. For the periods IV, V, and VI there are two rows (two series), a and b, one above the other.

As it shows *illinium* Il (as element 61), allegedly discovered in 1926, also named *florentium* Fl, by Luigi Rocca (1926) and later to be named *promethium* Pm (1945, but only announced in 1947) by IUPAC, this sets the lower time limit to 1926.

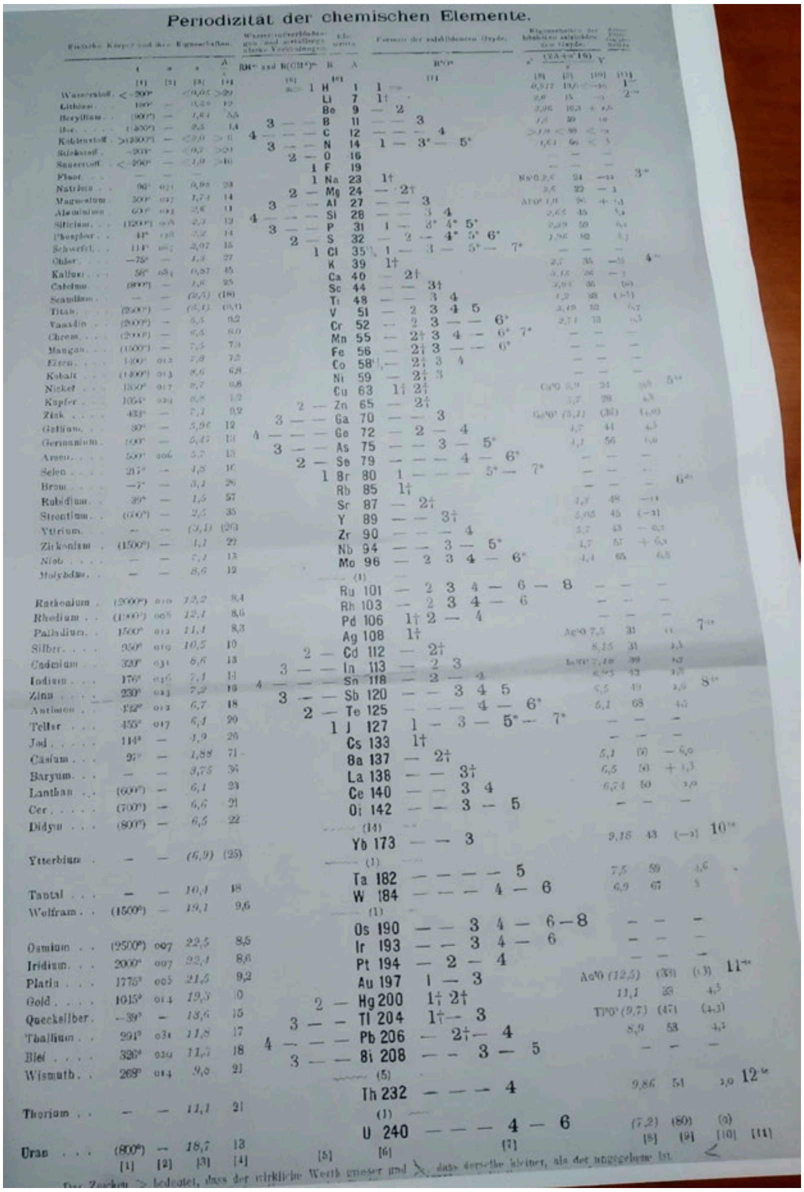
The fact that there is no indication of the atomic weight of *protactinium* Pa, first measured in 1934[103] by Aristid von Grosse (1905-1985), and only shown in an official table of atomic weights of the International Union of Chemistry, in 1937,[104] can be an argument to set the upper limit to 1937.

The last atomic number shown is 92, which corresponds to *uranium*. The next two elements, *neptunium* 93, and *plutonium* 94 were only discovered/synthetized in 1940, and their discovery being only shared after the war.

There is another interesting fact about this table. Element 86, with atomic mass of 222 is *radon*, and one early name was *niton*. However, its symbol is listed here as Em. It corresponds to the designation of 'emanation', which was used commonly until the late 1960s (despite IUPAC's decision in 1923 that element 86 is radon).

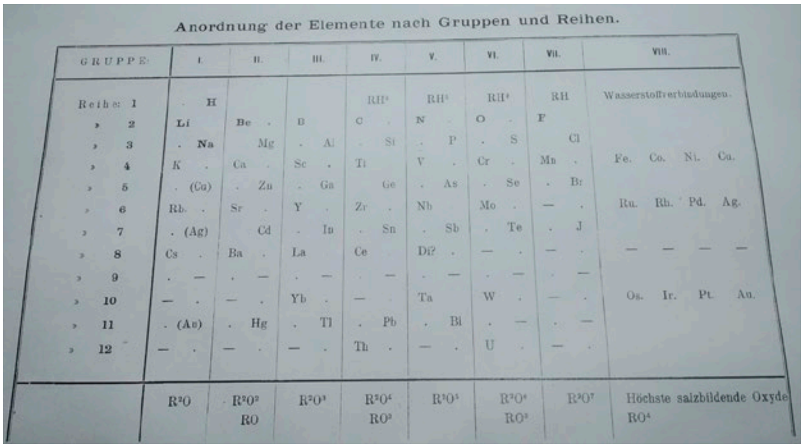
There is clearly a misprint as elements 37 and 45 have the same symbol Rb, since 37 is *rubidium* (Rb) and 45 is *rhodium* (Rh). Element 69 *thullium* is symbolized as Tu, in Portuguese, as well as in the periodic table of Meyer (1918),[105] while it seems that there was a widespread use of the actual symbol Tm.

It still presents the symbol Ma (*masurium*) for element 43 whose discovery was announced in 1925 but not confirmed experimentally. Since 1947, element 43 is named *technetium* (Tc) after it was artificially produced in 1937.



Periodizität der chemischen Elemente.

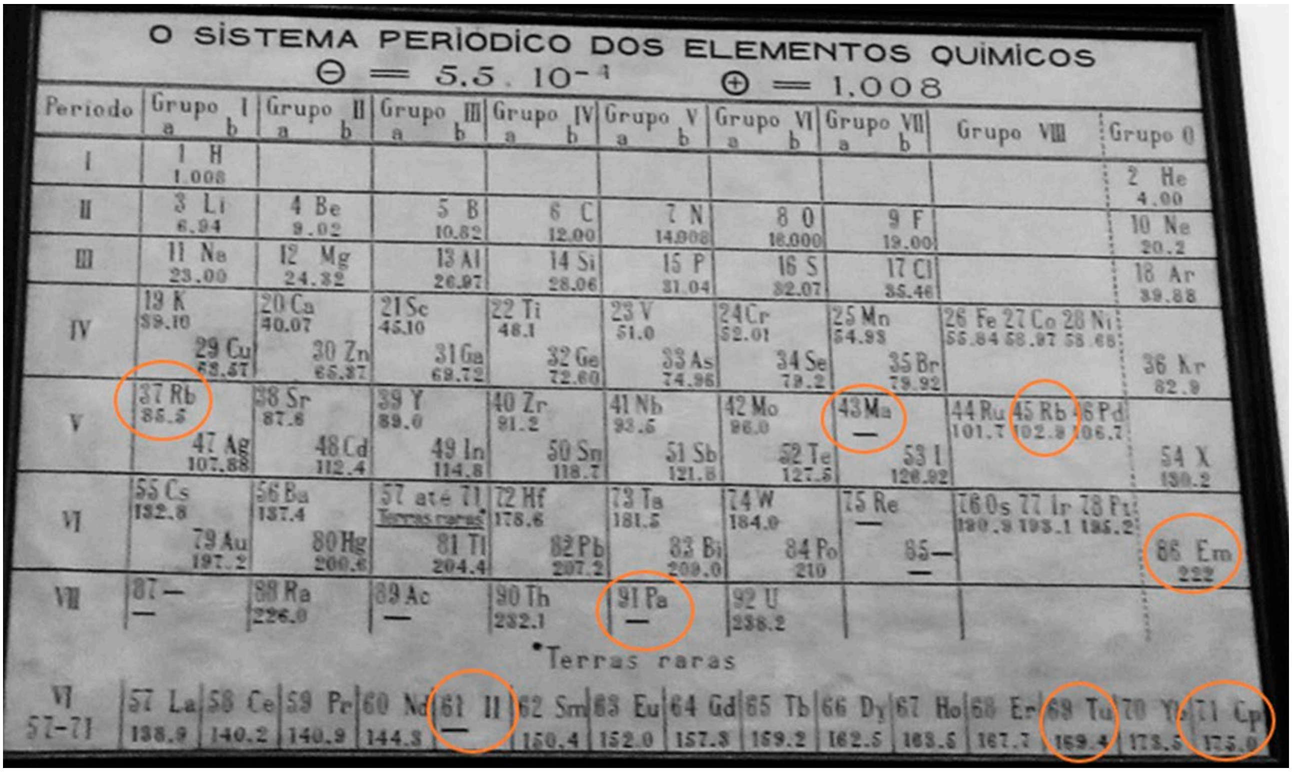
Das Zeichen > bedeutet, dass der wirkliche Werth grösser und <, dass derselbe kleiner, als der angegebene ist.



Anordnung der Elemente nach Gruppen und Reihen.

GRUPPE:	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
Reihe: 1	. H			RH⁴	RH³	RH²	RH	Wasserstoffverbindungen.
» 2	Li	Be .	B	C .	N .	O .	F	
» 3	. Na	Mg	. Al	. Si	. P	. S	Cl	
» 4	K .	Ca .	Sc .	Ti	V .	Cr .	Mn .	Fe. Co. Ni. Cu.
» 5	. (Cu)	. Zn	. Ga	Ge	. As	. Se	. Br	
» 6	Rb. .	Sr .	Y .	Zr .	Nb	Mo .	— .	Ru. Rh. Pd. Ag.
» 7	. (Ag)	Cd	. In	. Sn	. Sb	. Te	. J	
» 8	Cs .	Ba .	La	Ce	Di? .	— .	— .	— — — —
» 9	. —	. —	. —	. —	. —	. —	. —	
» 10	— .	— .	Yb .	—	Ta	W .	— .	Os. Ir. Pt. Au.
» 11	. (Au)	. Hg	. Tl	. Pb	. Bi	. —	. —	
» 12	— .	— .	— .	Th .	— .	U .	— .	
	R^2O	R^2O^2 RO	R^2O^3	R^2O^4 RO^2	R^2O^5	R^2O^6 RO^3	R^2O^7	Höchste salzbildende Oxyde RO^4

Figure 4. Tables inserted in D. Mendelejeff, *Grundlagen der Chemie*, 1891 (ref. 101, tables not paginated)



O SISTEMA PERIODICO DOS ELEMENTOS QUIMICOS

$\ominus = 5.5 \cdot 10^{-4}$ $\oplus = 1.008$

Periodo	Grupo I a b	Grupo II a b	Grupo III a b	Grupo IV a b	Grupo V a b	Grupo VI a b	Grupo VII a b	Grupo VIII	Grupo 0
I	1 H 1.008								2 He 4.00
II	3 Li 6.94	4 Be 9.02	5 B 10.82	6 C 12.00	7 N 14.008	8 O 16.000	9 F 19.00		10 Ne 20.2
III	11 Na 23.00	12 Mg 24.32	13 Al 26.97	14 Si 28.06	15 P 31.04	16 S 32.07	17 Cl 35.46		18 Ar 39.88
IV	19 K 39.10 29 Cu 63.57	20 Ca 40.07 30 Zn 65.37	21 Sc 45.10 31 Ga 69.72	22 Ti 48.1 32 Ge 72.60	23 V 51.0 33 As 74.96	24 Cr 52.01 34 Se 79.2	25 Mn 54.93 35 Br 79.92	26 Fe 27 Co 28 Ni 55.84 58.97 58.68	36 Kr 82.9
V	37 Rb 85.5 47 Ag 107.88	38 Sr 87.6 48 Cd 112.4	39 Y 89.0 49 In 114.8	40 Zr 91.2 50 Sn 118.7	41 Nb 93.5 51 Sb 121.8	42 Mo 96.0 52 Te 127.5	43 Ma — 53 I 126.92	44 Ru 45 Rb 46 Pd 101.7 102.9 106.7	54 X 130.2
VI	55 Cs 132.8 79 Au 197.2	56 Ba 137.4 80 Hg 200.6	57 até 71 Terras raras* 81 Tl 204.4	72 Hf 178.6 82 Pb 207.2	73 Ta 181.5 83 Bi 209.0	74 W 184.0 84 Po 210	75 Re — 85 — —	76 Os 77 Ir 78 Pt 190.9 193.1 195.2	86 Em 222
VII	87 — —	88 Ra 226.0	89 Ac —	90 Th 232.1	91 Pa —	92 U 238.2			

*Terras raras

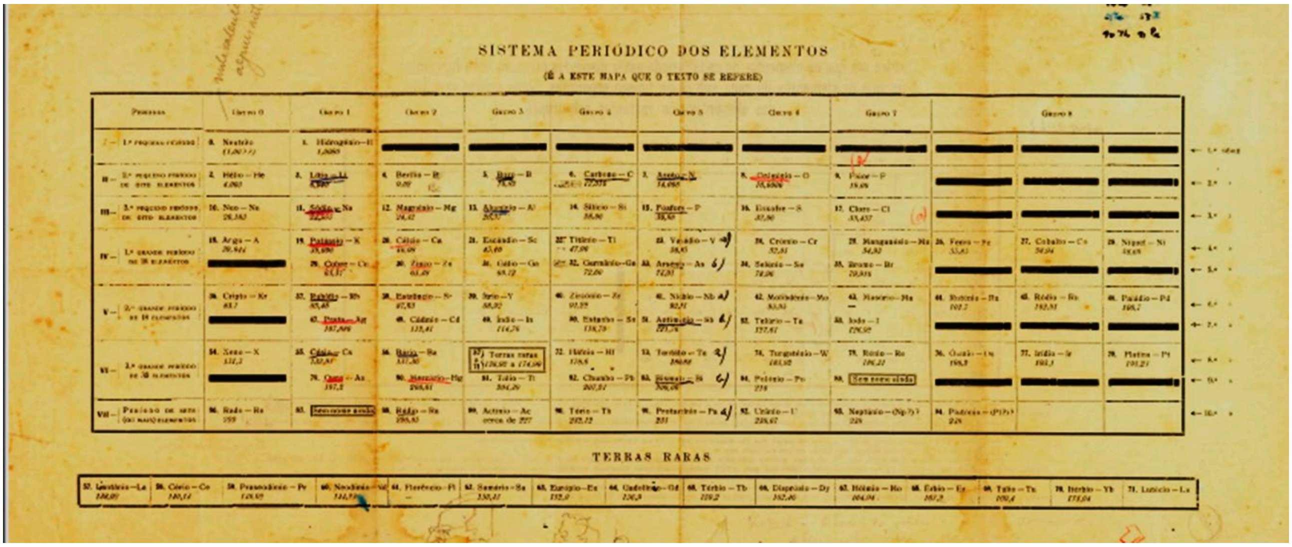
VI 57-71	57 La	58 Ce	59 Pr	60 Nd	61 Il	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tu	70 Yb	71 Cp
	138.9	140.2	140.9	144.3	—	150.4	152.0	157.3	159.2	162.5	163.5	167.7	169.4	173.5	175.0

Figure 5. Periodic table in display at the Science Museum, University of Coimbra. Photo by Isabel Malaquias.

As a last note, element 71 (*lutetium*) is still symbolized as Cp (*cassiopeium*), denoting some German influence. German scientists continued to name it *cassiopeium* until World War II.[106]

Analyzing the textbooks for upper secondary, it is interesting to observe the folding periodic table inserted in Sena Esteves' textbook (1946).[107] The chart is in Portuguese (Figure 6a), and is accompanied by a detailed 13-pages description (with two inserted diagrams). In a footnote the author mentions that a professor of the University of Lisbon, Manuel Valadares (1904-1982), who got his PhD under the supervision of Madame Curie and had been working in Geneva and Italy before returning to Portugal (1940), discovered the element 87 (1941).[108] From his work in Italy, Valadares published a series of papers dealing with the observation of new characteristic lines of element 85, and not 87, as referred in Sena Esteves' book.[109] The folding chart is inserted between pages 168 and 169. It shows seven periods and eight groups, the group zero starting with the neutron and followed by the noble gases. Considering the periods, it mentions the short periods: the first one, presenting neutron and hydrogen, the second and third period with eight elements; the seventh period with “sete (ou mais) elementos” (seven (or more) elements). For the large periods, IV, V and VI, each cell contains the A and B elements. Some cells have the indication of the elements known, although without a name (85 and 87). Element 61 is still named *florentium* (Fl), element 43 is *masurium*, occurring its change to *technetium* in 1947, and for *plutonium* (94), it appears a question mark for the symbol. In the reverse page, the periodic table is presented in full extension, i.e. showing all the elements of each period in a unique row (Figure 6b), group zero being the first one. It is mentioned that hydrogen should form a special group. There exists a separation between metals and non-metals and ten series, each two corresponding to groups IV, V, and VI. The author mentions that some elements, like Ge, Sb, etc., although present among metals could also be positioned among non-metals, such as Si and As.

By 1965, Portuguese upper secondary school students were able to purchase a periodic classification chart, similar to the one in Figure 7, by E. H. Sargent & Co. It is interesting to note that while the classes were held in Portuguese, the table was in English, foreseeing its future use at the university. Its handwritten notes were added while the student was taking Organometallic Chemistry at the Lisbon Technical University.[110]


SISTEMA PERIODICO DOS ELEMENTOS

(É A ESTE MAPA QUE O TEXTO SE REFERE)

TERRAS RARAS

Figure 6a. Recto of the unfolding chart with periodic classification system included in F. Sena Esteves' textbook (ref. 94).


Quadro em que os elementos de cada periodo estão dispostos numa só linha horizontal para que os elementos de cada sub-grupo fiquem separados, numa coluna privativa, dos elementos dos restantes sub-grupos

Figure 6b. Verso of the unfolding chart with periodic classification system included in F. Sena Esteves' textbook (ref. 94).

Nowadays, and according to the recommendations of IUPAC, the periodic table used in Portuguese classrooms has 18 groups, but this numbering system is not yet in wide use.[111] The traditional system involved the use of the letters A and B. The first two groups were IA and IIA, while the last six groups were IIA through VIIA. The middle groups use B in their titles and Group VIII was in between VIIB and IB. Noble gases were considered a separate group. In the early part of the twentieth century groups A and B were shown in the same slot, with or without explicit mention, and this is the reason why most of the books only show nine groups (eight plus group zero of the noble gases).

6. FINAL REMARKS

Based on the historical sources analyzed, it is possible to conclude about the early Portuguese acquaintance with Mendeleev´s classification and its reception and circulation. The Mendeleev's classification was more or less commonly known during the 1880 decade in Portuguese

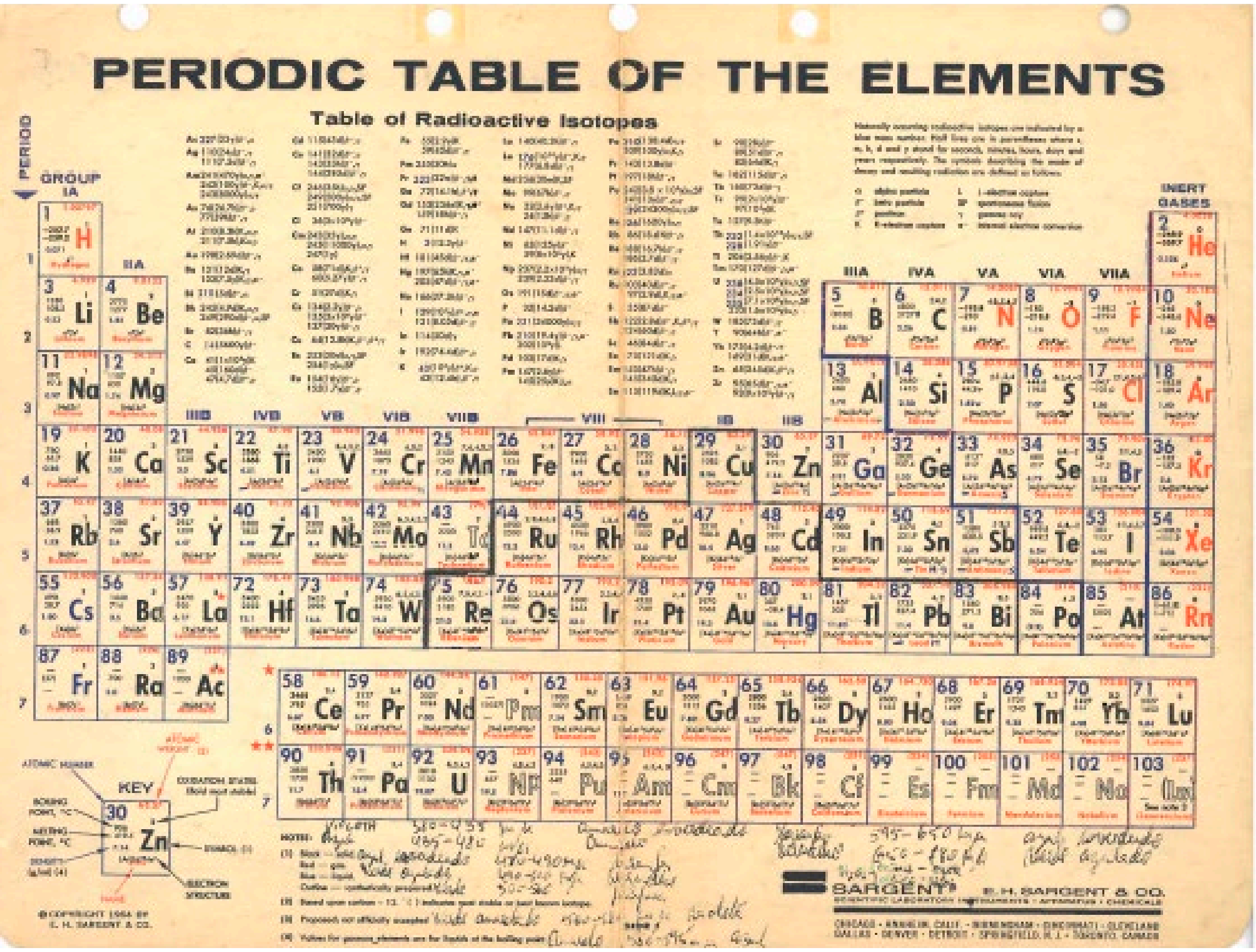


Figure 7. Periodic classification chart by E. H. Sargent & Co. Photo by João Oliveira.

higher education, and acknowledged and used by its professors.

The first mention in 1880 is framed in the discussion of primeval matter and a version of atomic theory based on Prout's hypothesis: Mendeleev is mentioned for his law, as a support to the unity of matter. In teaching manuals, there was the idea of avoiding the more philosophical theories from the chemistry presentation; even when some authors mention the atomic theory, they insist on taking a pragmatic approach. Very recently, we had access to a truncated version of a textbook published at the University of Coimbra in 1880, where clearly the author presents Mendeleev's law as accepted. From 1888 onwards, it was mostly used as a classification and a pedagogical tool, as it enabled a more rational presentation of chemistry to the students according to some professors' testimony.

For secondary level, the first presentation of Mendeleev's table occurs as an extra reading at the beginning of the twentieth century, but the situation in secondary school is split. Textbooks for basic secondary level did not address Mendeleev's classification, keeping instead a general division in metals and metalloids, with sometimes more detailed classification inspired by early 19th century chemists, and this was the case at least until 1967. The official programs for upper secondary included explicitly the periodic classification by the middle of 1940 decade. Unlike what happens for the basic level, and starting in 1892, one finds the presentation of the periodic classification in textbooks by Achilles Machado (1906-1938) for the upper secondary. After the reform in 1936 and until 1975, the periodic classification became a subject being taught and is from then on included in textbooks even though the amount of pages dedicated to its explanation can be very scarce in some cases.

The use of periodic classification wall charts started at the University of Coimbra in the 1890 decade, while the oldest surviving one appears to be produced between 1926 and 1937.

Interestingly, there is no printed periodic table for upper secondary level in textbooks before 1906. It took forty more years to include an updated configuration with a layout similar to the ones presently used. From then on until 1975, this subject entered the official programs and the textbooks included it systematically.

Through this study of the mention of Mendeleev's system, it is clear that the different contexts have triggered different interests for what we now regard as the indispensable tool for chemistry, and these contexts have shaped different responses, either philosophical or pedagogical. As a result, the appropriation of Mendeleev's classification occurred at different speed and stages depending on the usage it could be put to.

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3. *Ibid.*, p. 32.
4. *Ibid.*, p.71. Authors' translation.
5. *Ibid.*, p. 35.
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7. Atomicity relates with valence. For example, the alkaline metals all have the same atomicity because they form a series of closed related combinations.
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13. J. L. Brandão da Luz, *A propagação do positivismo em Portugal*, in *O Século XIX*, *vol. IV, Tomo I*, (Eds.: P. Calafate), Círculo de Leitores, Lisboa, **2004**, pp. 239–261, 246.
14. Amorim da Costa (note 1), pp. 273–274.
15. Amorim da Costa (note 1), pp. 274–275.
16. A. J. Ferreira da Silva, *Tratado de Chimica Elementar—Tomo I—Chimica Mineral*. 2nd edition, Typographia de A. J. da Silva Teixeira, Porto, **1895**.
17. Ferreira da Silva, *op. cit.*, (note 40), pp. ix–x. Authors' translation.
18. Ferreira da Silva, *op. cit.*, p. 102. Authors' translation.
19. Probably a copy of the French translation from the 5th German edition made by Albert Bloch *Les théories modernes de la chimie et leur application à la mécanique chimique* par Lothar Meyer; ouvrage traduit de l'allemand sur la 5e édition, par M. Albert Bloch et J. Meunier., G. Carré, Paris, **1887**, still existent in Coimbra.
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23. Gl – *glucinium*, later designated *beryllium*. On spurious elements, see M. Fontani, M. Costa, M. V. Orna, *The lost elements: the periodic table's shadow side*, Oxford University Press, Oxford, 2014.
24. Pp – *pelopium*, later found to be either identical to niobium or mixtures of niobium and tantalum. Cfr. *The lost elements*, ref. in note 23.
25. Il – *ilmenium*, later found to be either identical to niobium or mixtures of niobium and tantalum. Cfr. *The lost elements*, ref. in note 23.
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28. Az – *azote*, later designated *nitrogen*.
29. Fl – *fluore*, later designated *fluorine*.
30. Malaquias, *op. cit.*, p. 249.
31. Decipium was shown to be a mixture of samarium and other rare earth elements. Cfr. *The lost elements,* ref. in note 23.

32. Later to be found identical to another recently discovered element, *holmium*. Cfr. *The lost elements,* ref. in note 23.
33. Described as occurring with the cerium earths, like *decipium* and *philipium*. Cfr *The lost elements,* ref. in note 23.
34. Later shown to be a mixture of *iridium* and *rhodium*. Cfr *The lost elements,* ref. in note 23.
35. Discredited discovery. Cfr *The lost elements,* ref. in note 23.
36. Burnay, *op. cit.*, (note 50), 93. On spurious elements, see M. Fontani, M. Costa, M. V. Orna, *The lost elements: the periodic table's shadow side,* Oxford University Press, Oxford, **2014**.
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The St Andrews Periodic Table Wallchart and its Use in Teaching

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Abstract. An early surviving copy of a periodic table of the elements wallchart is described and it is compared with other early versions of the periodic table. The status of chemistry teaching in St Andrews at the time and particularly the lectures of Professor Thomas Purdie are considered to show the context in which this periodic table would have been used and gain some appreciation of it pedagogical importance.

Keywords. Periodic table wallcharts, Thomas Purdie, teaching tools.

INTRODUCTION

In June 2014 an old periodic table wallchart was discovered in the course of clearing out a storage space at the University of St Andrews. Based on the absence of the element germanium (discovered 1886), it could be dated to the 1880's and a subsequent investigation showed that it was produced in Vienna in 1885 and ordered for delivery to St Andrews by the newly appointed Professor Thomas Purdie from the scientific supply company C. Gerhardt of Bonn in October 1888.[1] In this article we describe in detail the features of this historic periodic table and how it relates both to other early periodic table wallcharts, and to the teaching of chemistry in St Andrews at that time.

Very fortunately, meticulous notes made by Professor Purdie have been preserved in the University of St Andrews Library. These report several instances of his teaching such things as atomicity (valency) and periodicity. In his lectures he refers to the periodic system of classification of the elements and mentions the discoveries made with the aid of the periodic law, in particular the correction of atomic weights and the discovery of new elements.

The wallchart also presents chalk markings recording some of the new elements such as the noble gases, which with the exception of helium (first recognised in the sun in 1868) were discovered in the 1890s. This interaction with the wallchart gives a remarkable insight into the teaching of chemistry in the late 19th century.

THE ST ANDREWS TABLE

The St Andrews periodic table was printed on canvas-backed paper and was found rolled up with a wooden hanging baton at the top (Figure 1).[2] Its size is approximately 115 × 85 cm and the layout closely follows Mendeleev's second Table of 1871 (Figure 2).[3] In this the known elements are arranged vertically in groups according to their properties and in particular the formula of their oxides and/or hydrides, and then horizontally according to increasing atomic weight. The title is in German and the table was produced in Vienna, at that time part of the Austro-Hungarian Empire. At the bottom left the publisher is identified: "Verlag v. Lenoir & Forster, Wien", while at the bottom right the printer is named: "Lith. v. Ant. Hartinger & Sohn, Wien". The publisher George André Lenoir (1825–1909) studied chemistry and physics in his native Kassel and in Paris and settled in Vienna in the 1850's where he established a scientific instrument factory as well as a publishing house, later run in partnership with Forster. [4] Originally based at Magdalenenstrasse 14, the business moved in 1888 to Waagasse 5 in Vienna's 4th district. Anton Hartinger (1806–1890) was a Viennese artist and lithographer who specialised in flower painting and was a pioneer of chromolithography.

Although the presence and absence of certain elements allows us to date the table to the time period 1879–1886, more definitive evidence for its precise date of publication was obtained by researching historical documents. In his definitive listing of historical chemistry resources,[5] H. C. Bolton (1843–1903) lists an item "Wandtafel der Periodische Gesetzmässigkeit der Elemente nach Mendelejeff. Wien, 1885." whose title corresponds exactly to that of the St Andrews table and with a date in the right range. However this gave no indication of the publisher or suppliers and to make further progress we had to check the university accounts and records from that time. In the archives of the University of St Andrews an invoice was discovered dated 16th October 1888 from C. Gerhardt (Bonn) to "United College, St Andrews, Scotland", accompanied by a receipt addressed to Professor Thomas Purdie, with an item:[6]

2359 1 Wandtafel von Mendelejeff 3.–

After some effort a copy of the catalogue of C. Gerhardt (7th edition, 1885) was located at the National

Periodische Gesetzmässigkeit der Elemente nach Mendelejeff.

Reihen	Gruppe I R^2O	Gruppe II RO	Gruppe III R^2O^3	Gruppe IV RH^4 RO^2	Gruppe V RH^3 R^2O^5	Gruppe VI RH^2 RO^3	Gruppe VII RH R^2O^7	Gruppe VIII RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	Sc=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59 Ni=59, Cu=63
5	(Cu=63)	Zn=65	Ga=68	–=72	As=75	Se=79	Br=80	
6	Rb=85	Sr=87	Yt=88	Zr=90	Nb=94	Mo=96	–=100	Ru=104, Rh=104 Pd=106, Ag=108
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	Ce=137	La=139	–	Di=145?	–	– – – –
9	(–)	–	–	–	–	–	–	
10	– 165	– 169	Er=170	–173	Ta=182	W=184	–	Pt=194, Os=195(?) Ir=193, Au=196
11	(Au=196)	Hg=200	Tl=204	Pb=206	Bi=210	–	–	
12	–	–	–	Th=231	–	U=240	–	– – – –

Verlag v. Lenoir & Forster, Wien

Lith. v. Ant. Hartinger & Sohn, Wien

Figure 1. The St Andrews Periodic Table Wallchart as discovered. R. Alan Aitken, 2014.

Museum of Natural History and Science, University of Lisbon, and in this the following entry appears:

> *2359 Periodische Gesetzmässigkeit der Elemente nach Mendelejeff. Wandtafel von 116 × 87 Mark 3.–*[7]

This then provided clear evidence that our table was printed in Vienna in 1885 and ordered for delivery to St Andrews in October 1888.

Interestingly, the immediately preceding item on the invoice:[7]

> *2358 Wandtafeln von 1–5 Lieferung I* 6.–

as well as the corresponding entries on a later invoice of 11th January 1889

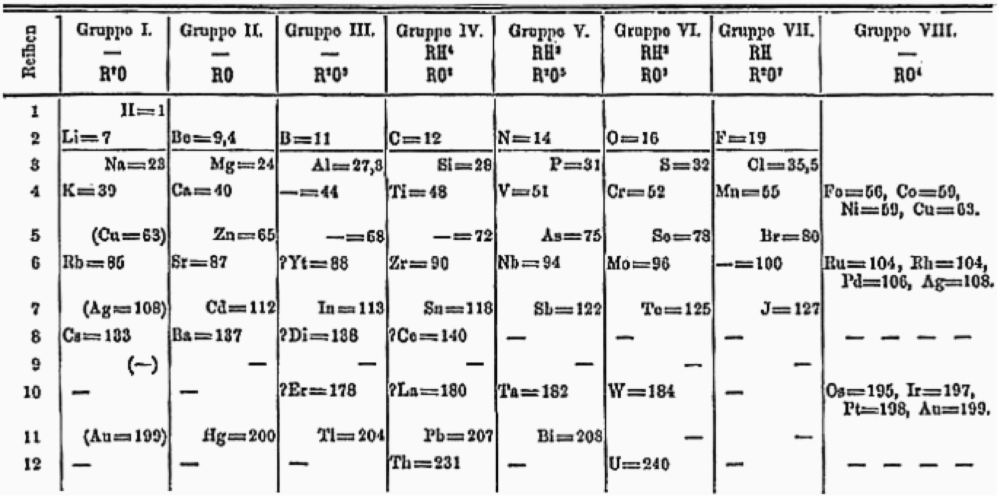
> *2358 Wandtafeln von 6-10 Lieferung II* 6.–
> *" " 11-15 " III* 6.–

could be identified as the series of 15 chemistry wallcharts produced by Dr Georg v. Schroeder (1843–1895) and Dr Julius v. Schroeder (1808–1888) of which number 3 showing the production of nitric acid ("Taf. III saltpetersaüre fabrikation") has also survived and was discovered in the same store-room along with the periodic table. These charts with the series title "Tafeln für den Unterricht in der allgemeinen Chemie und chemischen Technologie" also date from 1885 and were printed and published by Theodor Fischer in Kassel.[8] It is clear that the periodic table wallchart was by no means a unique item, but rather one of many such wallcharts that were ordered up and used routinely in teaching chemistry in St Andrews in the 1880's.

In view of its importance, plans were made to restore and conserve the table and this work was carried out between November 2017 and May 2018 by conservator Richard Hawkes at Artworks Conservation in Harrogate. First the paper was surface cleaned using a brush to remove loose surface dirt and debris. The canvas backing was peeled away gradually, scraping away the adhesive (flour paste) after swelling with methyl cellulose. To remove the soluble discolouration and some of the acidity, the paper was washed in de-ionised water adjusted to a neutral pH with calcium hydroxide. The paper was de-acidified and left with an alkaline reserve to counter future acidity by immersing in a bath of 0.1M magnesium hydrogen carbonate (pH 6.5). Strips of strong and long fibered Japanese paper derived from the kozo plant, were applied with wheat starch paste to repair tears and losses. The restored original is now housed in conservation grade material and is stored in Special Collections' climate-controlled stores in the University. A full-size facsimile is now on display in the School of Chemistry (Figure 3).

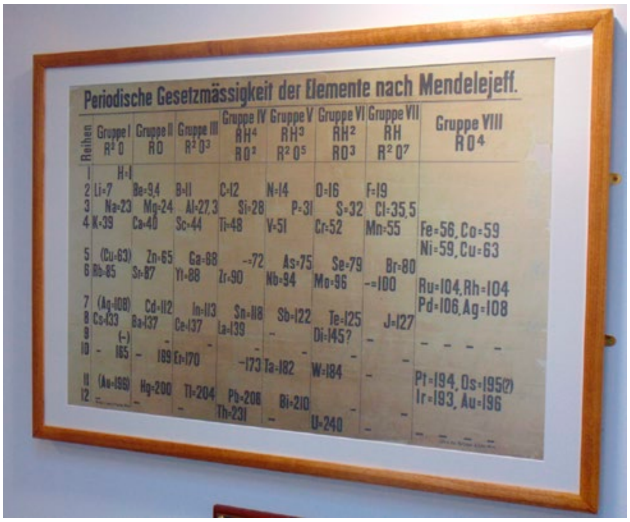
OTHER EARLY PRINTED WALL CHART TABLES

The most closely similar periodic table wallchart to the St Andrews table of which we are aware is one housed at Kyoto University Library, Japan and dated 1893 (Figure 4). This is also published by Lenoir & Forster, but from their later (post 1888) Waaggasse address and, following Hartinger's death in 1890, we have a new lithographer "Lith. v. Guberner & Hierhammer Wien, IV. Hptst. 51." The layout is essentially identical but crucially germanium (discovered 1886[9]) is now present, the posi-



Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

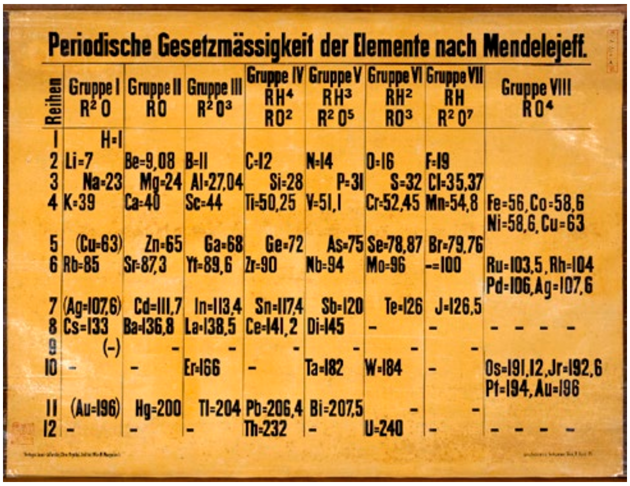
Figure 2. Mendeleev's second Table of 1871 taken from ref. 3 (p. 151).



Periodische Gesetzmässigkeit der Elemente nach Mendelejeff.

Reihen	Gruppe I R^2O	Gruppe II RO	Gruppe III R^2O^3	Gruppe IV RH^4 RO^2	Gruppe V RH^3 R^2O^5	Gruppe VI RH^2 RO^3	Gruppe VII RH R^2O^7	Gruppe VIII RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	Sc=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59 Ni=59, Cu=63
5	(Cu=63)	Zn=65	Ga=68	–=72	As=75	Se=79	Br=80	
6	Rb=85	Sr=87	Yt=88	Zr=90	Nb=94	Mo=96	–=100	Ru=104, Rh=104 Pd=106, Ag=108
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	Ce=137	La=139	–	Di=145?	–	– – – –
9	(–)	–	–	–	–	–	–	
10	– 165	– 189	Er=170	–173	Ta=182	W=184	–	Pt=194, Os=195(?) Ir=193, Au=196
11	(Au=196)	Hg=200	Tl=204	Pb=206	Bi=210	–	–	
12	–	–	–	Th=231	–	U=240	–	– – – –

Figure 3. Facsimile of the St Andrews Table on display following conservation. University of St Andrews School of Chemistry. R. Alan Aitken, 2018.



Periodische Gesetzmässigkeit der Elemente nach Mendelejeff.

Reihen	Gruppe I R^2O	Gruppe II RO	Gruppe III R^2O^3	Gruppe IV RH^4 RO^2	Gruppe V RH^3 R^2O^5	Gruppe VI RH^2 RO^3	Gruppe VII RH R^2O^7	Gruppe VIII RO^4
1	H=1							
2	Li=7	Be=9,08	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,04	Si=28	P=31	S=32	Cl=35,37	
4	K=39	Ca=40	Sc=44	Ti=50,25	V=51,1	Cr=52,45	Mn=54,8	Fe=56, Co=58,6 Ni=58,6, Cu=63
5	(Cu=63)	Zn=65	Ga=68	Ge=72	As=75	Se=78,87	Br=79,76	
6	Rb=85	Sr=87,3	Yt=89,6	Zr=90	Nb=94	Mo=96	–=100	Ru=103,5, Rh=104 Pd=106, Ag=107,6
7	(Ag=107,6)	Cd=111,7	In=113,4	Sn=117,4	Sb=120	Te=126	J=126,5	
8	Cs=133	Ba=136,8	La=138,5	Ce=141,2	Di=145	–	–	– – – –
9	(–)	–	–	–	–	–	–	
10	–	–	Er=166	–	Ta=182	W=184	–	Os=191,12, Jr=192,6 Pt=194, Au=196
11	(Au=196)	Hg=200	Tl=204	Pb=206,4	Bi=207,5	–	–	
12	–	–	–	Th=232	–	U=240	–	– – – –

Figure 4. Kyoto University periodic table, 1893. Kyoto University Rare Materials Digital Archive (https://rmda.kulib.kyoto-u.ac.jp/en/item/rb00024049)

tions of lanthanum and cerium have been interchanged, and many of the atomic weights are given with greater precision. The same basic layout was retained well into the 20th century and in the N. D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, Moscow, there is a large table following this original Mendeleev layout and going up as far as the element Mendelevium which was discovered only in 1955 (Figure 5).

A US table of intermediate age but retaining many of the features of the 19th century versions (Figure 6) was brought to our attention recently as a result of the publicity surrounding the St Andrews table.[10] This hangs in the Chemistry Department of the University of Northern Iowa, and probably dates from around 1910. All the inert gases are present as well as radium (discovered 1898) but not radon, actinium or lutetium. This table was supplied by the Eimer and Amend company.

ПЕРИОДИЧЕСКАЯ СИСТЕМА ЭЛЕМЕНТОВ
Д. И. МЕНДЕЛЕЕВА

Периоды	Ряды	ГРУППЫ ЭЛЕМЕНТОВ										
		I	II	III	IV	V	VI	VII	VIII			0
		R_2O	RO	R_2O_3	RH_4 RO_2	RH_3 R_2O_5	RH_2 RO_3	RH R_2O_7	RO_4			
I	1	H 1 1,0080						(H)				He 2 4,003
II	2	Li 3 6,940	Be 4 9,02	B 5 10,82	C 6 12,010	N 7 14,008	O 8 16,0000	F 9 19,00				Ne 10 20,183
III	3	Na 11 22,997	Mg 12 24,32	Al 13 26,97	Si 14 28,06	P 15 30,98	S 16 32,066	Cl 17 35,457				Ar 18 39,944
IV	4	K 19 39,096	Ca 20 40,08	Sc 21 45,10	Ti 22 47,90	V 23 50,95	Cr 24 52,01	Mn 25 54,93	Fe 26 55,85	Co 27 58,94	Ni 28 58,69	
	5	Cu 29 63,54	Zn 30 65,38	Ga 31 69,72	Ge 32 72,60	As 33 74,91	Se 34 78,96	Br 35 79,916				Kr 36 83,7
V	6	Rb 37 85,48	Sr 38 87,63	Y 39 88,92	Zr 40 91,22	Nb 41 92,91	Mo 42 95,95	Tc 43 (99)	Ru 44 101,7	Rh 45 102,91	Pd 46 106,7	
	7	Ag 47 107,880	Cd 48 112,41	In 49 114,76	Sn 50 118,70	Sb 51 121,76	Te 52 127,61	J 53 126,92				Xe 54 131,3
VI	8	Cs 55 132,91	Ba 56 137,36	La 57 * 138,92	Hf 72 178,6	Ta 73 180,88	W 74 183,92	Re 75 186,31	Os 76 190,2	Ir 77 193,1	Pt 78 195,23	
	9	Au 79 197,2	Hg 80 200,61	Tl 81 204,39	Pb 82 207,21	Bi 83 209,00	Po 84 210,0	At 85 (211)				Rn 86 222
VII	10	Fr 87 (223)	Ra 88 226,05	Ac 89 ** 227,0								

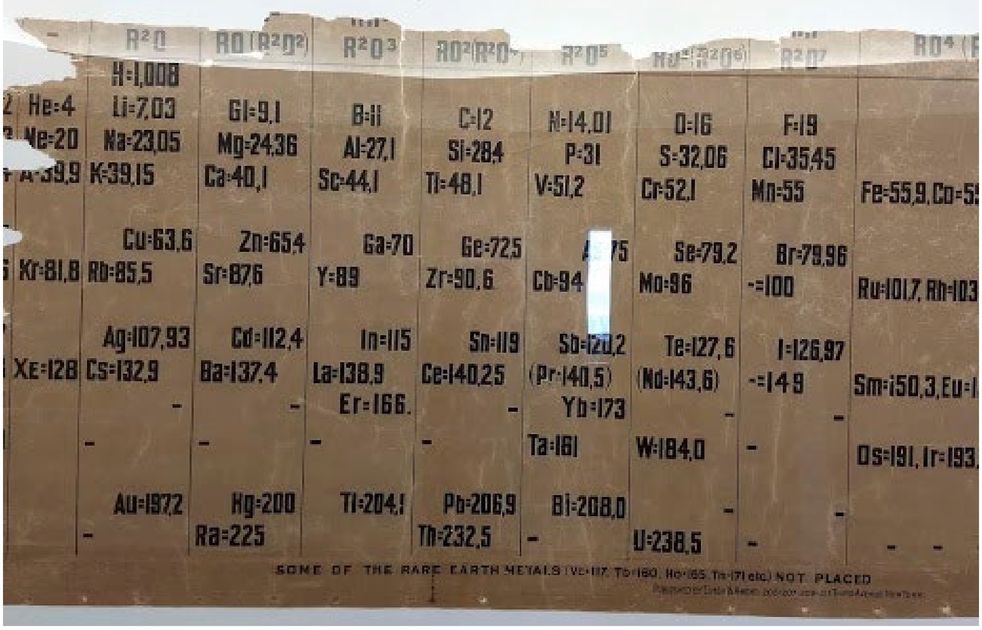
* ЛАНТАНОИДЫ							
	Ce 58 140,13	Pr 59 140,92	Nd 60 144,27	Pm 61 (147)	Sm 62 150,43	Eu 63 152,0	Gd 64 156,9
	Tb 65 159,2	Dy 66 162,46	Ho 67 164,94	Er 68 167,2	Tu 69 169,4	Yb 70 173,04	Lu 71 174,99

** АКТИНОИДЫ							
	Th 90 232,12	Pa 91 231	U 92 238,07	Np 93 (237)	Pu 94 (239)	Am 95 (241)	Cm 96 (242)
	Bk 97 (243)	Cf 98 (244)	E 99 (248)	Fm 100	Mv 101 (256)		

Figure 5. Table in the N.D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, Moscow. R. Alan Aitken, 2008.

Finally, we would like to mention a second, later, St Andrews table which nonetheless shows some interesting features (Figure 7). This is marked faintly in the bottom right corner “A. Gallenkamp & Co. Ltd., London” and probably dates after 1925 and before 1931 since hafnium (discovered 1922) is present but francium (discovered 1939) is not. In contrast to all the other tables mentioned here, this has names of elements written out in full rather than symbols. Less familiar names are used for several elements with columbium for niobium, celtium given as an alternative for hafnium, and brevium for protoactinium. An interesting case is masurium, which was announced along with rhenium by Noddack, Tacke and Berg in 1925 but was never isolated, as the element 43 was finally obtained in 1937 by bombarding molybdenum with deuterons and was named technetium.[11] It is also notable that rhenium (isolated in1925) appears but does not yet have an atomic weight value, the first measure of its atomic weight was done in 1928 and in 1931 IUPAC gave its first recommended value.[12] By this time the structure of the table was much better established and the few remaining gaps corresponded to confidently predicted elements that would soon be isolated such as francium (1939), astatine (1940) and promethium (1945).

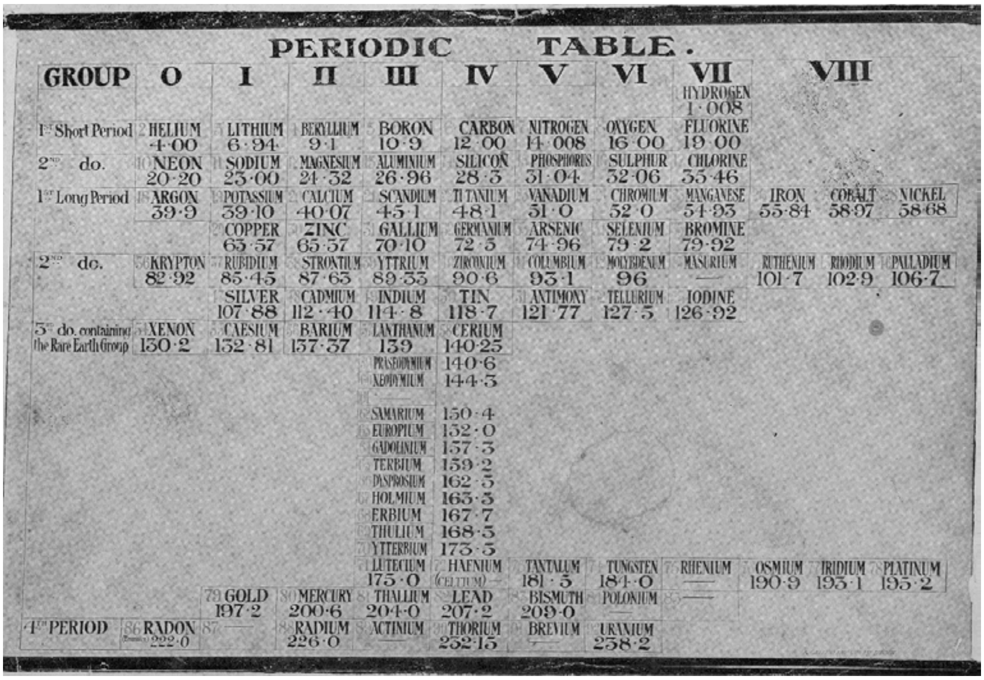
These are probably but a few examples of what still exists. The celebration in 2019 of the International Year of the Periodic Table of Chemical Elements has possibly led to the discovery or the resurfacing of old tables that, as in the case of St Andrews, have been put out of sight or mind for a number of years.



–	R^2O	$RO\,(R^2O^2)$	R^2O^3	$RO^2(R^2O$	R^2O^5	$RO^3(R^2O^6)$	R^2O^7	RO^4 (
	H=1,008							
He=4	Li=7,03	Gl=9,1	B=11	C=12	N=14,01	O=16	F=19	
Ne=20	Na=23,05	Mg=24,36	Al=27,1	Si=28,4	P=31	S=32,06	Cl=35,45	
A=39,9	K=39,15	Ca=40,1	Sc=44,1	Ti=48,1	V=51,2	Cr=52,1	Mn=55	Fe=55,9, Co=5
	Cu=63,6	Zn=65,4	Ga=70	Ge=72,5	A 75	Se=79,2	Br=79,96	
Kr=81,8	Rb=85,5	Sr=87,6	Y=89	Zr=90,6	Cb=94	Mo=96	-=100	Ru=101,7, Rh=103
	Ag=107,93	Cd=112,4	In=115	Sn=119	Sb=120,2	Te=127,6	I=126,97	
Xe=128	Cs=132,9	Ba=137,4	La=138,9	Ce=140,25	(Pr=140,5)	(Nd=143,6)	-=149	Sm=150,3, Eu=1
	-	-	Er=166.	-	Yb=173	-	-	
	-	-	-	-	Ta=161	W=184,0	-	Os=191, Ir=193,
	Au=197,2	Hg=200	Tl=204,1	Pb=206,9	Bi=208,0	-	-	
	-	Ra=225		Th=232,5	-	U=238,5	-	- - -

SOME OF THE RARE EARTH METALS (Vc=117, Tb=160, Ho=165, Tm=171 etc.) NOT PLACED

Figure 6. Table at the Department of Chemistry and Biochemistry, University of Northern Iowa, Cedar Falls. Courtesy of Laura Hoistad Strauss.



PERIODIC TABLE.

GROUP	O	I	II	III	IV	V	VI	VII	VIII		
								HYDROGEN 1·008			
1st Short Period	HELIUM 4·00	LITHIUM 6·94	BERYLLIUM 9·1	BORON 10·9	CARBON 12·00	NITROGEN 14·008	OXYGEN 16·00	FLUORINE 19·00			
2nd do.	NEON 20·20	SODIUM 23·00	MAGNESIUM 24·32	ALUMINIUM 26·96	SILICON 28·3	PHOSPHORUS 31·04	SULPHUR 32·06	CHLORINE 35·46			
1st Long Period	ARGON 39·9	POTASSIUM 39·10	CALCIUM 40·07	SCANDIUM 45·1	TITANIUM 48·1	VANADIUM 51·0	CHROMIUM 52·0	MANGANESE 54·93	IRON 55·84	COBALT 58·97	NICKEL 58·68
		COPPER 63·57	ZINC 65·37	GALLIUM 70·10	GERMANIUM 72·5	ARSENIC 74·96	SELENIUM 79·2	BROMINE 79·92			
2nd do.	KRYPTON 82·92	RUBIDIUM 85·45	STRONTIUM 87·63	YTTRIUM 89·33	ZIRCONIUM 90·6	COLUMBIUM 93·1	MOLYBDENUM 96	MASURIUM —	RUTHENIUM 101·7	RHODIUM 102·9	PALLADIUM 106·7
		SILVER 107·88	CADMIUM 112·40	INDIUM 114·8	TIN 118·7	ANTIMONY 121·77	TELLURIUM 127·5	IODINE 126·92			
3rd do. containing the Rare Earth Group	XENON 130·2	CAESIUM 132·81	BARIUM 137·37	LANTHANUM 139	CERIUM 140·25						
				PRASEODYMIUM	140·6						
				NEODYMIUM	144·3						
				—							
				SAMARIUM	150·4						
				EUROPIUM	152·0						
				GADOLINIUM	157·3						
				TERBIUM	159·2						
				DYSPROSIUM	162·5						
				HOLMIUM	163·5						
				ERBIUM	167·7						
				THULIUM	168·5						
				YTTERBIUM	173·5						
				LUTECIUM 175·0	HAFNIUM (CELTIUM) —	TANTALUM 181·5	TUNGSTEN 184·0	RHENIUM —	OSMIUM 190·9	IRIDIUM 193·1	PLATINUM 195·2
		GOLD 197·2	MERCURY 200·6	THALLIUM 204·0	LEAD 207·2	BISMUTH 209·0	POLONIUM —	—			
4th PERIOD	RADON 222·0	—	RADIUM 226·0	ACTINIUM —	THORIUM 232·15	BREVIUM —	URANIUM 238·2				

Figure 7. A later periodic table found at the University of St Andrews dating from the 1920's or 1930's. Courtesy of the University of St Andrews Library: ms38515/5/129/6.

THE PEDAGOGICAL USE OF EDUCATIONAL WALLCHARTS

In 1878 Professor Rudolf von Wagner, the Chair of Technology at the University of Würzburg, where Thomas Purdie received a doctorate in chemistry, wrote an article about the use of wallcharts in technological education.[12] In this communication von Wagner notes that in most educational institutions the available resources were insufficient and out of line with the essential equipment for teaching. The docents' ingenuity tried to meet this need delivering demonstrations by means of illustrations. This was the case for Professor Friedrich Knapp in Munich who conceived the idea of producing technological wall charts on a very large scale; his charts were a great success and made an important contribution to the teaching of technology. However, in an area subjected to constant change and improvement, von Wagner claims the need for new charts covering the newest chemical principles as well as the supply of new editions and of revisions of the existing charts.

In his article, von Wagner praises the initiative of the firm Lenoir and Forster in publishing new wallcharts, commenting on their wide distribution and on the high recognition and honours that, for this reason, the company received at the 1878 World Fair in Paris. von Wagner concluded his article mentioning the invaluable aid that photolithographic reproductions of the charts provided for educational purposes.

The didactic mission of Lenoir & Forster was engrained in the history of the company. Originally dedicated to the manufacture of chemical and pharmaceutical devices, the firm was also a successful publishing business, which, among other things, published a celebrated collection of natural science lithographs. Over time the company abandoned the production of chemistry equipment to focus on the distribution of teaching materials of all kinds and, according to the firm's advertisements that have survived, the company aimed "to procure all teaching materials from the whole field of natural sciences, especially chemistry, physics and natural history, as well as to set up chemical factories and metallurgical laboratories".[13]

One can speculate that a firm committed to providing teaching aids and with experience in publishing technological wallcharts as von Wagner refers to in his article, would feel inclined to produce high quality prints of a periodic table of the elements that, until that moment, had been confined to books and articles and had not generally made its way to the walls of the classrooms or laboratories. Lenoir & Forster were most probably pioneers in the mass production of periodic table wallcharts since in the H. C. Bolton compendium mentioned earlier, which exhaustively lists chemical related material published between 1492 and 1892,[5] there is only one entry for a periodic table wallchart and this corresponds to the one produced in Vienna in 1885 by Lenoir & Forster.

The tables were soon distributed by the firm C. Gerhardt in Bonn, being advertised in the catalogue of the company, written in German, and published in Bonn in 1888. Interestingly, the firm issued a catalogue in 1889 published in Bonn with the price in Marks, but written in English and aimed at the American market, that also contained the entry for the periodic table.[14] The earliest US catalogues selling periodic table wallcharts were published in New York in 1895 for the firm C. Gerhardt, in 1896 for Richards & Co. Ltd.[15] and in 1902 for Eimer & Amend. [16] By 1898 Gerhardt's catalogues ceased to advertise the periodic table wallchart.

PURDIE'S TEACHING OF CHEMISTRY

Thomas Purdie FRS (1843-1916) was born in Biggar in southern Scotland and attended Edinburgh Academy. As a young man he spent a period in South America as a cattle rancher but in the 1870's he returned and studied chemistry briefly in St Andrews before transferring to the Royal School of Mines (today's Imperial College, London) to study with Sir Edward Frankland (1825–1899) where he completed a B.Sc. in 3 years. He then went to Germany to work with Wislicenus (1835–1902) in Würzburg, completing his doctorate in 1881. After acting as interim in St Andrews during the absence of Professor Matthew Heddle (1828–1897) in 1882 and 1883, Purdie was elected to fill the chair of chemistry in 1884 and held the position until 1909. He was elected a Fellow of the Royal Society in 1895. As a researcher, Purdie made highly significant contributions to the study of stereochemistry of simple organic compounds and was the first person to resolve lactic acid.[17] He is perhaps best known, however, for developing the Purdie-Irvine method for methylation of hydroxyl groups (silver oxide and methyl iodide)[18] which played a key role in elucidating the structure of simple sugars and underpinned the development of a world-class school of carbohydrate chemistry in St Andrews in the early 20th century.

When he took up the chair he found the department poorly equipped, for the subject did not form part of a definite science curriculum and was instead loosely attached to the Faculty of Arts. In the late 19th century most students at the University took a Master of Arts degree and even the few who went on to complete a Bachelor of Science has usually done an M.A. first. The first Ph.D. degrees were not awarded until 1920.

To quote from his obituary: [19]

> *The situation offered few prospects for conducting research, and none whatsoever for inducing students to undertake original work in chemistry. Yet, in his introductory lecture, speaking to an audience consisting almost entirely of arts students, we find the new professor unfolding his plans: "I venture to hope," he said, "that I may soon have some students who will be willing to give the time required for original investigation, and I can promise them that, whether the results they may obtain be of scientific value or not, they themselves will be amply rewarded; for, among all the methods of scientific training, there is none of such high educational value as research." "Might it not be possible to remain at St. Andrews during the summer months and undertake some original investigation, the results being published, as is frequently done in Germany, in the joint names of professor and student, and as contributions from the United College, St. Andrews? A beginning once made, a little band of workers would soon collect.*

The obituary was written by his successor in the chair of chemistry and most brilliant pupil, James C. Irvine (1877–1952) who regarded Purdie as a "father figure". Indeed, in Irvine's own obituary,[20] we get an insight into the powerful influence that Purdie had on the future direction of chemistry teaching in St Andrews:

> *It was Purdie who gave him [Irvine] the first vision of the true function of a university science department, in which teaching must be linked with an active prosecution of research.*

Back to Irvine's words:[19]

> *His zeal for research, however, was not allowed to interfere in any way with the conscientious performance of what he felt to be his first duty – the teaching of undergraduates. The policy was sound, for he won students to research by the attraction of his teaching and by his sincere and unaffected interest in their welfare. The class could not fail to be impressed with the fact that the professor enjoyed his lectures, and some share of his keen enthusiasm for the subject inevitably found its way to the occupants of the benches. He spoke with easy, natural fluency, and the few scraps of notes which he faithfully arranged before beginning were soon pushed aside and forgotten.*
> *Naturally enough, it was in the small Honours (senior level) classes that Purdie's gifts as a teacher were best appreciated. Here he abandoned the formal lecture to which the Scottish student has been long accustomed, and the discourse often resolved itself into an informal discussion.*

The facilities were initially primitive with a single lecture room and one small laboratory which had to be used for both teaching and research, with the latter only able to begin once the day's classes were over and the materials had been cleared away. The situation improved in 1891 when a new laboratory was added thanks to a donation in memory of Purdie's uncle and just over a decade later, with the increased research activity having already outgrown the previous facilities, Purdie himself financed the construction of a new large building for teaching and research which was completed in 1905. This was the first such dedicated chemical research institute in Scotland and the building survives up to the present time, currently housing the University's Schools of Geography and Sustainable Development and Earth and Environmental Sciences. In 1905 there were eighteen graduate researchers and, within the next few years, the carbohydrate research school in St Andrews became world famous. An early photograph of the research laboratory within the new building (Figure 8) shows such innovative features as an electric light above each bench (at the time the "elementary" or undergraduate lab still had gas lights) and fume cupboards against the back wall.

To Purdie's left is a young James Irvine and the presence of a female chemist is significant. In fact St Andrews was one of the first UK universities to admit women with the first female student, Agnes Forbes Blackadder (1875-1964), graduating in March 1895. In chemistry the first female student was Agnes Marion Moodie (1881-1969) who graduated in 1904 having completed the degree of M.A. in 1902 and B.Sc. in 1903.[21]

Figure 8. The new chemical research laboratory in St Andrews around 1906. Professor Thomas Purdie is the figure in the black coat. Courtesy of the University of St Andrews Library: ID: 2012-12-16.

Significantly the first Ph.D. degrees in the University were awarded to two female chemists, Grace Cumming Leitch (1889-1942)[22] and Ettie Stewart Steele (1891?-1983) who graduated together in July 1920.

INTERACTING WITH THE PERIODIC WALL CHART IN THE CLASSROOM

Having given some impression of the general conditions in the University of St Andrews and the Department of Chemistry around 1888 when the periodic table and other teaching wallcharts were delivered, it is of interest to examine in more detail the precise teaching methods employed and how the chart would fit in with these. Fortunately, Purdie kept meticulous notes which have been carefully preserved.[23] In his own handwriting we have details of what was covered in each daily 50-minute lecture, how it was received by students, which lecture demonstrations did and did not work well and how things could be improved. The first notebook covers the session 1889-90 and the series continues with notes for each academic year until 1903. The annotations on the notebooks are copious and detailed for the first sessions, becoming more succinct over the years. Some illustrative examples follow.

About a lecture given on Wednesday 12th of March 1890, Purdie wrote (Figure 9a):

> *Lecture LXXX. Wednesday 12th March*
> *Relations of the Atomic Weights to each other.*
> *Prouts Hypothesis.*
> *Relations of the properties of Elements to their Atomic Weights.*
> *Discoveries of Dumas n*
> *Newlands Law of Octaves.*
> *The Periodic Law (Mendelejeff)*
> *Statement of.*
> *Meaning of the term periodic*
>
> *The lecture was fairly interesting. Attention was*
> *taken up with thermochem. phenomena. The*
> *description of Mendeleffs table might perhaps be*
> *touched on, but it is better I take that along with*
> *its practical applications which form an appropriate*
> *ending. The above ought not to take more than*
> *half a lecture.*
> *Details regarding Mendeleff in* Nature *June 27*
> *1889, p. 193.*[26]

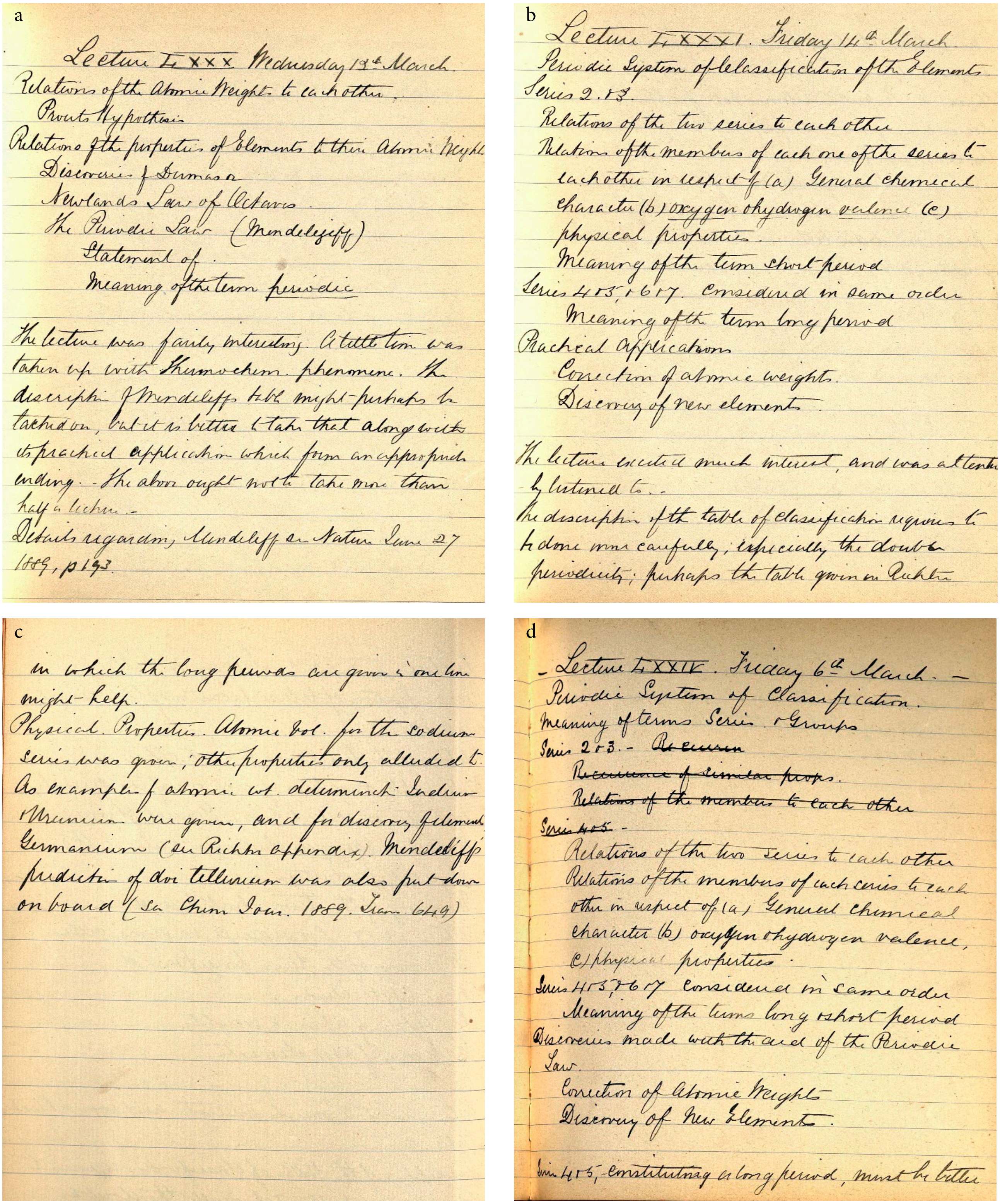
It is of interest to notice the different spellings of Mendeleev's name in Purdie's notes. In this lecture, when Purdie mentions the periodic law he spells the name in the customary German form at the time, with the same spelling that appears in the title of the periodic table. The other instances where Purdie writes the name he misses a syllable.

In this lecture's notes Purdie mentions Prout, Dumas, Newlands and Mendeleev. Both Prout's and Dumas's work made significant advances on measuring the atomic weights of the elements.[24] Newlands, for his part, had ordered the elements according to their atomic weights noticing that every eighth element in this system shared similarities. He postulated this *Law of Octaves* in 1865 and received the Davy medal in 1887, being recognized in the U.K. as one of the founders of the periodic system.[25]

Purdie explains Mendeleev's periodic law in this lecture but postpones the description of the periodic table to further lectures when talking about its practical applications. To portray Mendeleev's work, Purdie relies on Sir Edwards Thorpe's recent study on Mendeleev that had appeared in the series Scientific Worthies published in Nature in 1889.[26]

In the next lecture, Purdie continues his notes on the periodic system: (Figure 9b (recto) and 9c (verso)):

> *Lecture LXXXI. Friday 14th March.*
> *Periodic System of Classification of the Elements.*
> *Series 2. & 3.*
> *Relations of the two series to each other.*
> *Relations of the members of each one of the series to*
> *each other in respect of (a) General chemical*
> *character (b) oxygen or hydrogen valence (c)*
> *physical properties.*
> *meaning of the term short period*
>
> *Series 4 & 5, & 6 & 7. Considered in same order*
> *Meaning of the term long period*
>
> *Practical applications*
> *Correction of atomic weights.*
> *Discovery of new elements.*
>
> *The lecture excited much interest, and was attentive*
> *-ly listened to*
> *The description of the table of classification requires to*
> *be done more carefully; especially the double*
> *periodicity; perhaps the table given in Richter*
>
> *In which the long periods are given in one line*
> *might help.*
> *Physical. Properties. Atomic vol. for the sodium*
> *series was given; other properties only alluded to.*
> *As examples of atomic wt. determination Indium*
> *+ Uranium were given, and for discovery of elements,*
> *Germanium (see Richter appendix*[27]*). Mendeeleff's*
> *prediction of dvi tellurium was also put down*
> *on board (see Chem Jour. 1889. Trans. 649)*



a

Lecture LXXX Wednesday 12th March.
Relations of the Atomic Weights to each other.
Prouts Hypothesis
Relations of the properties of Elements to their Atomic Weight
Discoveries of Dumas &c
Newlands Law of Octaves.
The Periodic Law (Mendelejeff)
Statement of.
Meaning of the term periodic

The lecture was fairly interesting. A little time was taken up with Thermochem. phenomena. The description of Mendeleff's table might perhaps be tacked on, but it is better to take that along with its practical application which form an appropriate ending. – The above ought not to take more than half a lecture. –
Details regarding Mendeleff see Nature June 27 1889, p193.

b

Lecture LXXXI. Friday 14th March.
Periodic System of classification of the Elements.
Series 2 & 3.
Relations of the two series to each other
Relations of the members of each one of the series to each other in respect of (a) General chemical character (b) oxygen & hydrogen valence (c) physical properties.
Meaning of the term short period
Series 4 & 5, & 6 & 7. Considered in same order
Meaning of the term long period
Practical Applications
Correction of atomic weights.
Discovery of new elements.

The lecture excited much interest, and was attentively listened to.
The description of the table of classification requires to be done more carefully; especially the double periodicity; perhaps the table given in Richter

c

in which the long periods are given in one line might help.
Physical Properties. Atomic Vol. for the sodium series was given; other properties only alluded to. As examples of atomic wt. determination Indium & Uranium were given, and for discovery of elements Germanium (see Richter appendix). Mendeleff's prediction of dvi tellurium was also put down on board (see Chem. Jour. 1889. Trans. 649)

d

– Lecture LXXIV. Friday 6th March. –
Periodic System of Classification.
Meaning of terms Series & Groups
Series 2 & 3. – ~~Recurren~~
~~Recurrence of similar props.~~
~~Relations of the members to each other~~
Series 4 & 5 –
Relations of the two series to each other
Relations of the members of each series to each other in respect of (a) General chemical character (b) oxygen & hydrogen valence, (c) physical properties.
Series 4 & 5, & 6 & 7 considered in same order
Meaning of the terms long & short period
Discoveries made with the aid of the Periodic Law.
Correction of Atomic Weights
Discovery of New Elements.

Series 4 & 5, constituting a long period, must be better

Figure 9. Thomas Purdie Syllabus of Lectures. Courtesy of University of St Andrews Library: ms38620.

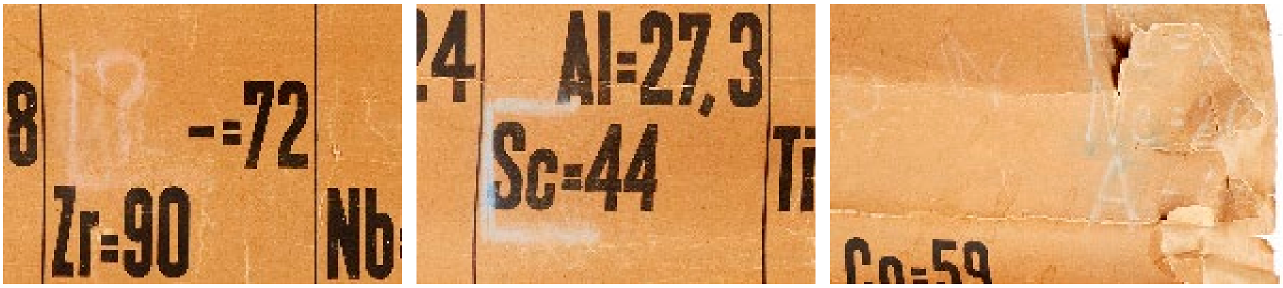


Figure 10. Close-up views of the St Andrews wallchart table showing chalk markings. R. Alan Aitken, 2014.

Some references to the pedagogical use of the periodic table wallchart can be extracted from Purdie's notes for this particular lecture. One of them is the mention of the relations of the members of each of the series to each other in terms of oxygen and hydrogen valence, a characteristic that is depicted in the head of the columns of this wallchart as in Mendeleev's 1871 table, but that was not common for all the tables at the time.

Another example is Purdie's allusion to the practical use of the periodic table for the discovery of new elements, mentioning particularly germanium. Here we must return to the St Andrews table as it was discovered in 2014 and observe the chalk additions to remark new or missing elements. Although it is not possible to ascertain if Purdie drew these marks, they certainly illustrate the interaction with the wallchart and thus the pedagogical use of the table. A close-up view shows the addition of a question mark in the space for germanium and underneath of this chalk addition the symbol Ge can be faintly noticed, suggesting that the marks on this space were erased and filled up according to the message that wanted to be conveyed to the student audience (Figure 10a). Also scandium, the latest element discovered before the printing of the St Andrews periodic table, is singled out in the wallchart with a chalk mark highlighting its symbol (Figure 10b).

Purdie seemed to be very attentive to his students and he often got feedback from them about the lecture and its contents. For instance, in the notes from his lecture on Wednesday 6th of November, 1889 he wrote:

"The interest of lecture pretty well sustained. The facts about the life of Lavoisier seemed to interest."

When trying to explain concepts in the most logical or intuitive way, Purdie mentions textbooks and, if needed, he goes away from the representation of the periodic law in the wallchart that he purchased recommending other periodic tables that might help to understand difficult messages as, for instance, the idea of double periodicity mentioned in Lecture LXXXI. The textbook that he uses, mentioned in 'The table given in Richter" and "Richter appendix" is the fifth German edition of Victor von Richter's *Lehrbuch der anorganischem Chemie*, or the translated edition published in London in 1887.[27] Von Richter (1841–1891), a German chemist, published the first edition of his textbook in 1875, followed afterwards with subsequent editions in German, Russian, English and French. In his book, he used the periodic arrangements of both Lothar Meyer and Mendeleev, thus contributing to their dissemination.

The article cited by Purdie in the last line of his notes for the lecture LXXXI, refers to a lecture on the periodic table given by Mendeleev at the Chemical Society of London (Faraday Lecture, 1889), where he forecasts an element analogous to tellurium, dvi-tellurium, that must be positioned after bismuth and with a predicted atomic weight of 212.[28] The characteristics of this predicted element match what we now call polonium.[29]

The following academic year (1890-91) Purdie dedicated a lecture to the "Classification of Elements in accordance with their atomicity" along with the "meaning of the term valency" and the "Classification of elements in accordance with their valency." (Lecture XXXIII. Tuesday 16th December 1890)

During the same session he dedicated one lecture to the introduction of the periodic law and during the following lecture he developed the notion of the periodic system (Figure 9d (recto)).

- Lecture LXXIV Friday 6th March. –
Periodic System of Classification.
Meaning of terms Series & Groups
Series 2 & 3. – Series 4 & 5 –
Relations of the two series to each other
Relations of the members of each series to each other in respect of (a) General Chemical character (b) oxygen & hydrogen valence, (c) physical properties.
Series 4 & 5, & 6 & 7 considered in same order
Meaning of the terms long & short period
Discoveries made with the aid of the Periodic Law.

Correction of Atomic Weights
Discovery of New Elements.

Series 4 & 5, constituting a long period, must be better

Verso:

described. Their [chemical] relations might be given,
expressly omitting the members of Group VIII, so
as to emphasize the fact that they are a repetition
of series 2 & 3.

Going forward a decade, in the summary of lectures for the session 1902-03, Purdie introduces a new lecture on the very recent discovery of the noble gases -W. Ramsay (1852–1916) and Lord Rayleigh (1842–1919) had announced the discovery of argon only 7 years earlier, followed closely by the discovery of helium, neon, krypton, xenon and radon.[30] Here again the use of the St Andrews periodic table as a teaching tool is apparent observing the chalk additions to fill in the noble gases, possibly when their discovery was explained to the students (Figure 10c).

Lecture LXVI Friday 6th Febry.
– Recently discovered atmospheric gases –
Argon. History of its discovery. Rayleighs' & Ramsays' Methods of isolating the gas. Its properties; probable Atomic Wt.
Helium. Existence in the sun; discovery
of terrestrial Helium by Ramsay. Isolation of the Helium Group of Gases. Helium, Neon, Argon, Krypton, Xenon by fractional distillation.

~~~~~~~~~~~~~~~~~~~~~~~~

Lecture LXVI Continued.
Numerical relations of the Atomic Weights
Prout's Hypothesis. Its significance.
Co-relation of the Atomic Weights & Properties of the Elements
Uniformities in the Atomic Weights of Chemically Similar elements. Newland's "Law of Octaves". Periodic Law. Meaning of the term periodic.
Periodic System of Classification
Series II & III. Illustration of the recurrence of similar
properties at definite intervals. Uniform variation of
properties in each series in respect of: 1. Electron affinity.
2. Oxygen valence. 3. Hydrogen valence. 4. Physical Properties
Meaning of term Period
Series IV & V Constitute a long period of 17 elements, consisting
of 2 short periods of 7 elements each, + 3 transitional elements
Application of the Classification
Correction of Atomic weights
Prediction of undiscovered elements

~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

The above is a complete syllabus. In this course the facts were
given very briefly. Lecture LXVI extended the illustration of recurrence of similar properties at definite intervals."

It is important to note that in this lecture Purdie introduces for the first time the concept of electron affinity. It is not just a mention in passing, as Purdie gives to this property of an element a special treatment since he mentions it before the oxygen and hydrogen valence that had been the properties highlighted in his lectures from previous years. This shows the evolving nature of his lectures and how he changes the syllabus and his interaction with the periodic table according to the latest discoveries. The electron affinity of an element can be defined as the amount of energy released when a neutral atom accepts an electron to form an anion. Considering that just 5 years had passed since the discovery of the electron by J. J. Thomson (1856–1940), the inclusion of this property in Purdie's description of the table shows his appreciation of the importance of having for the first time a measurable property on which to base the periodic arrangement of the elements. Across the periodic table, the electron affinity increases from left to right across periods and upward for the groups, i.e. metals generally have a lower electron affinity than nonmetals, with the exception of the noble gases.[31] Explaining this new concept to students in 1902, shows that Purdie was keeping abreast of the latest discoveries and understanding their importance.

These concrete examples extracted from Purdie's notes illustrate how the teaching of the periodic system evolved in the years that followed the publication of the St Andrews periodic table wallchart. Interestingly, this gradual change can also be attested in the chart itself, where the chalk marks, the handwritten elements that filled in empty spaces and the added symbols of the gases unknown at the time of the table's publication, show the didactic use of this periodic table at the University.

CONCLUSION

The delivery of the periodic table and other teaching wallcharts to the Department of Chemistry at the University of St Andrews in the late 1880's coincided with the start of a remarkable period of development in the fortunes of the department which led to its becoming, within 20 years, a world-renowned centre for research in carbohydrate chemistry. The small numbers of students at that time typically went on to successful scientific careers in which detailed awareness of the latest discoveries of new chemical elements and their properties would be important. Use of the latest available visual aids was only to be expected of an excellent teacher like Thomas Purdie. What is remarkable is that the 1885 periodic table wallchart was rolled up and stored away once it was rendered obsolete by the discovery of new elements such as the noble gases in the 1890's and survived undamaged for the next 120 years allowing us to enjoy it today.

Of almost as great significance are the notebooks of Thomas Purdie, which have also survived to the present day. In them he gives a detailed description of what he taught in each lecture and an evaluation of how he thought the various parts of the lecture were received by his students. Some of the lectures he records possibly correspond with the use of the wallchart in teaching. Hand written annotations to the wallchart can be seen as illustrating the discovery of new elements and other changes in the understanding of the periodic system in the decades after Mendeleev published his key hypothesis. The interplay between the wall chart and Purdie's notes gives a deep and unusual insight into the teaching of chemistry in the late 19th century and even sheds some light on the teacher student relationship.

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The Periodic System and the Nature of Science: The History of the Periodic System in Spanish and Norwegian Secondary School Textbooks

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Abstract. This essay analyses 31 science and chemistry textbooks from Spain and Norway with respect to their presentations of the history of the periodic system and what these presentations can teach students about the Nature of Science (NOS). The analysis is based on the SOURCE framework, where each letter in SOURCE represents an element from the history of science and corresponding attributes of NOS. Our comparative analysis reveals large differences in the role of history of chemistry between the Spanish and Norwegian teaching contexts, and similar differences in their inclusion of historical aspects in curricula and textbooks. We argue that the lack of references to women, to errors or failures in the history of the periodic system represents missed opportunities to discuss chemistry as a tentative, collective and socio-cultural enterprise.

Keywords. Periodic System, History of Chemistry, Chemical Education, Textbooks, Nature of Science.

INTRODUCTION

The periodic system is one of the best-known and most-used icons of science. It figures in every lecture hall where chemistry is taught, and it is hard to imagine chemistry teaching and chemistry textbooks without it. For chemistry students (and chemists) it might also be difficult to grasp that the periodic system was developed without knowledge of the structure of the atom, which we take for granted today. The history of the periodic system would certainly enlighten students about the particularities of its development, but also give them insight into the nature of scientific development in general. It has been argued that studying chemistry (or science) in a historical context may contribute to the understanding of chemistry as a dynamic process rather than a static set of theories or laws, as a diverse endeavour that relies on intuition as well as logic and clearly depends on the humans involved in the processes.[1,2,3,4] Aspects such as these are captured in the concept ‘Nature of Science’, which we will introduce below.

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Teaching science should therefore be more than just explaining models, theories and laws, and the history of science can help unveil a fuller picture of the scientific enterprise. For the historian, the end products, theories and facts must be understood as temporary end products of a long process. It is now generally acknowledged that knowledge about the process itself can provide very interesting insights about science. Despite greater consciousness about science as a process among science educators from the 1960s onwards, the emphasis in school curricula has not radically shifted away from teaching established "facts" or end products to instead exploring how this knowledge was constructed.[5] As McComas and colleagues put it, when summarizing reports from the 1990s, 'the ideas put forth in textbooks and school science concerning the nature of science are almost universally incorrect, simplistic, or incomplete'.[6] Although new aspects have been added to more recent curricula, in our experience the use of historical material is still limited; which clearly contrasts with the increased importance attributed to history in science education research in the past few decades.[7]

The aim of this essay is to explore to what extent and how the history of the periodic system is presented in recent textbooks, and which aspects of the nature of science are conveyed to students through the historical presentations. We will compare texts published in the last 13 years from two different teaching contexts: those of secondary schools in Spain and in Norway. Before presenting the methodology, our analyses and conclusions, we will introduce the concept of Nature of Science in science teaching, the theoretical framework based on that concept, and the contrasting curricular traditions in Spain and Norway when it comes to including the history of science. The aspects of the history of the periodic system that we have selected for our analyses will be introduced in the Materials and methods section.

Using history of science to teach the Nature of Science (NOS)

When science is taught, teachers and students create various images of science. This wide range of images is made up of values, features and conceptions about how science works. In the context of science education, learning the Nature of Science (NOS) refers to understanding presuppositions, values, aims, and limitations of science, and how knowledge is created and established.[5] Analyses of science curricula reveal that even though NOS is usually not explicitly mentioned, several objectives, contents, skills and evaluation criteria are deeply connected with NOS themes in many ways.[8] Studies of the history of science content in textbooks have, furthermore, provided insight into how NOS is presented in textbooks and teaching.[9] Although NOS is itself a dynamic area with no fixed list of attributes, a pragmatic 'consensus view' has been compiled, including the most important agreed-upon elements describing science as a process. This consensus view holds that science or scientific endeavour is tentative (always evolving), empirical (relies on observation, experimental evidence, arguments, scepticism), explanatory (attempts to explain natural phenomena), communicative (open and subject to peer review), structured in laws and theories (though they serve different roles in science), both evolutionary and revolutionary, interrelated with technology (a two-way relationship), diverse or multifaceted (there is no one scientific method), to a certain extent subjective (influenced by personal values and prior experiences), creative (involving imagination), and socio-cultural (influenced by cultural and social contexts).[5,9,10,11] Table 1 compares some of the different ways these NOS aspects are communicated in the literature. The selected aspects given in Table 1 will be used as a basis for our analyses of Spanish and Norwegian textbooks.

In 1974, in a paper entitled 'Should the history of science be rated X?' published in *Science*,[12] the historian of science Stephen G. Brush critically stated that 'the teacher who wants to indoctrinate his students in the traditional role of scientist as a neutral fact finder should not use historical materials of the kind now being prepared by historians of science: they will not serve his purposes'.[13] His point was that science teachers wanted to keep their success stories, and that the history of science challenged them. Although Brush's irony is evident,

Table 1. A comparative connection between DiGiuseppe's (2014)[10] and McComas-Kampourakis's (2015)[9] NOS aspects.

DiGiuseppe's NOS aspects	McComas-Kampourakis' NOS aspects Science (is)
Tentative	a way of knowing
	addresses questions about the natural and material world
	open to revision
Empirical	based on data and empirical evidence
Subjective	
Creative	a human endeavour
Socio-cultural	
Structured in laws and theories	assumes an order and consistency in natural systems
	models, laws and theories explain natural phenomena
Diverse	uses a variety of methods

he touched upon a dilemma, as the histories of scientific development presented through a history of science might, indeed, destroy the many 'hagiographic' (heroic) tales that are commonly used in textbooks and classrooms. Thirty years later, the philosopher and historian of science (and science educator) Douglas Allchin published a paper entitled 'Should the sociology of science be rated X?', echoing Brush's article from 1974.[14] While the 'new' history that Brush discussed took heroes of science down from their pedestals, Allchin discussed how a sociology of science threatens the image of the 'idealized and impersonal scientific method found in textbooks'.[15] Indeed, (degrees of) subjectivity and tentativeness are among the attributes of the 'consensus view' that do challenge the authority of science – which is why science educators do not always embrace all aspects of NOS. Allchin stressed that idealized, or romanticized, science is a lie. For this reason, he argued, science educators should distinguish between the normative and the descriptive elements of NOS in their teaching. Allchin also argued that science educators indeed should include errors or failed attempts from the history of science when teaching about the Nature of Science. In Allchin's words, 'teaching science without error is like teaching medicine without disease or law without crime'.[16]

In order to identify the sorts of historical narratives that introduced a misrepresented NOS in the teaching context, in another article Allchin used the term 'pseudohistory' of science (pHS).[17] He argued that the historical narratives in science education must present the history of science without idealizing past science. From Allchin's approach, historical narratives become pHS when they verge on myth. One such myth in the history of the periodic system might be that Dmitri Mendeleev (1834–1907) was the sole discoverer of the system and that it was conceived during one 'eureka' moment. Since every history of science teaches nature of science, science educators need to be wary of mythic narratives (what we have called NOS from pHS approach in Table 2). They need to use historical narratives that portray NOS more informatively (what we have called NOS from HS approach in Table 2).[17,18] One of the strategies proposed by Allchin is to neutralize mythical historical narratives of science by going from the source of the problem to the source of the solution, as we summarize in Table 2.[18] This so-called SOURCE approach allows teachers to recognize myths and control their effect on students. We will use this approach when analysing Spanish and Norwegian textbooks.

In recent years, science education literature has given some attention to the use of the history of the periodic system in chemistry teaching. In 2015, McComas and Kampourakis used Mendeleev's periodic table as an example of a historical case which shows that laws and theories represent distinct kinds of scientific knowledge (the NOS aspect 'structured in laws and theories').[9] As Bensaude-Vincent had pointed out almost three decades before, Mendeleev developed a periodic law which enabled new data to be discovered and phenomena to be explained, and which atomic theory later explained.[19] Furthermore, the knowledge of the development of the periodic system was among the topics in a questionnaire used by Franco-Mariscal, Olivia-Martínez and Amoraima-Gil in 2016 to analyse how Spanish high school students understood the idea of chemical element and its periodic classification.[20] Based on a review of analyses of the history of the periodic system in textbooks in the USA and Latin America, in 2016 Niaz suggested several guiding principles for teaching the periodic system using a history of science approach. Among them were how the classifications of the elements could be based on atomic mass, the important role of other co-discoverers of the periodic table, and what role predictions played for acceptance of the periodic law.[21] Similar aspects have been selected for the present analyses and will be presented under Materials and methods.

Table 2. Main features of NOS according to the SOURCE approach, based on Allchin (2003).[18] Every letter in the word SOURCE corresponds to an attribute from pseudo-history of science (pHS) as well as to an attribute from history of science (HS).

NOS from pHS approach	NOS from HS approach
Science-made	**S**cience-in-the-making
Overinflated genius	**O**pportunities
Unqualified Universality	**U**ncertainties
Retrospect	**R**espect for historical context
Caricatures	**C**ontingency, complexity, controversy
Expected results and Excuses	**E**rror Explained

History of chemistry in Spanish and Norwegian teaching contexts

During the past decades, the field of history of chemistry has undergone a significant consolidation and renovation.[22] However, the history of chemistry is still conspicuous by its absence in many teaching contexts. Spain and Norway represent different local contexts when it comes to the institutionalization and teaching of history of chemistry at different levels. Two surveys of the prevalence of the teaching of history of chemistry in Europe, stemming from 2007 and 2015, respectively, reveal that in fact, the situation with respect to history of chemistry teaching is not at all comparable in the two countries. In 2007, history of chemistry was taught for chemistry students at 14 of the 39 universities offering graduate, postgraduate and doctoral studies in Spain, most of them as special history of chemistry courses. In Norway, two of the four universities in the country offered teaching in history of chemistry, either as part of the chemistry curriculum or as part of a history of science course for prospective teachers. Although representatives from both countries in 2015 expressed worry about the lack of institutionalization of the field, history of chemistry is much more prevalent in Spain in terms of the history of chemistry groups, journals and teaching offered than is the case in Norway.[23] If we assume that the knowledge and use of history of chemistry at secondary school level echoes the situation at university level, we would expect a major prevalence of the history of chemistry in the Spanish curriculum. The analyses of the curricula in Norway and Spain have supported that.

The Spanish chemistry curriculum contains a few competency objectives on the history of chemistry at secondary school level. Five history of chemistry issues can be found: atomic models, classification of the chemical elements, acid-base theories, laws of chemical combinations and the origin of organic chemistry.[24,25] Among them are the 'importance of the periodic system for chemistry development'[26] and the 'historical development of the classification of the chemical elements'.[27] Both are part of the upper secondary chemistry curriculum (16–18 year-old students). The history of the periodic system is not explicitly mentioned in the lower secondary school chemistry curriculum (ages 14–16). A recent study on the history of chemistry in Spanish secondary education pointed out that several curricular elements make explicit the tentative (evolving), controversial (diverse and multifaceted), creative (involving imagination), under-construction (evolutionary) and social-cultural (influenced by cultural and social contexts) NOS for both lower and upper secondary education.[28]

In Norway, history of chemistry has had a less prominent role in the chemistry curriculum, which is not surprising given how little attention is paid to history at university chemistry level. A survey from 2004, before the most recent curriculum reform in Norway was launched, reveals that students who opted for chemistry in upper secondary school liked 'historical chemistry' least of all chemistry topics listed in the survey.[29] As of 2006, the national science and chemistry curricula hardly include any history of chemistry. The only specific competency objective for history of chemistry is related to the historical development of the atomic model and the concept of atoms, which is a topic that falls under the main area of 'Language and models in chemistry' in upper secondary school.[30] Another competency objective in the chemistry curriculum that is related to NOS aspects and might allow for some historical reflections, revolves around scientific method and explanatory models not compatible with chemical-scientific explanations (as part of the main content area, the meta-subject 'Research').[31] As a topic in chemistry, the periodic system is part of the curriculum for the integrated science course in lower secondary school in one competency objective for grades 8–10 (i.e. ages 13–15).[32] The periodic system is not explicitly mentioned in the curriculum for upper secondary school (ages 16–18), but might be taught as part of other topics if considered relevant and needed, though treated as 'repetition'. A new curriculum, which will be implemented from autumn 2020, follows the current curriculum in placing the periodic system as part of lower secondary science, and with no competency objectives for history of chemistry.[33]

MATERIALS AND METHODS

Although the curriculum is the formal guide to teaching at different levels in Spanish and Norwegian schools, in practice textbooks serve as the real guides when teachers prepare their teaching, as Park and Lavonen have pointed out for the American and Finnish cases.[34] For this reason, textbooks are well suited to inform us about teaching practices and what content is being taught in chemistry at different levels in school. Also, since competency objectives in curricula are few and general, textbook authors must interpret the curriculum and therefore, their texts will go beyond the curricula themselves. An example is the history of the periodic system, which as noted is not an explicit part of the lower secondary school curriculum in Spain, yet textbooks include it. This also applies to other historical topics. Likewise, the periodic system is mentioned in chemistry textbooks for upper secondary school in Norway, although it is not part of the curriculum for that level. In both samples textbooks in science/chemistry at lower and upper secondary school levels are included, for the years in which the periodic system is mentioned.

In the Spanish case, textbooks for compulsory lower secondary education, CSE (*Educación Secundaria Obligatoria-ESO*) and upper secondary education, USE (*Bachillerato*) from five recognized publishers have been analysed: *Anaya* (S1)*; Santillana* (S2)*; Vicens Vives* (S3)*; McGraw-Hill* (S4); *Oxford* (S5). The sample is made up of 20 textbooks from four educational levels: five textbooks

Table 3. The SOURCE approach adapted to the history of the classification of the chemical elements. For an explanation of S, O, U, R, C and E, see Table 2.

Research items (I) Textbooks mention…	NOS aspects Allchin (SOURCE approach)	 DiGiuseppe	 McComas & Kampourakis	HS aspects
I1. Different classifications of the chemical elements before and after Mendeleev's periodic system	Science-in-the-making vs. Science-made	Creativity	Human endeavour	Collective
I2. The work of women behind the periodic system	Opportunities vs. Overinflated genius	Socio-cultural		Equal
I3. Mendeleev predicted atomic weights and properties of several elements which were later corroborated	Uncertainties vs. Unqualified universality	Tentativeness	Open to revision	Non-hagiographical Non-teleological
I4. Mendeleev's periodic system gradually evolved	Respect for the historical context vs. Retrospect	Creativity		Contextualized
I5. The differences between Mendeleev's and Meyer's approaches to the classification of the elements	Contingency, complexity & controversy vs. Caricatures	Diverse	Variety of methods	Controversial
I6. Not all of Mendeleev's predictions were successful	Error explained vs. Expected results and excuses	Tentativeness	Open to revision	Non-hagiographical

for the third course of compulsory lower secondary education (14–15 year-old students, CSE3), five textbooks for the fourth (and last) course of compulsory lower secondary education (15–16 year-old students, CSE4), five textbooks for the first course of upper secondary education (16–17 year-old students, USE1) and five textbooks for the second (and final) course of upper secondary education (17–18 year-old students, USE2). All of these textbooks were widely used in Spanish upper secondary schools between 2007 and 2016. Moreover, these textbooks have been published by some of the most prestigious publishing houses for education (S1-S5), according to the Spanish ranking of the Scholarly Publishers Indicators in Humanities and Social Sciences Project.[35]

The Norwegian textbook sample consists of, first, four sets of science textbooks for compulsory lower secondary school (ages 13–15), grade 8 (CSE8) and for most of them, grade 9 (CSE9), which are the books that present and discuss the periodic system (seven books in total): *Tellus* (N1), *Trigger* (N2), *Eureka!* (N3), *Nova* (N4), published by four different publishing houses. Secondly, the first year of the specialized chemistry course in upper secondary school (year 2, USE2) uses three textbooks from three different publishers: *Kjemi 1* (N5), *Aqua Kjemi 1* (N6), *Kjemien Stemmer 1* (N7). In the first year there is a compulsory integrated science course, and in year 3 the periodic system is not discussed. Thirdly, as a reference we have included the textbook *Kjemi for lærere* (Chemistry for teachers, N8), used in the study programme for prospective science teachers in primary and lower secondary schools who have no prior knowledge of chemistry.[36] This study programme takes place either in a university college or at university (varies from city to city). For simplicity, we call it College Education (CE) in this article.

Framework and research items for textbook analyses

The methodological framework for our analyses of the history of the periodic system in textbooks is presented in Table 3. Here, we use the SOURCE approach proposed by Allchin (Table 2), where each letter in SOURCE stands for an aspect of NOS, and connects it with NOS aspects based on work by DiGiuseppe, and McComas and Kampourakis (Table 1). We will present the historical background for each research item separately.

I1: Different classifications of the chemical elements before and after Mendeleev's periodic system.

Far from being a product of a single man's flash of genius, the periodic table was the result of a collective aim which developed over a long period of time. Already in the beginning of the 19th century, after John Dalton (1766–1844) had introduced his atomic theory and characterized different atoms by their weight, attempts were made to group elements according to their atomic weights. The German chemist Johann Wolfgang Döbereiner (1780–1849) organized the elements into groups of three elements with related chemical properties (like reactivity) called triads, where the atomic weight of the central element of the triad was the mean value of the atomic weights of the first and the last elements of the triad. Several chemists identified triads, and the idea of triads has been highlighted as an important point in the history of the periodic system because it hinted at a relationship between numerical criteria (the atomic weight) and the properties of the elements.[37]

Atomic weight determinations continued over the course of the 19th century; however, discrepancies existed. The question of which system one should base the atomic weight determinations on was taken up at the first international chemistry congress held in Karlsruhe in September 1860. It is thus not by chance that several classifications of the elements emerged in the early post-Karlsruhe context. The British chemist William Odling (1829–1921), the German chemist Lothar Meyer (1830–1895) and Mendeleev were all present at the Karlsruhe congress, after which they had a basis on which to build a system of the elements.[38, 39] Twenty years after his first periodic system had been published, Mendeleev recognized the importance of the Karlsruhe meeting for his work on the elements, as '[o]nly such real atomic weights [proposed at Karlsruhe] – not conventional ones – could afford a basis for generalization'.[40] A total of six independent discoverers of the periodic system have been identified: The French geologist Émile Béguyer de Chancourtois (1820–1886), who in 1862 presented his *Vis tellurique* (a periodic helix), and the British chemist John Newlands (1837–1898), known for his 'law of octaves', are among them, along with the American chemist Gustavus Hinrichs (1836–1923), Odling, Meyer and Mendeleev. The development of periodic systems also continued after Mendeleev's famous 1869 system. In fact, between 1782 (with Louis Bernard Guyton de Morveau's simple table) and 1974, many hundred classifications and representations classifications and representations of the 'periodic law' appeared, including tables, zigzags, lemniscates, helixes and spirals.[41] All of these clearly show why the history of the periodic system can be considered as a history of shaping and sharing.

I2: The work of women behind the periodic system

In the 1860s, 63 chemical elements were known. Many new elements were identified from the 1870s onwards and in particular in the first decades of the 20th century. While it is well known that many (male) scientists contributed to the discoveries of elements, histories of women discoverers are rarely communicated. Recognizing that women from different backgrounds and in various roles have contributed to discoveries of elements and to the development of the periodic system is another way of conveying that science is a collective human enterprise where people from all cultures have taken part. By spotlighting women, such stories can also highlight that science is equal, an endeavour for both women and men.

Element discoveries demanded high-level analytical-chemical competence, and in some cases expertise on radioactivity. Examples of element discoveries by women, either alone or on research teams, are polonium and radium (1898), by Marie (1867–1934) and Pierre Curie (1859–1906), protactinium (1918) by Lise Meitner (1878–1968) and Otto Hahn (1879–1968), rhenium (1925) by Ida (1896–1978) and Walter Noddack (1893–1960), with the help of Otto Berg, and francium (1939) by Marguerite Perey (1909–1975). Women were also involved in work that led to positioning the elements in the right place (see I4 for the example of Julia Lermontova) and in revealing nuclear processes leading to a better understanding of the atom.[42]

I3: Mendeleev predicted atomic weights and properties of several elements which were later corroborated, and I6: Not all of Mendeleev's predictions were successful

Even though Mendeleev's classification underwent several modifications, one of the known features of all of Mendeleev's periodic systems was that he left blank spaces for as yet unidentified elements. He also predicted their atomic weights and foresaw some of their properties. Although the predictions that were later fulfilled influenced the acceptance of the periodic system, it has been argued that the importance of the predictions must be reconsidered.[43] For example, in 1882, Mendeleev and Meyer were both recognized by the Royal Society of Chemistry with the Davy Medal because of their contribution to the development of the classification of the elements, but no mention was made of Mendeleev's successful predictions. Also, it should be noted that Mendeleev had many failed predictions. Coronium, ether, eka-cerium, eka-molybdenum, eka-niobium, eka-cadmium, eka-iodine and eka-caesium were elements predicted by Mendeleev which were never found. Eka-boron (scandium), eka-aluminium (gallium) and eka-silicon (germanium) are examples of elements predicted by Mendeleev which were later identified and which properties turned out to fit well with what Mendeleev had foreseen.

I4: Mendeleev's periodic system gradually evolved

The different versions of Mendeleev's classifications were more than a succession of changes in shape. Chemists continued to refine their analytical methods in order to obtain more accurate atomic weights. In the 1870s, the Russian chemist Julia Lermontova (1846/47–1919) worked on the separation of the platinum metals in minerals so that more accurate atomic weights could be determined. This was necessary since the atomic weights of the platinum metals were close in value, and so were their chemical properties; hence it was difficult to place them in the right order in the periodic system.[44] Another example is the difficulty in positioning tellurium and iodine in the periodic system. In 1871, Mendeleev assumed an atomic weight of 125 for tellurium although weights up to 128 had been determined, since placing tellurium before iodine (127) constituted a better match in terms of chemical properties than *vice versa*.[45] Thirty-three years later, in 1904, Mendeleev presented both elements with the same atomic weight (127) in his periodic table. In fact, tellurium had been found to have a slightly higher atomic weight than iodine (127.6 vs. 126.85), but there was nevertheless no doubt about which family they belonged to in the system – evidence that atomic weight could not be the primary criteria for ordering the elements.[45,46] Other changes can also be observed by comparing Mendeleev's different periodic systems: Some elements disappeared from the system (like didymium, Di) and others appeared (like group zero gases – now known as the noble gases in group 18) in subsequent classifications.

The periodic system as a table also continued to develop after Mendeleev's time. In 1905, for example, two years before Mendeleev died, the Swiss chemist Alfred Werner (1866–1919) reorganized the periodic table, separating the lanthanides so they occupied a separate place in the table similar to the placement of the transition metals in our current long periodic table. In subsequent decades, the British chemist Friedrich Adolf Paneth (1887–1958) moved the lanthanides beneath the main table. Likewise, in 1945 the American chemist Glenn Theodore Seaborg (1912–1999) added a separate group of elements beneath the table, the actinides, thereby moving elements 89–96 from the main table to the new group. The justification of the concept of 'atomic number' by the British physicist Henry Moseley (1887–1915) in 1913 was also an important milestone in the history of the periodic system after Mendeleev's work. The introduction of the atomic number as a better ordering principle for the elements than atomic weight and the irruption of quantum physics in the study of subatomic structure also had an important influence on the development of the periodic system to the present day.

I5. The differences between Mendeleev's and Meyer's approaches to the classification of the elements

As noted above, in 1882 Lothar Meyer and Mendeleev were awarded the Davy Medal jointly. As with the systems of Mendeleev and the other co-discoverers, the elements in Meyer's periodic systems were organized by increasing atomic weight. Both chemists developed their periodic systems while preparing a textbook.[47] However, Meyer's and Mendeleev's approaches were different. Mendeleev thought chemical properties should take precedence over physical criteria, except for atomic weight. Mendeleev also made elaborate predictions for still unidentified elements (not all successful, as stated above) and suggested revisions to what he presumed were inaccurate atomic weights.[48] Meyer, too, left blank spaces for as yet undiscovered elements and made interpolations for the atomic weights of unknown elements' based on the values for neighboring elements, but he did not make extensive predictions for unidentified elements like Mendeleev did. Instead, Meyer explored the concept of periodicity through a graph where atomic volume was plotted as a function of atomic weight, making visible trends in atomic volume as a property of atoms.[49]

Scoring system

For our content analyses we have defined a scoring system to indicate the extent to which selected aspects of the history of the periodic system have been addressed in the named textbooks (Table 4). The scoring system is inspired by Niaz.[21]

The mention has been considered satisfactory (SM) if the textbook:

(SM-I1) presents the classifications of the chemical elements as a collective and creative challenge for several chemists before (as well as after) Mendeleev.

(SM-I2) is inclusive in the sense that women are mentioned, e.g. as discoverers of elements.

(SM-I3) uses Mendeleev's 'correct' predictions in order to emphasize chemistry-in-the-making instead chemistry as a static corpus of knowledge, but not as a way to emphasize his role as a 'hero of chemistry'.

(SM-I4) refers to post-1869 developments of the periodic system, such as changes in the positioning of elements, introduction of new elements or disappearance of others, the introduction of the atomic number by Moseley or the interpretation of the periodic law based on quantum theory.

Table 4. Recording instrument. I1-I6 refer to historical items presented above. The scoring system includes the following scores: SM, satisfactory mention; NS, non-satisfactory mention; NM, no mention.

Textbook	I1	I2	I3	I4	I5	I6
Score	SM	SM	SM	SM	SM	SM
	NSM	NSM	NSM	NSM	NSM	NSM
	NM	NM	NM	NM	NM	NM

(SM-I5) emphasizes that although Mendeleev and Meyer had important roles in the emergence of the periodic system, their approaches offer similarities and differences.

(SM-I6) notes the failed predictions of Mendeleev as an opportunity to show that scientific development is not linear, but includes errors and blind alleys.

RESULTS AND DISCUSSION

The results of the categorization of the texts based on the aforementioned methodological framework are presented in two tables: the Spanish textbooks in Table 5, and the Norwegian textbooks in Table 6, followed by analyses of the results by country.

Spanish textbooks

The history of the classification of the chemical elements in Spanish textbooks is usually a part of the atomic structure unit, running up to two of four pages. Overall, as can be deducted from Table 5, Spanish textbooks lack references to women in the history of the periodic system and the discovery of the elements (I2) and to the failed predictions of Mendeleev (I6). The texts also tend to neglect the differences between Mendeleev's and Meyer's approaches (I5). Meyers system is mostly considered identical to Mendeleev's, but independently made. Those textbooks that mention the difference between Meyer's and Mendeleev's approaches point out that 'Meyer used atomic volume as a criterion for his classification of the chemical elements' (*Santillana* (S2) *1º Bachillerato,* p. 92; *Santillana* **2º** *Bachillerato,* p. 53). Other textbooks present Meyer as 'a less audacious chemist' (*Oxford* (S5) *1º Bach,* p. 97) or Mendeleev as a chemist that 'garnered Meyer's success' (*Oxford 2º Bach.*, p. 59). All of these non-satisfactory mentions neglect the differences in approaches of Mendeleev and Meyer that have been previously indicated, such as the role of prediction or the inclusion of elements with non-established atomic weights.

The historical narratives of the classification of the chemical elements presented in the Spanish textbooks include pre-Mendeleevian proposals (I1). References to

Table 5. Results from categorization of Spanish texts on the history of the periodic system. SM, satisfactory mention; NSM, non-satisfactory mention; NM, no mention.

Research item **Level**	**I1**	**I2**	**I3**	**I4**	**I5**	**I6**	**Publisher**
CSE3 (*3º ESO*) 14-15 year-old students	NM	NM	NM	**SM**	NM	NM	**S1**
	NSM	NM	**NSM**	NM	NM	NM	**S2**
	NM	NM	**NSM**	NM	NM	NM	**S3**
	NM	NM	NM	NM	NM	NM	**S4**
	NM	NM	NM	NM	NM	NM	**S5**
CSE4 (*4º ESO*) 15-16 year-old students	**NSM**	NM	**NSM**	NM	NM	NM	**S1**
	NM	NM	NM	NM	NM	NM	**S2**
	NM	NM	**NSM**	NM	NM	NM	**S3**
	NM	NM	NM	NM	NM	NM	**S4**
	NSM	NM	**NSM**	NM	NM	NM	**S5**
USE1 (*1º Bachillerato*) 16-17 year-old students	**SM**	NM	NM	**NSM**	NM	NM	**S1**
	SM	NM	NM	**NSM**	**NSM**	NM	**S2**
	NM	NM	**NSM**	NM	NM	NM	**S3**
	NM	NM	NM	**SM**	NM	NM	**S4**
	SM	NM	**SM**	**SM**	**NSM**	NM	**S5**
USE2 (*2º Bachillerato*) 17-18 year-old students	**SM**	NM	**SM**	**SM**	NM	NM	**S1**
	SM	NM	**NSM**	**SM**	**NSM**	NM	**S2**
	NSM	NM	**NSM**	**NM**	NM	NM	**S3**
	SM	NM	**NSM**	**SM**	NM	NM	**S4**
	NSM	NM	**SM**	**SM**	**NSM**	NM	**S5**
Books which mention research items (out of total)	11/20	0/20	12/20	9/20	4/20	0/20	

Döbereiner's triads and Newland's octave law are quite common, especially in upper secondary education textbooks (*Bachillerato/Bach.*). One textbook (*Santillana* (S2) *2º Bach.*) mentions Chancourtois' *vis tellurique* from 1862. The inclusion of a such a helical periodic system may help give nuance to the traditional tale of the periodic system as a table and table only. Likewise, the mention of several contributors before Mendeleev helps to highlight the periodic system as a collective endeavour. That many scientists were involved in its development is explicitly mentioned in one textbook, which indicates that 'the history of the periodic table is a reflection of the work of a large number of scientists and the effort of the scientific community' (*Santillana* (S2) *2º Bach.*, p. 52). The history of the pre-Mendeleev classifications in Spanish textbooks emphasizes the creative and collective NOS.

References to Mendeleev's correct predictions (I3) were also found in Spanish textbooks. These predictions could be interpreted as an opportunity to show chemistry as a dynamic activity instead of a static corpus of knowledge. However, most of the textbooks introduce hagiographical and teleological images of the history of chemistry, which make some of these texts unsatisfactory. Several qualifiers are used to present Mendeleev as a prophet of chemical order. Lower secondary chemistry textbooks, for example, mention Mendeleev's correct predictions as a way to present Mendeleev as a 'genius' (*Santillana* (S2) *3ºESO*, p. 104) or to emphasize 'the boldness of his work' (*Anaya* (S1) *4ºESO*, p. 200) and 'his great intuition' (*Vicens Vives* (S3) *4ºESO*, p.162). In upper secondary chemistry textbooks, Mendeleev's predictions are presented as 'the culmination of his career' (*Vicens Vives* 1º Bach., p. 240), 'a milestone' (*Santillana* 2º Bach., p. 53), 'a great merit' (*Vicens Vives* 2º Bach., p 15.), 'a brilliant confirmation' (*McGraw-Hill* (S4) *2º Bach.* p. 28) and as an example of 'his sagacity' (*Oxford* (S5) *2º Bach.*, p. 58). Textbooks often refer to the discoveries of what Mendeleev had called eka-boron (Sc), eka-silicon (Ge) and eka-aluminium (Ga), which are easy to locate in our current periodic system. One textbook (*Santillana* 2º Bach.) refers to eka-manganese (but using the current name, technetium). Mendeleev's wrong predictions are, however, completely neglected. This adds to the narrative of the periodic system and Mendeleev as a success story. A mention of failed predictions could have contributed to a more critical and less idealized approach of the NOS in science teaching.

Approximately half of Spanish textbooks analysed describe the evolution of the periodic system after Mendeleev's periodic table (I4). References to the contribution of the English physicist Henry Moseley, the Swiss chemist Alfred Werner, the Austrian-born British chemist Friedrich A. Paneth and the American physicist Glenn T. Seaborg have been found in several books. All of these reveal the periodic system as an expanding model shaped by several scientists in different historical contexts. This is a satisfactory NOS conception, which emphasizes tentativeness as an important feature of science. Finally, it should be noted that no significant differences between publishers have been found. Furthermore, more references to the history of the periodic system have been observed in chemistry textbooks for higher levels (USE).

Norwegian textbooks

As noted above, the history of the periodic system is not part of the Norwegian curriculum at any level in school. It is therefore up to the textbook authors and their publishers to include aspects from the history of chemistry if considered useful, and also to select which aspects are relevant. According to the curriculum, the periodic system is to be taught during lower secondary school as part of the integrated science course, but in which year is not specified. Most of the authors responsible for the textbooks at this level have included it in grade 9 (the second year of lower secondary school). A few authors have included a brief introduction of the system in grade 8, and delve more deeply into the topic in grade 9. One textbook presents the periodic system only in grade 8 (N4). Likewise, a few textbooks for the optional chemistry course in upper secondary school describe the periodic system briefly, even though it is not part of the curriculum. But even where the periodic system is explained in these textbooks, the history of the system is not necessarily touched upon. For example, *Kjemien stemmer 1* (N7) includes no history at all, but most of the textbooks mention Mendeleev and a brief history of the system. Some include the mention only in a figure caption, others as part of the main text – usually between a paragraph and a page long (three and a half pages for *Kjemi for lærere*, N8).

Overall, the historical descriptions in the Norwegian textbooks are scarce. No textbook mentions any women in the history of the periodic system (I2), nor do they mention Meyer or any other co-discoverer (I5) or Mendeleev's failed predictions (I6). One textbook from lower secondary school (*Eureka!* 9, N3) and one from upper secondary school (*Kjemi 1*, N5) are the only textbooks hinting that any pre-Mendeleevian history might exist (I1). *Eureka!* 9 simply states that 'many people have contributed to solving this difficult task' (p. 10), while *Kjemi 1* explains that Mendeleev 'combined earlier scientists'

Table 6. Results from categorization of Norwegian texts on the history of the periodic system. SM, satisfactory mention; NSM, non-satisfactory mention; NM, no mention.

Level \ Research item	I1	I2	I3	I4	I5	I6	Book series
CSE8 (*Grade 8*) 13-14 year-old students	NM	NM	NM	NM	NM	NM	**N1**
	NM	NM	NM	NM	NM	NM	**N2**
	NM	NM	NM	NM	NM	NM	**N3**
	NM	NM	**NSM**	NM	NM	NM	**N4**
CSE9 (*Grade 9*) 14-15 year-old students	NM	NM	**NSM**	NM	NM	NM	**N1**
	NM	NM	**NSM**	NM	NM	NM	**N2**
	NSM	NM	NM	**NSM**	NM	NM	**N3**
USE2 (*2nd year of Upper secondary school*) 17-18 year-old students	**NSM**	NM	**NSM**	NM	NM	NM	**N5**
	NM	NM	**NSM**	NM	NM	NM	**N6**
	NM	NM	NM	NM	NM	NM	**N7**
CE (teacher education at college level)	**SM**	NM	**NSM**	**SM**	NM	NM	**N8**
Number of books which mention research items (out of total)	3/11	0/11	6/11	2/11	0/11	0/11	

works into an original and genial system' (figure caption, p. 22). The textbook for teacher trainers (*Kjemi for lærere*, N8) is the only one giving a satisfactory account on the periodic system as a collective effort. In this book Döbereiner's triads are mentioned, as are Odling's groups of elements and the discussion around atomic weight determinations leading up to 1860 (p. 77). But Odling is not credited as co-discoverer of the periodic system. That the system did take different forms is, however, exemplified by Frederick Soddy's spiral system of 1911 (p. 80), giving insight into the many possible ways of organizing the elements periodically, based on the same principles.

The most represented topic among our historical items (in 6 out of 11 books) are Mendeleev's 'correct' predictions (I3). However, none present the predictions as a complex process including trial and error, not even the textbook for teacher trainers, which states:

Mendeelev set aside spaces in the periodic system for new elements which would likely be discovered. He predicted which properties these new elements and their compounds would have, and the predictions later turned out to fit very well (p. 78).

Nova 8 (N4) is more cautious, informing readers that 'most' predictions were successful, not all (p. 102). *Tellus* 9 (N1) adds that the predictions of Mendeleev helped scientists in their 'hunt' for new elements, since the properties of these elements were known. This is how germanium was discovered, the authors state (p. 14).[50] Another book (*Kjemi 1*, N5) gives gallium as an example (p. 22). Two textbooks also include tables comparing Mendeleev's predictions for 'eka-silicon' from 1871 with Clemens Winkler's (1838–1904) descriptions after his discovery of germanium in 1886, to show how good Mendeleev's predictions were (*Kjemi for lærere* (N8), p. 79; a simplified version is presented in *Aqua Kjemi 1* (N6), p. 28). This 'success approach' of the history of the periodic system is in line with traditional, popular accounts of the periodic system of today, which often emphasize linear (Whiggish) history and explain Mendeleev's success on the basis of his predictions.

Only two textbooks mention that Mendeleev's periodic system continued to be developed after his time (I4). *Eureka!* 9 (N3), the textbook for lower secondary school, simply states that '[t]he periodic system has been improved in the course of the last 140 years, but has much in common with the one Mendeleev devised' (p. 10). *Kjemi for lærere* (N8) mentions the problems of accommodating rare earth elements (what we today know as lanthanoids) and how this challenge was solved with the use of the concept of 'atomic number', introduced by H. Moseley in 1913 (p. 79).

Discussion

Even though Norway and Spain represent different teaching contexts, the history of the periodic system presented in textbooks in these countries share some similarities. Both Spanish and Norwegian textbooks neglect the role of the women in the history of the discovery (I2) of the chemical elements and Mendeleev's failed predictions

(I6), not surprisingly perhaps, since these aspects have not been highlighted in international textbooks on history of chemistry at university level either. Nevertheless, this neglect can be interpreted as a missed opportunity to foster an equal and non-hagiographical approach to the history of science in school. In Spanish textbooks, as well as in Norwegian ones, references to the history of the periodic system before Mendeleev (I1) and after his time (I4) can be found. However, Spanish textbooks offer a wider range of references to historical actors and classifications than do the Norwegian textbooks. Such mentions may contribute to a view of science as a collective and creative enterprise. Mendeleev's successful predictions (I3) can be found in Spanish and Norwegian textbooks. However, textbooks tend to address this historical issue unsatisfactorily, if it is mentioned at all. Instead of presenting chemistry as a complex and tentative activity that is always subject to revision, textbooks use Mendeleev's successful predictions merely to present a success story, just as Brush observed in the 1970s. Little or no reference to Meyer's and Mendeleev's different approaches (I5) further adds to the depiction of an individual-centred science and thus neglects to illustrate how several approaches to the same phenomena often coexist in science. The political dimension in the history of the periodic system is also neglected in historical narratives in the chemistry textbooks. Cases such as the controversies around the name or symbol of some elements (like wolfram and tungsten for element 74 or rutherfordium and kurchatovium for element 104) could have been one way of including such aspects.

Even though the periodic system has a natural place in today's chemistry teaching, our analyses have pointed out that authors of current textbooks in Spain and Norway do not take the opportunity to teach about the Nature of Science (Table 7). Of the 31 textbooks that we have analysed, only eight (7/20 in Spain and 1/11 in Norway) refer to post-Mendeleev developments of the periodic system, such as the introduction of the atomic number by Moseley or the reinterpretation of the periodic system based on quantum theory. Seven textbooks (6/20 in Spain and 1/11 in Norway) present the classification of the chemical elements as a collective and creative challenge for several chemists before Mendeleev, while all but three texts (3/20 in Spain and 0/11 in Norway) use Mendeleev's successful predictions as a way to emphasize his role as a 'hero of chemistry'. Using the SOURCE approach, we can draw the conclusion that these historical narratives do paint an image of science as a process (S) with uncertainties (U) and developed in a historical context (R), not just as a corpus of knowledge (science as a product). However, the other parts of SOURCE (O, C, E) are neglected (Table 7). As Brush predicted many years ago, textbook authors prefer to present science as a work of bright and successful men. Nothing could be further from the stories presented by historians of science and NOS scholars in science education.

Table 7. SOURCE approach applied to Norwegian and Spanish textbook analysis. SM, satisfactory mention; NSM, non-satisfactory mention; NM, no mention.

Research item	SM	NSM	NM	NOS implication
I1	7	7	17	**S**cience-in-the-making and science-made combined
I2	0	0	31	**O**verinflated genius
I3	3	15	13	**U**nqualified universality and uncertainties
I4	8	3	20	**R**espect for the historical context
I5	0	4	27	**C**aricature and **C**ontroversies unattended
I6	0	0	31	**E**xpected results and Excuses – **E**rror dimension missed

CONCLUSION

In this essay, we have explored the extent to which the history of the periodic system is presented in recent textbooks, and which aspects of the nature of science can be taught based on historical narratives of the periodic system. Our analyses have pointed out that textbooks in Spain and Norway (though to various extents) introduce three historical contexts: developments before Mendeleev's periodic system, in Mendeleev's time and after his contributions. These aspects, if sufficiently described, may contribute to a portrayal of science as a creative endeavour based on a collective effort. However, the textbooks in our samples seem to miss the opportunity to give a fuller picture through references to women discoverers of chemical elements and to Mendeleev's failed predictions. We may argue that the way the historical narratives are presented in these textbooks contributes to masking the tentative and socio-cultural aspects of NOS as a human endeavour. Likewise, textbooks in Spain and Norway tends to be less concerned with the differences between Meyer's and Mendeleev's approaches, losing an opportunity to show the diversity in NOS – that scientists use different methods to achieve the same goal.

The history of the periodic system offers a wide range of possibilities for teaching chemistry – if teachers, textbook authors and publishers are willing to use it. The textbooks in our sample explore only a few of these possibilities. We argue that the uses of the history of the periodic system in textbooks for secondary school could be explored further by introducing women as well as men, and errors as well as successes – as Allchin has argued. Finally, it should be noted that rather than aspiring to present a complete and exhaustive history of the classification of the chemical elements at any level in school, textbooks should instead adjust the content to specific teaching contexts and curricula, and introduce small changes which could contribute to a more nuanced image of science. Hence, the history of the periodic system has the potential to endow science teaching with a collective, creative, diverse, tentative and inclusive portrayal of chemistry. To this end, world-wide initiatives such as the International Year of the Periodic Table can help to bring less well-known aspects and recent scholarship to the fore, for the benefit of young people, their teachers and the general public.

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51. Publications such as the forthcoming volume in women and elements (ref. 42) may contribute to make women's contributions more visible in the future.

APPENDIX: TEXTBOOK SAMPLES

Norwegian textbooks

(N1) P. R. Ekeland, O-I Johansen, S. B. Strand, O. Rygh & A-B Jenssen, *Tellus: Naturfag for ungdomstrinnet,* **2007,** Aschehoug, Oslo.
(N2) H. S. Finstad, E. C. Jørgensen & J. Kolderup, *Trigger,* **2008**, Damm, Oslo.
(N3) M. Frøyland, J. Haugan & M. Munkvik *Eureka! Naturfag for ungdomstrinnet*, **2006**, Gyldendal undervisning, Oslo.
(N4) E. Steineger & A. Wahl, *Nova: Naturfag for ungdomstrinnet*, **2014**, Cappelen Damm, Oslo.
(N5) H. Brandt & O. T. Hushovd, *Kjemi 1*, **2010**, Aschehoug, Oslo.
(N6) B.-G. Steen, N. Fimland & L. A. Juel, *Aqua1: Kjemi 1 Grunnbok*, **2010**, Gyldendal undervisning, Oslo.
(N7) T. Grønneberg, M. Hannisdal, B. Pedersen & V. Ringnes, *Kjemien stemmer 1,* **2012**, Cappelen Damm, Oslo.
(N8) M. Hannisdal & V. Ringnes, *Kjemi for lærere,* 2nd ed., **2013**, Gyldendal akademisk, Oslo.

Spanish textbooks

CSE-3 (*3º ESO*)

(S1) S. Zubiaurre, A. M. Morales, J. M. Arsuaga & A. Pérez, *Física y Química 3. Educación Secundaria*, **2011**, Anaya, Madrid.
(S2) M. C. Vidal-Fernández, F. Prada, J. L. García & P. Sanz Martínez, *Física y Química 3. ESO: Proyecto Los Caminos del Saber*, **2011**, Santillana, Madrid.
(S3) À. Fontanet & M. J. Martínez, *Física y Química 3. Educación Secundaria: Proyecto Nuevo Ergio*, **2012**, Vicens Vives, Barcelona.
(S4) A. Peña, A. Pozas, J. A. García-Pérez, A. Rodríguez & A. J. Vasco, *Física y Química 3. ESO*, **2007**, McGraw-Hill, Barcelona.
(S5) I. Piñar-Gallardo, *Física y Química 3. ESO: Proyecto Adarve*, **2011**, Oxford, Madrid.

CSE-4 (*4º ESO*)

(S1) S. Zubiaurre, A. M. Morales, F. Gálvez & I. Molina, *Física y Química 4. Educación Secundaria*, **2012**, Anaya, Madrid.
(S2) M. C. Vidal-Fernández, F. Prada, J. L. García & P. Sanz-Martínez, *Física y Química 4. ESO: Proyecto Los Caminos del Saber*, **2011**, Santillana, Madrid.

(S3) À. Fontanet & M. J. Martínez, *Física y Química 3. Educación Secundaria: Proyecto Nuevo Ergio*, **2012**, Vicens Vives, Barcelona.

(S4) A. Cardona, J. A. García, A. Peña, A. Pozas & A.J. Vasco, *Física y Química 4. ESO*, **2008**, McGraw-Hill, Madrid.

(S5) I. Piñar-Gallardo, *Física y Química 4. ESO: Proyecto Adarve*, **2012**, Oxford, Madrid.

USE-1 (*1º Bachillerato)*

(S1) S. Zubiaurre, J. M. Arsuaga, J. Moreno & B. Garzón, *Física y Química 1. Bachillerato*, **2014**, Anaya, Madrid.

(S2) F. Barradas , J. G. López, P. Valera & M. C. Vidal, *Física y Química 1. Bachillerato: Proyecto La Casa del Saber*, **2008**, Santillana, Madrid.

(S3) M. J. Martínez & À. Fontanet, *Física y Química 1. Bachillerato*, **2012**, Vicens Vives, Barcelona.

(S4) A. Rodríguez, A. Pozas, J. A. García, R. Martín & Á. Peña, *Física y Química 1. Bachillerato*, **2012**, McGraw-Hill, Madrid.

(S5) M. Ballestero & J. Barrio, *Física y Química 1. Bachillerato: Proyecto Tesela*, **2008**, Oxford, Navarra.

USE-2 (*2º Bachillerato)*

(S1) S. Zubiaurre, J. M. Arsuaga & B. Garzón, *Química 2. Bachillerato*, **2012**, Anaya, Madrid.

(S2) C. Guardia, A. I. Menéndez-Hurtado & P. Prada, *Química 2. Bachillerato: Proyecto La Casa del Saber*, **2011**, Santillana, Madrid.

(S3) À. Fontanet, *Química 2. Bachillerato*, **2014**, Vicens Vives, Barcelona.

(S4) A. Pozas, R. Martín, A. Rodríguez & A. Ruiz, *Química 2. Bachillerato*, **2009**, McGraw-Hill, Madrid.

(S5) J. Peña & M. C. Vidal, *Química 2. Bachillerato: Proyecto Tesela*, **2009**, Oxford, Vizcaya.

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Are History Aspects Related to the Periodic Table Considered in Ethiopian Secondary School Chemistry Textbooks?

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Abstract. The aim of this study was to evaluate Ethiopian secondary school chemistry textbooks with respect to presentation of history and philosophy of science (HPS) related aspects of the periodic table. We focused on how the textbooks approached the periodic table as a conceptual tool for organizing the chemical elements, and understanding their properties. For this purpose, three grade 9 chemistry textbooks (introduced in the last two decades by the Ministry of Education of Ethiopia) were selected. We conducted the evaluation qualitatively using an adopted version of a four-point criterion developed based on HPS framework. Our evaluation revealed that that only one of the three textbooks addressed just only one of the four HPS aspects of the periodic table satisfactorily, while in the other two textbooks all of the four aspects are generally ignored. It is concluded that most HPS related aspects of the periodic table are missed from Ethiopian secondary school chemistry textbooks, and the few aspects which are addressed are not properly presented. We believe that this could have negative consequences on the students' attitude and interest towards science as well as on their understanding of science concepts and performance in the subject.

Keywords. History and philosophy of science (HPS), chemistry textbooks, Ethiopian secondary school, periodic table, evaluation.

1. INTRODUCTION

The current structure of the Ethiopian education system can be described as 8-2-2-3+ i.e. eight years primary (grade 1–8; age 7–14), two years secondary first cycle (grade 9–10), two years secondary second cycle (grade 11–12), and 3 to 6 years university education. In Ethiopia, formal teaching and learning of science begins at the primary level; and chemistry, biology and physics begin to be taught as separate subjects, compulsory for all students, at grade 7. This continues up to grade 10. Starting from grade 11, as a preparation for higher education, students have to choose between two options: *natural science* and *social studies*. Students majoring in science study chemistry, biology, and physics as principal subjects. Each subject has its own syllabus, teacher's guide and textbook (prepared by the Ministry of Education) which is uniformly used across the country. Despite the policy recommendations for a concise and student-centered curricula (where a variety of teaching methods shall be used)[1], studies have indicated that the Ethiopian science curricula were too theoretical and overloaded; and the method of teaching used by teachers as teacher-centered (commonly called "chalk and talk") emphasizing recall of large amounts of factual information to pass examinations.[2,3,4,5]

Textbooks are usually considered to be the primary reference materials to carry out classroom instruction in many countries. This is particularly true in schools of developing countries where both teachers and students heavily rely on textbooks for their lessons. For instance, according to Yager, nearly 100% of Nigerian science teachers rely on textbooks to select appropriate content to teach their students.[6] In our experience as science educators and researchers in the country, due to various reasons, Ethiopian science/chemistry teachers too rely solely on textbooks. However, these textbooks have not yet reached the standards of developed communities as they are prepared by individuals (usually school teachers or university lecturers) who have little/no experience in textbook preparation, or even worst by foreign (commonly Indian) writers who are unacquainted with the Ethiopian classroom context. As such, these textbooks can be a source of students' learning and teachers' teaching difficulties. This is in agreement with the findings of other international studies which reported that textbook presentation of science content are often incompatible with the suggestions of science education research, and may entail problems if used uncritically.[7,8] In addition, in the Ethiopian context, studies revealed that school chemistry teachers have a variety of misconceptions about various chemical concepts.[9,10,11] As indicated in the country's national learning assessment report and in a survey study conducted by USAID/IQPEP Ethiopia, the presence of such compounded problems might be among the possible causes of the alarmingly declining students' science performance in regional and national examinations.[12]

As a remedy to the above mentioned problems as well as other teaching-learning deficiencies, many researchers and teachers have suggested the inclusion of history and philosophy of science (HPS) in the science curriculum, textbooks, and classroom.[13,14,15] Teaching and learning of science using HPS approach has been reported to have several merits: e.g. for teaching and learning about science as a process, for promoting conceptual change and a deeper understanding of scientific ideas, for fostering public understanding of science, and for positively impacting students' attitudes and interests toward science.[14,15,16] However, it has been argued that science textbooks rarely address in a meaningful way the historical development of science and the nature of science, instead presenting science in a distorted and ahistorical way.[17,18]

In the Ethiopian context, there is no explicit standard which promotes the inclusion of the HPS approach of teaching and learning of science. In addition, despite the Policy recommendation for application of a variety of teaching approaches, the curricular materials (syllabus, student textbooks and teacher's guide) which are issued by the Ministry of Education do not allow for flexibility as teachers are expected to strictly follow these documents. This practically means that there is little/no room for teachers to flexibly implement HPS based teaching (i.e. to use historical cases) in their lessons. This is similar to what has been reported by Van Bertel et al.[19], who on the basis of content analysis of school chemistry textbooks (published in UK and Netherlands) identified school chemistry as a form of "normal science education" which is considered to be "dangerous" in that it isolates the learner from the HPS and, as such, is narrow and rigid and tends to instill a dogmatic attitude towards science.

The periodic table is considered to be an important topic of secondary school and undergraduate chemistry textbooks worldwide. It serves as a source of information for students to learn the fundamental building blocks of chemistry, the chemical elements, and the relationship between them. However, previous studies have reported problems in presenting the periodic table in the textbooks which led to difficulties in teaching and learning the concepts behind it.[20,21,22] According to Niaz and Luiggi, most students consider the periodic table to be a difficult topic.[23]

Studies on chemistry textbooks dealing with the periodic table can be found in many developed countries. This is not, however, the case in developing countries. In Ethiopia, specific well-documented studies of chemistry textbooks presentations of the periodic table are lacking. The purpose of this study was therefore to contribute to the understanding of how the periodic system is taught in Ethiopia. This way, based on textbook presentations, we will help provide perspectives from an African school practice, and by so doing, contribute to giving a fuller picture of how the periodic table is taught in schools all over the world.

2. ASPECTS OF HISTORY OF THE PERIODIC TABLE WORTHY OF CONSIDERATION IN CHEMISTRY TEXTBOOKS

The periodic table has been considered a conceptual tool because it has contributed much more than mere classification; it has predicted new elements, predicted unrecognized relationships, served as a corrective device, and fulfilled a unique role as a memory and organization device[24] which in turn has led to a better understanding of chemistry. In this section, some selected HPS related aspects of the periodic table (based on Brito et. al.[25] and Niaz and Luiggi[23]) which we believe are worthy of including in secondary school chemistry textbooks are briefly discussed.

In view of this, it should be noted that there were early ideas about atomic theory and accumulation of data with respect to the atomic weights of the elements and their properties; and that there were several attempts to classify elements between 1817 and 1860. For example, by 1829, the German chemist Johann Döbereiner (1780-1849) presented the law of triads as he noted a similarity among the physical and chemical properties of several groups of three elements and the relation of their atomic weights.[24] A major hindrance to the widespread acceptance of such classifications was that no consensus on atomic weight values existed. A significant progress was made only after the Karlsruhe conference of 1860 at which the Italian chemist Stanislao Cannizzaro (1826-1910) presented one specific system for atomic weights and wrote a pamphlet which convinced many chemists, after which the stage was set for the discovery of the periodic system. It is generally acknowledged that the periodic system was independently discovered during the 1860s by six individuals, namely: French geologist and mineralogist Alexander Beguyer De Chancourtois (1820-1886), English chemist William Odling (1829-1921), American chemist Lothar Meyer (1830-1895), English chemist John Newlands (1837-1898), German chemist Gustavus Hinrichs (1836-1923), and Russian chemist Dmitri Mendeleev (1834-1907).[28,27] By 1869, a total of 63 elements had been discovered and in the same year, Mendeleev completed his first form of the periodic system in which he arranged all of these elements based on their atomic weights.[23,28] In the 1920s, based on the work of the English physicist Henry Moseley (1887-1915) and others some years earlier,[25] the periodic table was organized according to atomic number instead of atomic weight. This, and the discoveries of the sub-atomic particles, in turn helped chemists to have a deeper understanding of the organization of the periodic table and the properties of the individual elements. Inclusion of the above HPS related aspects of the periodic table in textbooks may help present the development of the periodic table as a progressive, collective and at the same time sequential and simultaneous endeavor based on different contributions; and thus, it stimulates and encourages students to understand how science progresses and the tentative nature of scientific findings.

Other HPS related aspects of the periodic table that arguably deserve attention in chemistry textbooks are the importance of *accommodation* (i.e. agreement of observed properties of the elements such as atomic weight/number and other properties with the theory) and *prediction* (of new elements). The latter can be highlighted by providing as an example at least one of the three elements gallium, scandium, or germanium, and a comparison of the predicted and experimental properties without forgetting to mention that not all predictions were successful. It should also be explained to readers that there has been some controversy among historians and philosophers of science with respect to the relative importance of accommodation and prediction[25]. However, for classroom teaching, it is sufficient to explain that the success of the periodic table could be partly attributed to accommodations, predictions, or both. This might facilitate the understanding that the same experimental data can be explained by alternative interpretations.

Overall, inclusion of the HPS aspects of the periodic table in chemistry textbooks might help students understand how science evolves through the interactions of theories, experiments, and the work of actual scientists.[18]

3. RESEARCH METHOD

Overall, the study involved four stages. In the first stage, we reviewed literatures that are relevant to the historical and philosophical development of the periodic table and their educational implications. In the second stage, based on the reviewed literature, and particularly inspired by Brito et al.,[25] we designed a four point evaluation criteria for evaluating Ethiopian secondary school chemistry textbooks with respect to how they addressed the periodic table. The third stage involved selection of textbooks for the evaluation in which we selected three 9th grade chemistry textbooks (written by Sharma et al.,[29] Abera and Abusie,[30] and Mamo and Tassew[31]) that the Ministry of Education of Ethiopia has introduced in the last two decades. We selected 9th grade textbooks for the reason that in the Ethiopian secondary school chemistry curricula, the topic of periodic table is included in grades 9 and 11 only; and from our survey of these textbooks, we learned that no historical cases of the periodic table are presented in the grade 11 textbooks (as the discussion started from the topic of 'the modern periodic table'). The grade 9 chemistry textbooks, however, had addressed some of the historical aspects. The fourth stage of the study involved evaluation of the selected textbooks based on the developed criteria in which each criterion was scored qualitatively as Satisfactory (S), Mention (M), or No Mention (N). Detailed description of the evaluation criteria is given below:

Evaluation criteria

Criteria 1: Development of the periodic table as a case of progressive sequential/simultaneous discovery.

- **Satisfactory (S)**: If the textbook emphasizes the development of the periodic table as progressive, collective and at the same time sequential and simultaneous endeavor based on the following contributions: (a) early ideas about atomic theory and accumulation of data with respect to the atomic weights of the elements and their properties; (b) the first attempt to classify the elements by Döbereiner, and later by De Chancourtois, Odling, Meyer, Newlands, Hinrichs, and other attempts before Mendeleev; (c) Mendeleev's first periodic table in 1869 based on atomic weights and subsequent contributions; and (d) the contribution of Moseley (1913), and the shift from atomic weight to atomic numbers (modern periodic table).
- **Mention (M):** if the textbook mentions some of the major contributors without establishing a sequential, collective and progressive development explicitly.
- **No mention (N):** if the textbook included Mendeleev and Moseley only or if the textbook simply starts from the modern periodic table.

Criteria 2: The importance of accommodation in the development of the periodic table:

- **Satisfactory (S):** If the textbook explains and emphasizes that an important aspect of the periodic table is accommodation of the different elements with respect to atomic weight/number and other properties such as density, atomic volume, atomic/ionic radii, ionization energy, electronegativity, electron affinity, etc.
- **Mention (M):** if the textbook simply mentions that accommodation of the different elements was important.
- **No mention (N):** If the textbook did not at all mention the role played by accommodation.

Criteria 3: The importance of prediction as evidence to support the periodic law.

- **Satisfactory (S):** If the textbook emphasizes the importance of prediction in the development of the periodic table by providing as an example at least one of the three elements gallium, scandium, or germanium, and a comparison of the predicted and experimental properties; as well as reminding the reader that not all predictions were successful.
- **Mention (M):** A simple mention that Mendeleev made predictions of new elements, and provides an example (without comparing predicted and experimental properties).
- **No mention (N):** If the textbook states that Mendeleev made predictions, and does not provide an example.

Criteria 4: Relative importance of accommodation and prediction in the development of the periodic table.

- **Satisfactory (S)**: If the textbook explicitly explains the presence of debates among historians and philosophers of science with respect to the relative importance of accommodation and prediction, and presents the merits and demerits of each, and indicates to the students that the success of the periodic table could be partly attributed to accommodations, predictions, or both.
- **Mention (M)**: A simple mention and comparison of alternate ways of explaining the success of the periodic table with no mention of rivalry and controversy.
- **No Mention (N)**: If the textbook mentions the role played by accommodation and prediction with no attempt to compare the two.

4. ETHIOPIAN SECONDARY SCHOOL CHEMISTRY TEXTBOOKS ACCOUNTS: RESULTS AND DISCUSSION

As outlined above, three secondary school chemistry textbooks were analyzed to see how the textbooks presented the historical and philosophical aspects of the periodic table; and how accurate, coherent and complete these presentations are.

Criterion 1: Development of the Periodic Table as a case of progressive simultaneous/ sequential discovery

The key idea behind this criterion is to assess the chemistry textbooks to see whether or not they presented the development of the periodic table as a case of progressive and simultaneous/sequential discovery based on different contributions in such a way that it stimulates and encourages students to think that there is more to scientific progress than simple accumulation of data and linear progress through individual discoveries.[25] We found that none of the textbooks presented this aspect of the periodic table satisfactorily (S). All the three textbooks simply mentioned (M) three to four of the contributors without establishing a sequential, collective and

Table 1. Some quotations from the evaluated textbooks.

Textbook	Quote
Sharmaet al.[29]	Early attempts to classify elements were based on atomic mass [weight]. The first attempt was made in 1817 by J.Dobereiner [who presented the law of triads]. In 1864, John Newlands reported the law of octaves. In 1869 Mendeleev and Lothar Mayer independently published periodic arrangements. In 1913 Henry Mosley determined the atomic number by analyzing X-ray spectra.
Abera andAbusie[30]	The periodic table has been developed over many years. In 1817 J.W. Dobereiner observed that the atomic mass [weight] of bromine was very nearly equal to the average masses [atomic weights] of chlorine and iodine. In 1864, John Newlands reported the law of octaves. The periodic law was proposed independently by Mendeleev and Lothar Mayer. [Clemens]Winkler, in 1876 [1886], discovered germanium. Henry Moseley, between the years 1911 and 1914, discovered a new fundamental property of elements.
Mamo and Tassew[31]	In 1817 J.W. Döbereiner observed groups of three elements with similar properties. In 1864, John Newlands reported the law of octaves. The periodic law was proposed independently by Mendeleev and Lothar Mayer.

progressive development explicitly. The following quotes (see Table 1) are provided as examples:

As can be understood from the quotes, the writers of the textbooks have tried to endorse the tentative nature of scientific theories/models. However, the information presented is not articulated, it's just a string of events with no details; it confuses the teachers and the students even more, as it does not provide them with a way to relate these earlier developments to the final outcome. The scientific process looks even messier. So this is unsatisfactory and unproductive.

Criterion 2: Importance of Accommodation in Development of the Periodic Table

From the analysis, we found that there are no substantial differences in the way the three textbooks emphasized the importance of accommodation (of the different elements with respect to their physicochemical properties) in the development of the periodic table. None of the three textbooks presented a satisfactory (S) description; three of them just give a simple mention (M). For example Sharma et al.[29] mentioned the following: "Dmitri Mendeleev developed the periodic table and formulated the periodic law. Because his classification revealed recurring patterns (periods) in the elements…" (p. 39).

Criterion 3: The importance of prediction as evidence to support the periodic law

Sharma et al.[29] is the only textbook to emphasize the importance of prediction satisfactorily (S) as evidence to support the periodic law. Furthermore this textbook compared the properties of at least one of the predicted

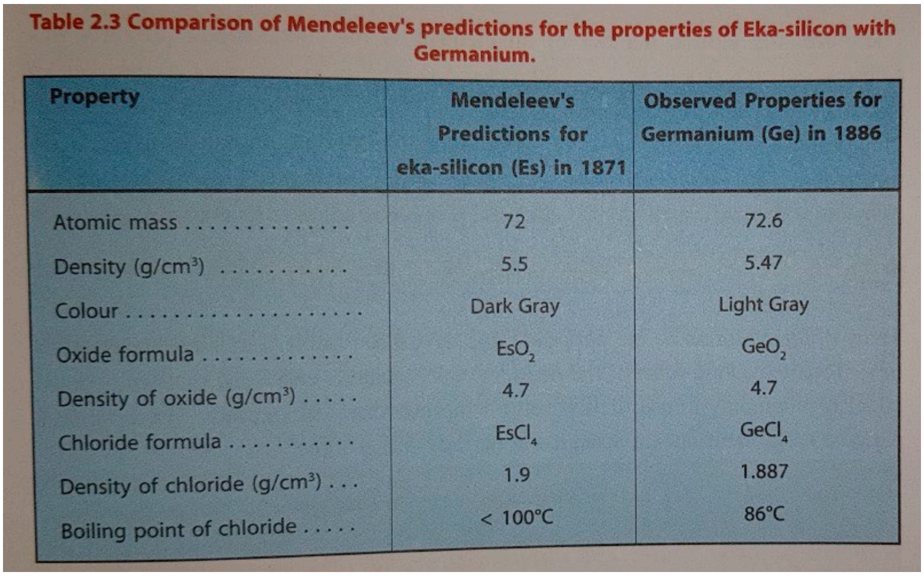

Table 2.3 Comparison of Mendeleev's predictions for the properties of Eka-silicon with Germanium.

Property	Mendeleev's Predictions for eka-silicon (Es) in 1871	Observed Properties for Germanium (Ge) in 1886
Atomic mass	72	72.6
Density (g/cm^3)	5.5	5.47
Colour	Dark Gray	Light Gray
Oxide formula	EsO_2	GeO_2
Density of oxide (g/cm^3)	4.7	4.7
Chloride formula	$EsCl_4$	$GeCl_4$
Density of chloride (g/cm^3)	1.9	1.887
Boiling point of chloride	< 100°C	86°C

Figure 1. Sharma et al.[29] textbook representation of importance of prediction as evidence to support the periodic law.

elements (Ga, Sc, and Ge) with the observed values. The following are specific examples taken from Sharma et al.[29]: "Mendeleev left blank spaces for these two elements in the table, just under aluminum and silicon. He called these unknown elements 'eka-aluminum' and 'eka-silicon'. What he meant by 'eka-aluminum' is a currently known element (gallium) following aluminum. Later on, in 1874, the element gallium (eka-aluminum' in Mendeleev's system) was discovered. The observed properties of these elements were remarkably very close to those in Mendeleev's prediction." (p. 39)

This textbook also compared the properties of at least one of the predicted elements (eka-silicon) with the observed properties of germanium. In the textbook, the comparison is clearly presented in the form of a table (see Figure 1). The other two textbooks made no mention (N) and hence ignored the issue.

In the same way, Abera andAbusie[30] stated the following: "The periodic law provided a working basis for the predication of new elements or unfamiliar elements. It also provided an important stimulus for further chemical investigations." (p. 75)

Criterion 4: Relative importance of accommodation and prediction in the development of the periodic table

None of the textbooks explained the relative importance of accommodation and prediction in the development of the periodic table satisfactorily, and only a textbook by Sharma et al.[29] made a simple mention (M) and comparison of alternate ways of explaining the success of the periodic table with no mention of rivalry and controversy as exemplified in the quote below:

> *Early attempts to classify elements were based merely on atomic mass [weight]... scientists begun to seek relationships between atomic mass and other properties of the elements (p. 37).*
> *Mendeleev observed that when elements are arranged according to increasing atomic mass, the chemical and physical properties of the elements recur at regular intervals (p. 40).*
> *Mendeleev left blank spaces for the undiscovered elements and also predicted masses [atomic weights] and other properties of these unknown elements almost correctly (p. 40).*

From the above quote, one can conclude that the textbook by Sharma et al.[29] does recognize the importance of accommodations and predictions separately but not the relative importance of the two. In agreement with Brito et al[25]., we argue that textbooks should inform learners that the success of the periodic table could be attributed to accommodations, predictions, or both. This will help students to take the view that the same experimental data can be explained by alternative interpretations.

5. CONCLUSION AND IMPLICATIONS FOR CHEMISTRY EDUCATION

The purpose of this study was to evaluate Ethiopian secondary school chemistry textbooks with respect to the presentation of the historical development of the periodic table of chemical elements which is considered to be a conceptual tool[24] that helps to organize a great deal of information, leading to a better understanding of chemistry. As mentioned earlier, three grade 9 chemistry textbooks were selected for the evaluation. We conducted the analysis qualitatively by reading the relevant pages of the textbooks based on a four point evaluation criteria adopted from previous researchers[25]. As can be seen from Table 2, of the four historical aspects of the periodic table, a satisfactory description of only one of them (namely, the importance of *prediction*s as evidence to support the periodic law) is presented by one textbook (by Sharma et al.[29]) only. The same textbook has attempted to present the first aspect i.e. *the development of the periodic table as a sequence of discoveries* but not in such a way that it informs the student that such development of the periodic table went through a continual controversy in which scientists presented various tentative theoretical ideas. In addition, the information presented is not articulated; it is just a string of events with no details; it may confuse the teachers and the students even more; and as such the scientific process looks even messier. In the other two textbooks (Abera and Abusie[30]and Mamo and Tassew[31]), all the four historical aspects of the periodic table including the importance of *accommodation* in development of the periodic table, and the *relative importance of accommodation and prediction* are generally ignored (i.e. simple mention or no mention).

We may conclude that the HPS aspects of the predict table are not satisfactorily addressed in Ethiopian secondary school chemistry textbooks. That means, the textbooks' presentation of the said aspects does not

Table 2. Results of analysis of Ethiopian secondary school chemistry textbooks accounts of the periodic table based on the history and philosophy of science framework.

Textbook	Criteria				
	1	2	3	4	5
Sharma et al.[29]	M	M	S	M	N
Abera and Abusie[30]	M	M	N	N	N
Mamo and Tassew[31]	M	M	N	N	N

facilitate the students' understanding of how science evolves as well as its tentative nature which in turn may have negative implications on the students' chemistry/science interest as well as on their understanding of and performance in the subject. This is similar to what is concluded by Van Berkel, De Vos, Verdonk, Pilot[19], who based on their study identified school chemistry as a form of "normal science education" which is considered to be "dangerous" in that it isolates the learner from the HPS and, as such, is narrow and rigid and tends to instill a dogmatic attitude towards science. As the scope of the current study is limited in several ways, to get a fuller understanding of how HPS related aspects of science are taught in Ethiopian/African schools, it is recommended for more comprehensive studies to be conducted in the future.

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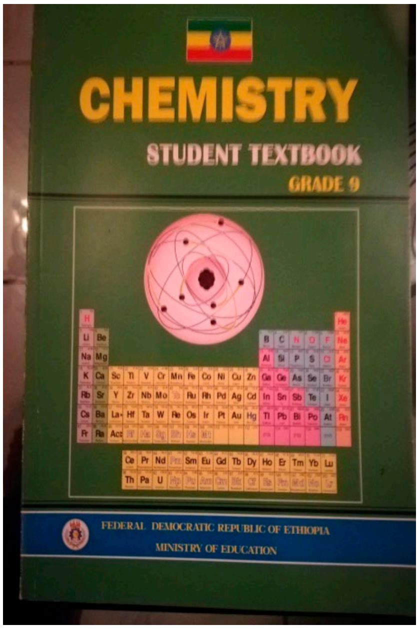
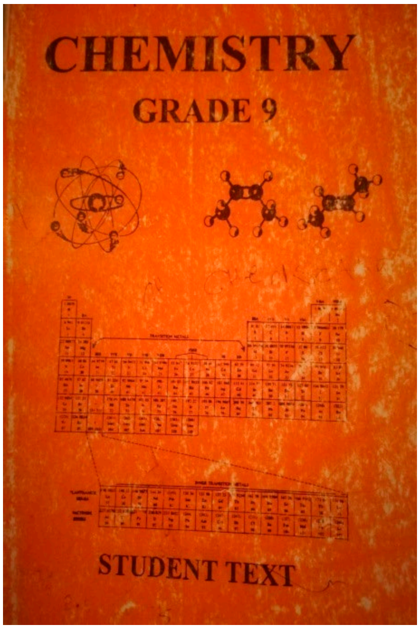
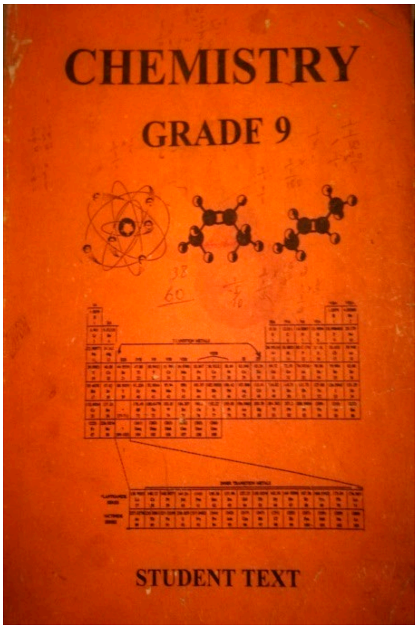
APPENDIX.
ETHIOPIAN GRADE 9 CHEMISTRY TEXTBOOKS CONSIDERED FOR THE STUDY



Published in 2010



Published in 2005



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Order From Confusion: International Chemical Standardization and the Elements, 1947-1990

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Abstract. The International Union of Pure and Applied Chemistry (IUPAC) is the international standards making body for chemistry whose goal is to create a common language for the global chemistry community. The IUPAC governs the use and creation of names, symbols, and terminology. It also establishes criteria for the discovery of new elements and assesses discovery claims, develops rules for naming new elements, and defines group numbering and collective names. This paper examines a series of episodes in which the Commission on Nomenclature of Inorganic Chemistry (CNIC) made changes in the nomenclature of the elements and to the periodic table. They faced protests in their attempts to harmonize the names of elements, create a systematic nomenclature for elements with an atomic number greater than 100, and changed the group numbering on the periodic table, dropping the use of A and B sub-group labels in favor of Arabic numbers 1 through 18. By allowing for difference while advocating for uniformity, CNIC persevered in creating order out of confusion through standardized nomenclature.

Keywords. Chemical elements, periodic table, IUPAC, nomenclature.

1. INTRODUCTION

The need for standardization in chemical terminology, symbols, and nomenclature was well-recognized in the nineteenth century. The first international chemical conference held at Karlsruhe in 1860 made some attempt at this.[1] A congress was held at Geneva in 1892 to create a standardized nomenclature for organic chemistry. This nomenclature did not cover the entirety of organic chemistry and it failed to be adopted, although it did later form the basis for today's standardized nomenclature.[2] International chemical conferences in the first decades of the twentieth century made gestures towards standardization but little was accomplished. A notable exception was the International Committee on Atomic Weights (IACW), formed in 1900 after a mail ballot found overwhelming acceptance of O=16 as the basis for the determination of atomic weights, rather than H=1.[3] Although it took several years for the O=16 standard to be fully accepted, the IACW continues to carry out its mandate regarding atomic weights.

The International Association of Chemical Societies (IACS) was formed in 1911 with the intention of developing international chemical standards in the areas of nomenclature and notation, classification, atomic weights, and information related activities such as the indexing of chemical literature. Commissions were created to study the nomenclature of organic and inorganic chemistry and the standardization of symbols for physical constants.[4] The proposed work of the IACS was "Promethean" and questions were raised regarding its funding and membership.[5] Before these could be resolved, World War I intervened and the IACS was dissolved in its wake.

The International Union of Pure and Applied Chemistry (IUPAC) was formed in 1919 to replace the IACS. Its purpose is to organize cooperation between scientific societies around the world, to coordinate their activities, and to contribute to the advancement of chemistry as a whole.[6] The IUPAC is the international standards making body for chemistry whose goal is to "create a common language for the global chemistry community."[7] The common language for chemistry is largely a standardized one. The IUPAC publishes several books of nomenclature rules, known as the color books, that cover the many subdisciplines of chemistry. These rules govern the use and creation of names, symbols, and terminology.

Many of the IUPAC's standardization activities are related to the elements and thus to the periodic table. The IUPAC reviews atomic weights, establishes criteria for the discovery of new elements and assesses discovery claims, develops rules for naming new elements and coordinates their naming, and defines group numbering and collective names. However, the IUPAC does not recommend the use of a specific form of the periodic table.[8]

Much of the standardization work regarding the elements and the periodic table fell to two commissions within the IUPAC's Inorganic Division.[9] The Commission on Atomic Weights, the continuation of the IACW, was responsible for the regular evaluation and dissemination of the atomic weights of the elements. It was also responsible for officially naming new elements until after World War II when that duty was shifted to the Commission on Nomenclature of Inorganic Chemistry (CNIC). The CNIC was responsible for the development, maintenance, and publication of rules relating to the names of inorganic substances, including the elements. The CNIC, in particular, was responsible for several major changes in the nomenclature of the elements and to the periodic table during the second half of the twentieth century.

This paper examines several episodes associated with these changes. The first set of changes regarded the elimination of alternate names for the elements, in which the CNIC opted for the adoption of "good names" over the wishes of chemists in France, the United States, and elsewhere (sections 2 and 3). The second set of changes occurred in the wake of new elements being synthesized in accelerators rather than being isolated from materials found in the earth. In their attempt to name these elements, the CNIC came up against the belief in the traditional right of discoverers to name that which they discovered (sections 4 and 5). The final set of changes examined in this paper are associated with the group numbering found on the periodic table. Although the use of A and B sub-group labels with the traditional Roman numeral group numbering was pedagogically useful, the CNIC insisted on changing the group numbers to resolve confusion that was perceived to be important for the chemical literature (sections 6 and 7). As I will show, these episodes reveal that the CNIC walked a line between uniformity and the allowance of difference as they persisted in making changes they believed were necessary to achieve order from confusion through standardized nomenclature.

2. THE NEED FOR INTERNATIONALIZED ELEMENT NAMES

The elements are the foundation of the periodic table. Their names are the cornerstone of inorganic chemical nomenclature, the basis on which the names of compounds, minerals, and other substances are derived. Standardized element names are the cornerstone of a common language for chemistry. Atherton Seidell (1878-1961),[10] a chemist with the U.S. Public Health Service, argued in 1929 that "one of the most urgently needed improvements is probably the unification of the names of the earliest recognized elements."[11] At that time, there were 80 known elements. Thirty-eight of those elements had the same names in English, French, and German, and all but five ended with the suffix *-ium*. Another 24 elements had names that differed only in spelling in the three languages. A further four elements were generally comparable and would be easy to modify for the sake of uniformity. The remaining 14 elements, however, had a great variety of names (Fig. 1). Chemists were required to learn all of these names in order to read the literature, particularly with regard to compounds.

Seidell surveyed 150 chemists who had attended meetings of the IUPAC and who were otherwise known to be interested in nomenclature matters.[12] He sent a letter outlining the advantages of having uniformity in chemical terminology, as well as a list of five questions regarding the unification of nomenclature in general and the unification of the names of the elements in particu-

Symbol	French name	German name	English name	Early name
Ag	Argent	Silber	Silver	Argentum
Au	Or	Gold	Gold	Aurum
C	Carbone	Kohlenstoff	Carbon	Carbon
Cu	Cuivre	Kupfer	Copper	Cuprum
Fe	Fer	Eisen	Iron	Ferrum
H	Hydrogene	Wasserstoff	Hydrogen	Hydrogen
Hg	Mercure	Quecksilber	Mercury	Hydrargyrum
K	Potassium	Kalium	Potassium	Kalium
N	Azote	Stickstoff	Nitrogen	Nitrogen
Na	Sodium	Natrium	Sodium	Natrium
O	Oxygene	Sauerstoff	Oxygen	Oxygen
Pb	Plomb	Blei	Lead	Plumbum
Sa	Etain	Zinn	Tim	Stannum
S	Soufre	Schwefel	Sulfur	Sulfur

Figure 1. The 14 elements with the greatest variety of names according to Seidell (1929).

lar. Among the questions Seidell asked was, "Will the advantages resulting from a unification of the names of the more common elements repay the effort to accomplish this end?"[13] More than half of the responses were opposed to the unification of the names of the elements. Among the reasons given were the belief that atomic numbers and internationalized symbols should be used rather than internationalized names, the belief that universal approval of new names would not be possible, as well as concern that confusion would result if the names of the most commonly known elements were to be changed and that relations between chemists and the public would be strained. The survey, Seidell concluded, showed "that efforts to improve the nomenclature of chemistry must be confined to new names and to the harmonizing of variations in usage which do not conflict with fundamental language differences."[14]

Seidell had also asked if a permanent international committee should be responsible for the formulation and promulgation of rules for chemical nomenclature. About two-thirds responded favorably to this idea and half of the survey respondents thought any standardization attempts should be handled by the IUPAC. In fact, the IUPAC Committee for the Reform of Inorganic Chemical Nomenclature was already at work. Their 1926 report noted that all of the "very diverse propositions" that had been submitted to date could be divided into roughly ten categories, none of which included the names of elements.[15] Draft rules were issued in 1940, although this draft was only published in Germany, Britain, and the United States. The aim of these rules was "the unification of Inorganic Chemical Nomenclature and the removal of names which are out of date or incorrect."[16] However, the names of the elements were not considered. This was because the IUPAC Committee on Atomic Weights was in charge of naming new elements. It was not until after World War II that the responsibility for element names was shifted to the Commission on Nomenclature of Inorganic Chemistry (CNIC).[17]

A more comprehensive set of nomenclature rules for inorganic chemistry was developed in the early 1950s. Before the 1951 IUPAC meeting in New York City, a chemical nomenclature symposium was held at which several members of the CNIC presented papers. These papers reflected many of the same views that Seidell's survey brought to the fore. Henry Bassett (1881-1965) noted that it was desirable for nomenclature to differ as little as possible as chemistry was an international pursuit. But he also allowed that some differences were inevitable, particularly in areas "where chemistry touches the lives of people," as in the case of commonly used elements such as silver or lead.[18] Kai A. Jensen (1908-1992), on the other hand, saw "no fundamental reason for not introducing a much more radical unification of chemical terms."[19] Reaching a middle ground between these two perspectives would be the task of the CNIC when it came to the naming of the elements, both old and new.

3. ELEMENTS WITH MORE THAN ONE NAME

The CNIC held their first post-war meeting in London in 1947 where they returned to the draft rules that had been drawn up in the late 1930s. They recognized that "a prerequisite of any international system of nomenclature was the acceptance, in all countries adhering to the Union, of the same list of names and (particularly) symbols for the elements themselves."[20] Towards this end, they resolved to obtain a set of symbols for the elements that was internationally acceptable. They also asked that the responsibility of naming new elements should be shared by the Commission on Atomic Weights and by the CNIC.[21] This was an important step in the process of harmonizing the names of all of the elements.

Much of the discussion at the CNIC's 1949 meeting in Amsterdam revolved around the names of elements. The CNIC recommended names for eight recently discovered or synthesized elements (Fig. 2). They also recommended names for six elements that were known by more than one name (Fig. 3).[22] Little controversy was expected at the recommendation for three of the elements. Element 91 was known as both protoactinium

Atomic Number	Name & Symbol
41	Technetium, Tc
61	Promethium, Pm
85	Astatine, At
87	Francium, Fr
93	Neptunium, Np
94	Plutonium, Pu
95	Americium, Am
96	Curium, Cm

Figure 2. Newly synthesized elements named by the CNIC in 1949.

Atomic Number	Official Name (1949)	Alternate Name
4	Beryllium	Glucinum
41	Niobium	Columbium
71	Lutetium	Cassiopium
72	Hafnium	Celtium
74	Wolfram	Tungsten
91	Protactinium	Prototactinium

Figure 3. Elements whose names were changed by the CNIC in 1949.

and protactinium, and it was decided that protactinium was more convenient. Element 72 had been known as both hafnium and celtium. Although the differing names were the result of a now settled priority dispute,[23] hafnium was the more generally accepted name. Element 71 also had two names stemming from a resolved priority controversy,[24] lutecium and cassiopium, but lutecium was more widely used. The CNIC changed the spelling from lutecium to lutetium.

The CNIC anticipated that the remaining three elements would be more controversial. The first of these three elements was element 4, which had been known as glucinium, glucinum, and beryllium. The conflicting names were the product of a tangled history, as well as a question of priority and a conflict in language.[25] Glucinium fairly quickly fell out of use in favor of glucinum, which was used in both English and French. Germanic languages tended to use beryllium. The two names co-existed fairly peaceably although the question of which should be used was regularly raised at the turn of the twentieth century. The American Association on the Spelling and Pronunciation of Chemical Terms approved the use of glucinum, largely on the basis of priority, but despite the decision it was still a matter of debate in the United States and elsewhere.[26] In 1949, the CNIC recommended the use of beryllium. By this time the name was widely accepted although glucinum continued to be used in French-language journals into the 1980s.

Element 41 was the second element with multiple names that the CNIC felt could be controversial. It was known as both columbium and niobium. This element also had a somewhat complicated history and both names co-existed for many years.[27] In 1913, the IASC, the IUPAC's precursor, endorsed the name niobium.[28] This decision did not go over well in the United States as the mineral in which the element had been discovered, columbite, was found in America. The English chemist who isolated the element named it columbium, after Columbia, a historic as well as poetic name for America (Fig. 4). The CNIC likewise recommended the use of niobium in 1949 with a similar outcry from American chemists. Evan J. Crane (1889-1966), an American member of the CNIC, argued that cooperation was more important than selfishness and noted, "Our French colleagues made a similar concession in giving up 'glucinum' in favor of 'beryllium.'"[29] Much like their French colleagues, American chemists were reluctant to give up the name columbium and it continued to be used for many years after the 1949 recommendation.

The last of the three elements that was thought to be controversial was element 74. It had been known from the late eighteenth century as both wolfram and tungsten. Wolfram was generally preferred in Germanic and Scandinavian countries while other countries preferred to use tungsten, although here, too, there were priority issues.[30] The first attempt to harmonize these names was undertaken by the CNIC in 1949. They recommended the use of wolfram, although they allowed that tungsten could be used for commercial purposes. There were

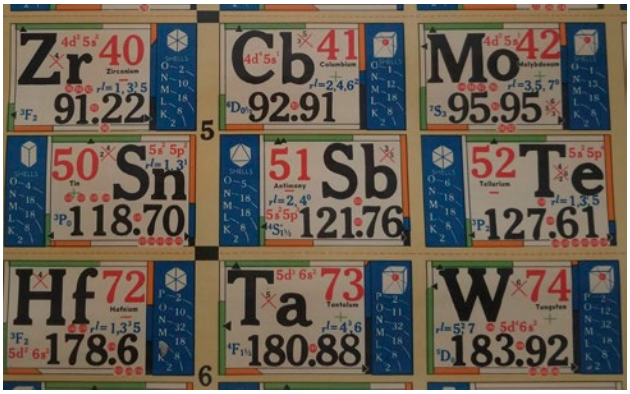


Figure 4. Detail from the 1947 edition of the Periodic Chart of the Atoms (Welch Scientific Company) showing element 41 with the name columbium, as well element 74 with the symbol W and the name tungsten (Photo taken by the author; table in author's personal collection).

objections to this recommendation and the matter was taken up again at the 1951 meeting. An erroneous report appeared in the press that the CNIC was abolishing the use of tungsten which "provoked a storm of protest from all over the world."[31] Although no other recommendation was made, future editions of the rules for inorganic chemical nomenclature almost exclusively used the name tungsten, albeit with the symbol W which required a note explaining its origin.[32] Protests, however quiet, continued to be made. It was not until 2009 that the IUPAC's Division on Chemical Nomenclature and Structure Representation[33] declared that "the case was now closed" – tungsten was the only recommended name for element 74.[34]

There was a traditional belief that the person who discovered an element was the person to name it, therefore the name chosen by the person with priority should be the one used. However, the names chosen by the CNIC did not always follow this tradition, one reason why the alternate names for elements 4, 41, and 74 continued to linger after the 1949 recommendation. One of the important – and controversial – stances taken by the CNIC in 1949 was antithetical to this tradition. No importance was placed on priority, rather, as Bassett, the CNIC chair, stated at the time, "a good name was always preferable to a bad one."[35] (What constituted a "good" name was not explained.) This decision was enshrined as a part of Rule 1.12 in the official *Nomenclature of Inorganic Chemistry*: "It should be emphasized that their selection carries no implication regarding priority of discovery."[36] The CNIC would fall back on this rule frequently in the following decades as they struggled to prevent confusion in element names while confronted with discoverers demanding their traditional right to name their discovery.

4. THE CHALLENGES OF SYNTHETIC ELEMENTS

The first official inorganic nomenclature rules, known as the Red Book, were published in 1957. At the same time, the CNIC was faced with new challenges as a result of the discovery of new synthetic elements. These elements were different in several ways. In regard to nomenclature, a new trend arose in naming elements after people rather than after characteristics, places, or mythological figures, which created new difficulties in standardizing names across languages. Scientifically, these elements were different as they were created in accelerators. As the elements get heavier, it becomes possible to create only one or a handful of atoms at a time. They had very short half-lives. They were generally detected through physical rather than chemical methods. Although there were only a handful of laboratories in the world that synthesized new elements, they frequently criticized each other's discoveries, leading to priority disputes. The CNIC's stance that element names had no implication regarding priority of discovery was put to the test.

With the increasing importance of physics in the detection of new elements, the IUPAC would need to cooperate with the International Union of Pure and Applied Physics (IUPAP). Similar to the IUPAC, the IUPAP was founded in 1922 to promote international cooperation in physics; create standards in the areas of symbols, units, and nomenclature; and prepare and publish tables of physical constants and abstracts of papers.[37] The IUPAP has a Commission on Symbols, Units, Nomenclature, Atomic Masses, and Fundamental Constants (SUN-AMCO), founded in 1931, who also publishes a so-called Red Book that provides authoritative guidance on the matters in its name.[38] Despite its interest in nomenclature, the responsibility for the naming of new elements resides with the IUPAC, not the IUPAP. However, due to the IUPAC's lack of expertise in physics, a series of joint working groups was instituted to deal with the priority issues arising from the discovery of new synthetic elements.

The first synthetic element that would highlight the IUPAC's lack of expertise was element 102. At their 1957 meeting in Paris, the CNIC received word from the Nobel Institute in Stockholm that a new element had been synthesized. Element 102 was the result of a collaboration between Argonne National Laboratory in the United States, the Harwell Atomic Energy Research Establishment in England, and the Nobel Institute. The meeting minutes reflect a sense of excitement at the news, as well as a sense of urgency.[39] If the report could be confirmed while the CNIC was meeting, the proposed name could be considered immediately rather than waiting until their next meeting two years hence. The Nobel Institute was contacted and news reports of the discovery were confirmed. The name, nobelium, was approved for element 102.

The hasty naming of element 102 was unfortunate. When the Commission on Atomic Weights had been in charge of naming new elements, they had waited to accept an element until a measurable amount had been separated and its atomic weight determined, a process that could take years.[40] The CNIC, however, did not wait for another lab to reproduce and confirm the Nobel Institute's results. In 1963, they were informed by Glenn T. Seaborg (1912-1999) that his group at the Lawrence Berkeley Laboratory (LBL) in the United States had been unable to reproduce the Stockholm results. However, they had been able to synthesize a different isotope of element 102 and therefore objected to the use of the name nobelium. The CNIC reiterated Rule 1.12 and suggested that as the name nobelium was already in use, it would remain.[41] They were in part concerned that a change in element names could cause confusion, particularly for indexing services as *Chemical Abstracts*, but they also did not want to set a precedent that element names could be changed upon request.

In 1968, the CNIC learned that Georgi N. Flerov (1913-1990) and his group at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, had obtained different isotopes of element 102 and called into question the results of both the original experiment in Stockholm and the LBL experiments. At their meeting in Copenhagen that year, the CNIC "unanimously decided that it could not re-open discussion concerning the name of an element on which a definitive decision had already been taken." They again reiterated Rule 1.12, that an element's name had little to do with priority of discovery. The CNIC also noted that priority could be difficult to determine and, as a nomenclature committee, they "had no special competence to judge" in matters of priority. [42] In short, determination of priority was not a matter of nomenclature.

Element 102 was not the only element whose discovery was under dispute. In 1961, LBL announced the discovery of element 103. The CNIC confirmed the suggested name, lawrencium, at their meeting in Brighton in 1963. But again in 1968, JINR announced that the results obtained at LBL were incorrect and that they had discovered element 103, for which they suggested a different name. The CNIC received this notification during their meeting in Copenhagen and their stance on the name of element 102 was also applied to the situation with element 103. The name lawrencium was reconfirmed.[43]

Another issue arose when the name for element 103 was proposed by LBL in 1963. The name lawrencium was derived from Ernest O. Lawrence (1901-1958), the founder of LBL and the inventor of the cyclotron. The proposed symbol for lawrencium was Lw. Heinrich Remy (1890-1974), a member of the CNIC, observed that the letter w was "an uncommon letter in many languages and difficult to pronounce." He suggested that the spelling of the lawrencium be changed to laurentium. After discussion, Jensen, the chair, remarked that they had "no right to modify the spelling" of a proper name but in order "to make the name more acceptable," the symbol was changed from Lw to Lr.[44]

This was not the first element for which the symbol was modified. In 1955, the CNIC approved the name mendelevium for element 101 with the symbol Mv, after Dmitrii Mendeleev (1834-1907). At the 1957 meeting in Paris, however, the CNIC voted to change the symbol to Md. No reason was given in the minutes, but as later explained this was done because "it is not customary to choose one of the last letters of the name as the second letter of a two-letter symbol" and because not all transliterations of Mendeleev's name use the letter v.[45] Another element whose proposed symbol was changed was element 99. The name einsteinium was proposed, with symbol E, after Albert Einstein (1879-1955). At their meeting in Reading in 1956, the CNIC approved the name but expressed concern at having an element with a single letter symbol. Two letter symbols were preferred so as to avoid any confusion with the symbols of physical quantities.[46] They suggested the symbol Es and it was officially recommended at the 1957 meeting.

The challenges faced by the CNIC in regards to the names and symbols of new synthetic elements were the result of several factors. One was the desire for a truly global chemical nomenclature. Although standardization was the goal, the realities of language could put the achievement of that goal into question. The increasing use of personal names as the basis for element names, such as those of Lawrence and Mendeleev, prevented the ability of the CNIC to attain true standardization for both element names and symbols. Another factor was the insistence of discoverers exercising what they perceived to be their traditional right to name the element they discovered. Competing names offered by competing laboratories was a step back from the harmonization in element names the CNIC began to achieve in 1949. Although the CNIC reiterated Rule 1.12, their insistence that names had little to do with discovery was a roadblock on the path to a standardized nomenclature.

5. THE TENSION BETWEEN CHEMISTRY AND PHYSICS

Elements on the periodic table have only one name and symbol. Even those elements that have lingering alternate names, such as wolfram and tungsten, are shown with only one name and symbol. The CNIC had refrained from renaming elements 102 and 103 when new claims about their discovery were reported, citing the confusion that could be caused by changing their names. In reiterating Rule 1.12, they reinforced their position that element names had little to do with priority of discovery. However, elements 104 and 105 presented a new test of their resolve as the discoverers frequently

– and increasingly publicly and vitriolically – presented their claims while denigrating the claims of others.[47]

The first claim for the discovery of element 104 came in 1964. Flerov's group at JINR announced they had identified an isotope of element 104 but found it "quite desirable to conduct chemical experiments for additional identification."[48] This announcement was followed in 1966 by publication of chemical studies of element 104. Flerov then sent a letter to the IUPAC claiming the discovery of element 104 and suggesting a name, kurchatovium. This name was in honor of Igor V. Kurchatov (1903-1960), who was widely regarded as the founder of the Soviet atomic bomb program and had recently passed away.

The group at LBL was also attempting to synthesize element 104. They had not been able to confirm the results of JINR's experiments but, after running a different experiment, announced in 1969 they had synthesized two isotopes of element 104.[49] A name was not proposed in the initial announcement, however in a paper given at the Welch Foundation Conference later that year, Albert Ghiorso (1915-2010) proposed the name rutherfordium in honor of Ernest Rutherford (1871-1937), "the great pioneer of nuclear science."[50] Ghiorso and the LBL group then notified the CNIC of this suggestion. Ghiorso's letter also included the news that LBL had discovered element 105. They proposed the name hahnium, in honor of German chemist Otto Hahn (1879-1968).[51] In much the same manner, Flerov's group wrote to the CNIC in the summer of 1969 announcing they had discovered element 105. They proposed to name the element after Niels Bohr (1885-1962).[52] Though they left the name and symbol unspecified at the time, they later suggested nielsbohrium (Fig. 5).

This situation was not tolerable to the CNIC. An element having two unofficial names in use ran contrary to the goal of a standardized international chemical nomenclature. The use of multiple names for these new elements was a potential source of confusion, not only in publications but also in indexing. At their 1969 meeting in Cortina d'Ampezzo, they had discussed the matter with the Commission on Atomic Weights. The CNIC ultimately recommended that elements should not be named for a period of five years after the initial announcement of their discovery. This would allow for confirmation of the discovery to occur, preferably at another laboratory and in another country.[53] The CNIC also once again reiterated their position on element names having little to do with priority of discovery.

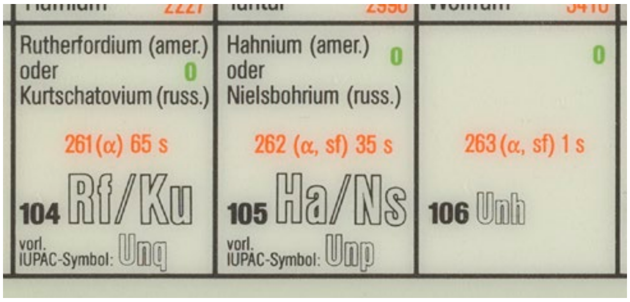


Figure 5. Detail from a 1985 German periodic table (VCH Verlagsgesellschaft) showing multiple names for elements 104 and 105 (Original courtesy of the Science History Institute, Philadelphia, PA, https://digital.sciencehistory.org/works/k3569525k).

At the 1968 meeting in Copenhagen, the CNIC had raised the possibility of a systematic nomenclature for the elements. This would, they believed, end the "needless controversy" that had arisen.[58] The idea was again raised in 1969. At the 1971 meeting in Washington, D.C., it was unanimously recommended that a systematic nomenclature be devised for elements beyond 105. (They still hoped that LBL and JINR would solve the problems regarding elements 104 and 105 themselves.) This systematic nomenclature was to be a numerically derived system based on atomic number.[55] With this nomenclature in place, all elements claimed to have been discovered would have a name ready to be used until priority could be determined and a new name proposed by the discoverer (Fig. 6).

In 1971, the CNIC chair W. Conard Fernelius (1905-1986) wrote a position paper on the naming of the elements. It began, "Communication among chemists and between chemists and other professionals has been greatly aided through the years by the existence of a logical, systematic, and generally agreed-upon nomenclature practice." However, there were still "real problems that require the vigilance, vision, and persuasion of nomenclature committees and commissions to establish order in their use, to secure agreement among users and to avoid duplicate names and patterns."[56] It was by these means that a common language for chemistry would be achieved, a part of which was the recognition of a single name for each element.

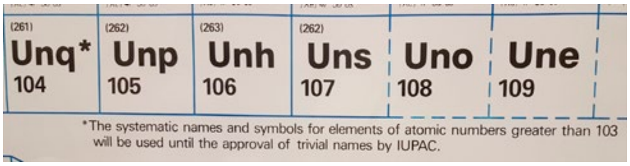


Figure 6. Detail from a 1988 periodic table wallchart (Central Scientific Company) showing the IUPAC systematic nomenclature for elements with an atomic number greater than 100 (Photo taken by the author at Wellesley College, September 2016).

A systematic nomenclature ensured that names be ready for use upon discovery, preventing the use of multiple, unofficial, names in publications as well as in indexing services such as *Chemical Abstracts*. It had long been acknowledged that these services were vital to chemists. The development of a standard international nomenclature was meant, in part, to facilitate their creation and use. Among the responses Seidell had received to his survey in 1929 were recommendations for the use of symbols and Latin names for the elements, amid other suggestions, in indexes and compendia if names could not be harmonized (see Section 2).

The systematic nomenclature was a major topic of discussion at the CNIC's meeting in Munich in 1973. They agreed that the names used should be short, related to atomic number, and end in the suffix *-ium*, while the symbols should be three letters rather than the usual two. The names would be derived from a standard set of numerical roots, based on a mixture of Latin and Greek on the grounds that they were easily recognizable by chemists.[57] Thus, for example, the name of element 106 would be Unnilhexium (un + nil + hex) with the symbol Unh, and 116 would be Ununhexium (un + un + hex) with symbol Uuh. The system was able to accommodate elements up to number 999. Although this system would be in place, the CNIC did not want to deny the right of discoverers to name new elements.[58]

Although there was no expectation that the systematic names for elements 101 through 103 would be used, the CNIC's system was expanded to begin with element 101 after a "virtually unanimous" vote by the Bureau, one of the IUPAC's executive bodies.[59] The systematic nomenclature was eventually published as an official IUPAC Recommendation in 1979.[60] Even then the system was not welcomed. The IUPAP's SUN-AMCO commission expressed dismay that its proposal, as well as that of the IUPAP's Commission on Nuclear Physics, were seemingly not taken into consideration by the CNIC. Both preferred a system in which the atomic number took the place of a lettered symbol.[61]

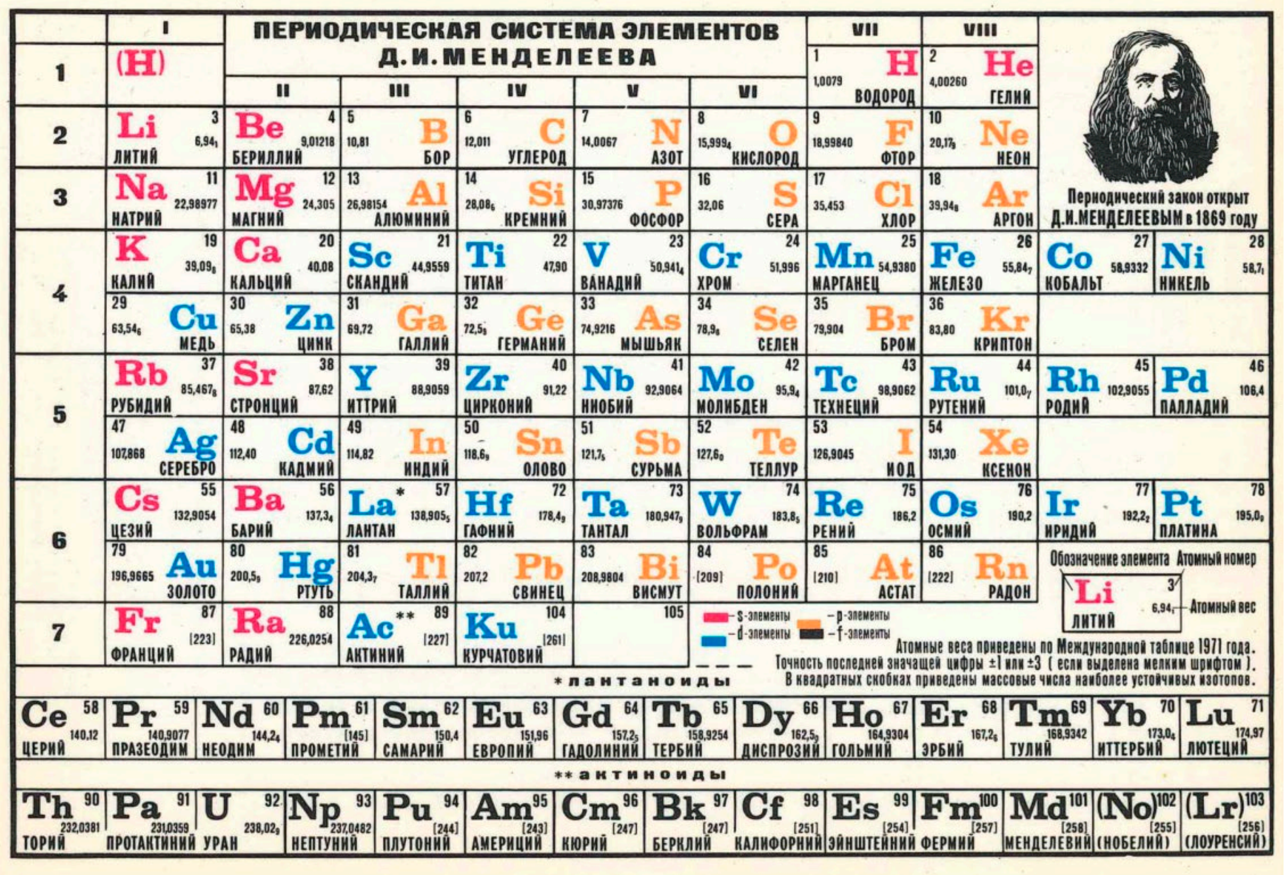
In a letter regarding another controversy (see sections 6 and 7), one chemical educator wrote, "I don't really care if all the new elements are named after Soviets, Germans, or Martians, so long as they are named after someone, someplace, or something."[62] Chemical and physical researchers described the systematic nomenclature as "artificial and ugly" and "utterly ridiculous," and one physicist commented that he doubted anyone would use it.[63] This may not have been the reaction the CNIC was hoping for when they developed the systematic nomenclature. However, it served its intended purpose. Elements that were claimed to have been newly discovered had placeholder names that allowed them to be discussed in the literature and located in indexing services and reference works without the confusion of multiple names.

The systematic names avoided the appearance of official acceptance of one discovery claim over another. In order to solve the priority disputes over the synthetic elements, a joint IUPAP-IUPAC group, the Transfermium Working Group (TWG), was formed in 1986 at the behest of the IUPAP. The TWG formulated a set of criteria that needed to be satisfied in order to determine if an element had been developed and then applied those criteria to the claims for elements 101 through 109.[64] Once discovery had been assigned by the TWG, discoverers were asked to suggest names and symbols to the CNIC for official approval. By way of the systematic nomenclature and the creation of the TWG, the CNIC adroitly escaped from adjudicating discovery claims and instituted a standardized chemical nomenclature that furthered their goal of a common language for chemistry.

6. CONFUSION IN GROUP NUMBERING

The names and symbols of the elements are one of the important aspects of the periodic table. Another is the group numbers which run across the top of the table, one number for each column. Group numbers are used to refer to a set of elements which have similar characteristics and propertiers. These group numbers have been the subject of confusion for many years. Until the 1980s, most group numbers on periodic tables consisted of eight Roman numerals, with some of these having sub-group labels of A and B, such IIIA or IVB. These labels were considered an important pedagogical device as they made a clear distinction between main group elements and the transition elements. The main, or major, group elements comprise the s-block and p-block, referring to their electron configuration. The transition elements, often called the transition metals, comprise the d-block. Without A and B sub-group labels on a periodic table, the distinction would need to be made through the use of mnemonics or a visual cue, such as different colors as seen in Fig. 7.

The periodic table developed by Horace G. Deming (1885-1970), first published in 1923 and widely adopted in the following decades, gave the main group elements the sub-group label A and the transition elements the sub-group label B. Another popular table in the United States, the Periodic Chart of the Atoms, created by



ПЕРИОДИЧЕСКАЯ СИСТЕМА ЭЛЕМЕНТОВ
Д.И.МЕНДЕЛЕЕВА

	I	II	III	IV	V	VI	VII	VIII		
1	(H)						H 1 1,0079 ВОДОРОД	He 2 4,00260 ГЕЛИЙ		
2	Li 3 6,94$_1$ ЛИТИЙ	Be 4 9,01218 БЕРИЛЛИЙ	B 5 10,81 БОР	C 6 12,011 УГЛЕРОД	N 7 14,0067 АЗОТ	O 8 15,999$_4$ КИСЛОРОД	F 9 18,99840 ФТОР	Ne 10 20,17$_9$ НЕОН		
3	Na 11 22,98977 НАТРИЙ	Mg 12 24,305 МАГНИЙ	Al 13 26,98154 АЛЮМИНИЙ	Si 14 28,08$_6$ КРЕМНИЙ	P 15 30,97376 ФОСФОР	S 16 32,06 СЕРА	Cl 17 35,453 ХЛОР	Ar 18 39,94$_8$ АРГОН		
4	K 19 39,09$_8$ КАЛИЙ	Ca 20 40,08 КАЛЬЦИЙ	Sc 21 44,9559 СКАНДИЙ	Ti 22 47,90 ТИТАН	V 23 50,941$_4$ ВАНАДИЙ	Cr 24 51,996 ХРОМ	Mn 25 54,9380 МАРГАНЕЦ	Fe 26 55,84$_7$ ЖЕЛЕЗО	Co 27 58,9332 КОБАЛЬТ	Ni 28 58,7$_1$ НИКЕЛЬ
	Cu 29 63,54$_6$ МЕДЬ	Zn 30 65,38 ЦИНК	Ga 31 69,72 ГАЛЛИЙ	Ge 32 72,5$_9$ ГЕРМАНИЙ	As 33 74,9216 МЫШЬЯК	Se 34 78,9$_6$ СЕЛЕН	Br 35 79,904 БРОМ	Kr 36 83,80 КРИПТОН		
5	Rb 37 85,467$_8$ РУБИДИЙ	Sr 38 87,62 СТРОНЦИЙ	Y 39 88,9059 ИТТРИЙ	Zr 40 91,22 ЦИРКОНИЙ	Nb 41 92,9064 НИОБИЙ	Mo 42 95,9$_4$ МОЛИБДЕН	Tc 43 98,9062 ТЕХНЕЦИЙ	Ru 44 101,0$_7$ РУТЕНИЙ	Rh 45 102,9055 РОДИЙ	Pd 46 106,4 ПАЛЛАДИЙ
	Ag 47 107,868 СЕРЕБРО	Cd 48 112,40 КАДМИЙ	In 49 114,82 ИНДИЙ	Sn 50 118,6$_9$ ОЛОВО	Sb 51 121,7$_5$ СУРЬМА	Te 52 127,6$_0$ ТЕЛЛУР	I 53 126,9045 ИОД	Xe 54 131,30 КСЕНОН		
6	Cs 55 132,9054 ЦЕЗИЙ	Ba 56 137,3$_4$ БАРИЙ	La* 57 138,905$_5$ ЛАНТАН	Hf 72 178,4$_9$ ГАФНИЙ	Ta 73 180,947$_9$ ТАНТАЛ	W 74 183,8$_5$ ВОЛЬФРАМ	Re 75 186,2 РЕНИЙ	Os 76 190,2 ОСМИЙ	Ir 77 192,2$_2$ ИРИДИЙ	Pt 78 195,0$_9$ ПЛАТИНА
	Au 79 196,9665 ЗОЛОТО	Hg 80 200,5$_9$ РТУТЬ	Tl 81 204,3$_7$ ТАЛЛИЙ	Pb 82 207,2 СВИНЕЦ	Bi 83 208,9804 ВИСМУТ	Po 84 [209] ПОЛОНИЙ	At 85 [210] АСТАТ	Rn 86 [222] РАДОН		
7	Fr 87 [223] ФРАНЦИЙ	Ra 88 226,0254 РАДИЙ	Ac** 89 [227] АКТИНИЙ	Ku 104 [261] КУРЧАТОВИЙ	105					

Периодический закон открыт Д.И.МЕНДЕЛЕЕВЫМ в 1869 году

Обозначение элемента Атомный номер

Li 3 6,94$_1$ – Атомный вес ЛИТИЙ

🟥 – s-элементы 🟧 – p-элементы

🟦 – d-элементы ⬛ – f-элементы

Атомные веса приведены по Международной таблице 1971 года.
Точность последней значащей цифры ±1 или ±3 (если выделена мелким шрифтом).
В квадратных скобках приведены массовые числа наиболее устойчивых изотопов.

* лантаноиды

Ce 58 140,12 ЦЕРИЙ	Pr 59 140,9077 ПРАЗЕОДИМ	Nd 60 144,2$_4$ НЕОДИМ	Pm 61 [145] ПРОМЕТИЙ	Sm 62 150,4 САМАРИЙ	Eu 63 151,96 ЕВРОПИЙ	Gd 64 157,2$_5$ ГАДОЛИНИЙ	Tb 65 158,9254 ТЕРБИЙ	Dy 66 162,5$_9$ ДИСПРОЗИЙ	Ho 67 164,9304 ГОЛЬМИЙ	Er 68 167,2$_6$ ЭРБИЙ	Tm 69 168,9342 ТУЛИЙ	Yb 70 173,0$_4$ ИТТЕРБИЙ	Lu 71 174,97 ЛЮТЕЦИЙ

** актиноиды

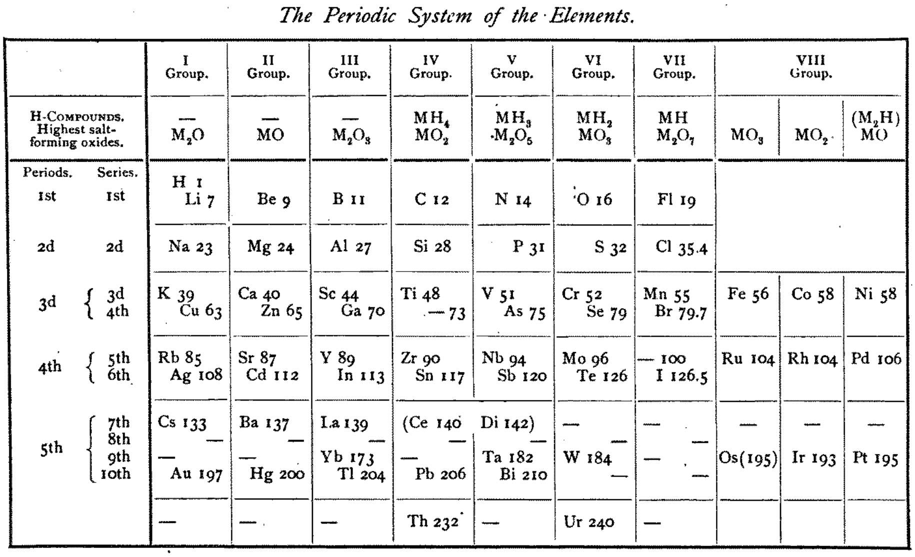
Th 90 232,0381 ТОРИЙ	Pa 91 231,0359 ПРОТАКТИНИЙ	U 92 238,02$_9$ УРАН	Np 93 237,0482 НЕПТУНИЙ	Pu 94 [244] ПЛУТОНИЙ	Am 95 [243] АМЕРИЦИЙ	Cm 96 [247] КЮРИЙ	Bk 97 [247] БЕРКЛИЙ	Cf 98 [251] КАЛИФОРНИЙ	Es 99 [254] ЭЙНШТЕЙНИЙ	Fm 100 [257] ФЕРМИЙ	Md 101 [258] МЕНДЕЛЕВИЙ	(No) 102 [255] (НОБЕЛИЙ)	(Lr) 103 [256] (ЛОУРЕНСИЙ)

Figure 7. A Russian short-form periodic table that uses colors to denote the elements belonging to different blocks (Khimia, Moscow, 1987) (Photo taken by the author; table in author's personal collection).

Henry D. Hubbard (1870-1943), gave the sub-group labels in the opposite manner of Deming.[65] Unlike Hubbard's table, many short-form tables popular in the Soviet Bloc as well as in Europe well into the 1960s, did not use the A and B labels. When the long form table began to become popular in Europe, the A and B sub-group labels were applied somewhat arbitrarily. A survey of publications found that "in more than 10% of the articles it was nearly impossible, from the wording of the text, to recognize which elements were being discussed."[66] Confusion could also be caused in the classroom. British chemist Joseph Chatt (1914-1994) noted of wall charts purchased from American companies, "In England students are usually told that the chart is wrong and in some Universities I have seen sticky labels with the correct sub-group numbering stuck over the [other] numbers."[67]

Early on, in 1958, the question of group names was first raised by Lamberto Malatesta (1912-2007), a member of the CNIC. The first edition of the Red Book had been sent to the publisher and it was too late to make any changes. It was decided to consider the question for the second edition, work on which was just beginning.[68] At their next meeting in Munich in 1959, the CNIC discussed the topics of the form of the periodic table, the confusion in group numbering, the need for a definition of transition elements, and the group names used for the rare earth elements. It was decided that "no firm rules should be laid down" but nonetheless the CNIC should issue a statement. A small sub-committee was appointed to examine these matters and make a recommendation regarding the use of A/B sub-group labels and group names for the elements.[69]

K. A. Jensen, a member of the sub-committee, prepared a report on these issues. The majority of this report – six of the eight pages – concerned solely the form of the periodic table. He stated: "There are so many types that a standardization seems highly desirable. Even if the commission can not *[sic]* agree on one standard table we could perhaps agree on a small number of different tables which could be recommended for different purposes."[70] The report then examined three main



The Periodic System of the Elements.

		I Group.	II Group.	III Group.	IV Group.	V Group.	VI Group.	VII Group.	VIII Group.		
H-Compounds. Highest salt-forming oxides.		— M_2O	— MO	— M_2O_3	MH_4 MO_2	MH_3 M_2O_5	MH_2 MO_3	MH M_2O_7	MO_3	MO_2	(M_2H) MO
Periods.	Series.										
1st	1st	H 1 Li 7	Be 9	B 11	C 12	N 14	O 16	Fl 19			
2d	2d	Na 23	Mg 24	Al 27	Si 28	P 31	S 32	Cl 35.4			
3d	3d	K 39	Ca 40	Sc 44	Ti 48	V 51	Cr 52	Mn 55	Fe 56	Co 58	Ni 58
	4th	Cu 63	Zn 65	Ga 70	— 73	As 75	Se 79	Br 79.7			
4th	5th	Rb 85	Sr 87	Y 89	Zr 90	Nb 94	Mo 96	— 100	Ru 104	Rh 104	Pd 106
	6th	Ag 108	Cd 112	In 113	Sn 117	Sb 120	Te 126	I 126.5			
5th	7th	Cs 133	Ba 137	La 139	(Ce 140	Di 142)	—	—	—	—	—
	8th	—	—	—	—	—	—	—			
	9th	—	—	Yb 173	—	Ta 182	W 184	—	Os(195)	Ir 193	Pt 195
	10th	Au 197	Hg 200	Tl 204	Pb 206	Bi 210	—	—			
		—	—	—	Th 232	—	Ur 240	—			

Figure 8. Von Richter's Periodic Table (1885) which used no A/B sub-group labels.

types of tables: short tables with eight groups and no sub-groups, short tables with sub-groups, and medium and long tables. Jensen concluded that "the most satisfactory – I should even say the only satisfactory – periodic system is a slightly modified form of the old von Richter table."[71] The table used in Victor von Richter's (1841-1891) popular nineteenth century textbook was a short-form table with no sub-groups (Fig. 8).[72]

The sub-committee discussed this report at a meeting in Elsinore in 1962. It was agreed to begin with "the least controversial matters" and move towards the most controversial. Given that the majority of the report was about the form of the periodic table, the minutes do not reflect any discussion of which, if any, forms should be recommended as a standard. There was a decision that the inert gases should be on the left-hand side of the table as Group 0, although placing them on both sides would be permissible. The committee also agreed to accept the neutron as the first element, with atomic number 0, and placed in Group 0 with the inert gases. A definition of transition elements was agreed upon, as well as names for the rare earths series.[73]

It was decided to use sub-group labels A/B. These sub-groups would apply only to periods 4 through 7. In order to prevent confusion, the first of the sub-groups in each group was to be given the label A while the second would be B. Sub-groups labeled A were those headed by the elements K, Ca, Sc, Ti, V, Cr, and Mn. Sub-groups labeled B were those headed by the elements Cu, Zn, Ga, Ge, As, Se, and Br.[74] These A and B groups would become the ones officially recommended in the IUPAC Red Book.[75]

A sample table was drawn and the sub-committee chair asked the members to privately inquire if the table would be acceptable. This was a standard practice for the IUPAC nomenclature commissions who preferred to "test the water" before issuing official recommendations.[76] In this case, it was a particularly prudent precaution. Some reactions to the proposals were moderate. Marguerite Perey (1909-1975) agreed with the placement of the inert gases on the left-hand side but questioned the inclusion of the neutron in the periodic table.[77] Kazuo Yamazaki (1911-2010) presented the thoughts of Japanese chemists who likewise were against the inclusion of the neutron but were divided over the location of the inert gases, they also believed that the placement of the A and B sub-group labels within the sample table needed further consideration.[78]

The Chemical Society relayed the comments of British chemists to the CNIC. Their comments focused more on the form of the sample periodic table that was enclosed with the sub-committee's recommendations. Their reactions ranged from astonishment to dread. The Chemical Society argued that all chemical education was based on the long-form table, not the short-form which was considered to be obsolete.[79] As one British chemist put it, "if we must have a party line about the Periodic Table, let us at least base it on the ideas of 1963, and not those of 1863."[80] Another was less sanguine, stating he had read the proposals "with a feeling little short of complete horror" and was distressed to find the IUPAC recommending a return to the short-form table.[81]

There was nothing in the nomenclature sub-com-

Recommended Format for the Periodic Table of the Elements

1	2	3d	4d	5d	6d	7d	8d	9d	10d	11d	12d	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac**															
3f		*Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		**Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

Figure 9. Periodic Table recommended by the ACS in 1984 (Courtesy of the American Chemical Society).

mittee's proposals about the form of the periodic table. However, they sent only one sample table and it was a short-form. Many asked to comment on the proposals justifiably assumed the committee was recommending that specific form of the periodic table. Chatt, member of the sub-committee, stated that he strongly recommended a long-form table be used to illustrate their proposals as it was "so much more useful in teaching chemistry that we should take care that we do not create the impression that the short form has I.U.P.A.C. preference."[82] Despite this warning, he was voted down.[83]

At their 1963 meeting in Brighton, the CNIC discussed the sub-committee's proposals as well as the responses that had been received. After deliberations, they decided that whether or not the neutron was an element was a matter of definition rather than nomenclature, so it was dropped. It does not seem they discussed the position of the inert gases in the periodic table. Following some discussion, they recommended that if subgroup labels A/B were used, they should be capitalized. Otherwise, the CNIC decided they did "not wish to encourage the use of these letters or of any particular form of the Periodic Table."[84]

The second edition of the Red Book was issued in 1970. It included a recommendation for sub-groups for those who wished to use them, but no recommendation that they must be used. There is no mention of the form of periodic table nor is there a periodic table printed anywhere in the text.[85] The reactions of chemists, particularly those who were educators, were likely a shocking and unwelcome surprise to the CNIC. In response, the minutes of their 1975 meeting in Santiago de Compostella contain a statement that it is "desirable" that a periodic table "portray groups, periods of differing lengths, A and B subgroups, transition elements, and the accepted chemical families." A "policy decision" reflected their new belief that, "Approval of an[y] particular form of the periodic table is not a problem of nomenclature."[86]

7. RENUMBERING THE GROUPS

The CNIC's recommendation for the use of A/B sub-group labeling had consequences they likely did not expect. Scientific supply companies in the United States took note of their recommendations and began selling periodic tables with the new recommended labeling. However, they placed these labels in a different place than usual, sparking even more confusion.[87] The Committee on Nomenclature of the American Chemical Society (ACS) attempted to solve the confusion and in 1984 approved a recommended format for the periodic table (Fig. 9). It was a long-form table with group numbers 1-18, groups 3-12 had a sub-label of *d* to denote the d-block elements, and the lanthanides and actinides below the table were given the label 3f.

This new table was published in the *Journal of Chemical Education* and in *Chemistry in Britain*,[88] where it sparked a series of letters about the use (or lack thereof) of A/B labels and the advisability of moving to the 1-18 group numbering. The chair of the Royal Society of Chemistry's Educational Publications Committee, wrote that they had "recommended that the RSC should not adopt the 18-group formulation."[89] Another letter writer expressed the hope that "all enlightened non-teaching members of the RSC will add their weight of protest along with the teachers."[90] A different writer had at first wondered whether "this was one of the more elegant spoofs perpetrated by the quality press on All Fools' Day," but he was disabused of that notion by checking the date and concluded, "There is no valid reason for falling into line with the ACS model and the IUPAC recommendation unless it really does aid learning and understanding and avoid confusion."[91]

A year later, a member of the CNIC, G. Jeffery Leigh (1934-), published a short article in *Chemistry International* that proposed the use of the long-form table with the group numbers 1-18.[92] Meanwhile, *Chemical & Engineering News* published a brief story titled, "Group notation revised in periodic table," that erroneously stated an IUPAC recommendation for the use of group numbers 1-18 was "working its way through IUPAC approval procedures."[93] This article also sparked a storm of letters.[94] One chemistry professor wrote, "Unfortunately, the recommended numbering system … represents a giant step backward from a pedagogical standpoint" as it destroyed the relationship between group number and atomic structure.[95] Another argued that, "This revision 'to remove ambiguities' between the U.S. and European practices seems to be one of those compromises in which chemical education in the U.S. loses – again."[96]

Reactions in other countries varied. The Portuguese Chemical Society requested more information "on the appropriateness of enforcing the new numbering scheme for the periodic table … in secondary school education," particularly "given the strong controversy that this IUPAC ruling has provoked."[97] In response, the chair of the CNIC, Daryle H. Busch (1928-), stated that the Ducth Ministry for Education "has advised the use of numbering scheme and has accepted it for state examinations" and the State of New York had done similarly. "The system appears to be well used in France … and in Sweden." Busch also noted that "special versions" of the periodic table using the 1-18 numbering had been published for display in Germany, the Netherlands, and the United States.[98]

One of the "special versions" was published in a German chemistry magazine which sparked astonishment in Klaus Brodersen (1926-1997), chair of the ADUC, a society of German chemistry professors. In a letter to *Nachrichten aus Chemie, Technik und Laboratorium* titled "Save the 8-Group Periodic Table," he stated, "The 18-group periodic table will certainly do a disservice to chemistry." He noted that "many rules of the behavior of the elements, which are easy to learn for every student, are now made more difficult or dull." This included the loss of relationships between valence and group numbers as well a variety of mnemonics.[99] Ekkehard Fluck (1931-), a member of the CNIC, and Karl Rumpf (1908-1997) laid out the case for the 18-group table and stated that it would be easy enough to create new mnemonics.[100]

The West German Deutscher Zentralausschuß für Chemie raised "a formal objection" to the 1-18 recommendation. The proposal, they wrote, "does not make sense and should be rejected since it will create great confusion in chemistry lessons."[101] This confusion would in part be due to a unique situation in West Germany. "While universities are usually free to use whatever nomenclature they want, schools in the Federal Republic are bound to follow IUPAC recommendations." This could potentially cause great confusion as students moved from elementary and secondary schools into universities where they would be confronted with an unfa-

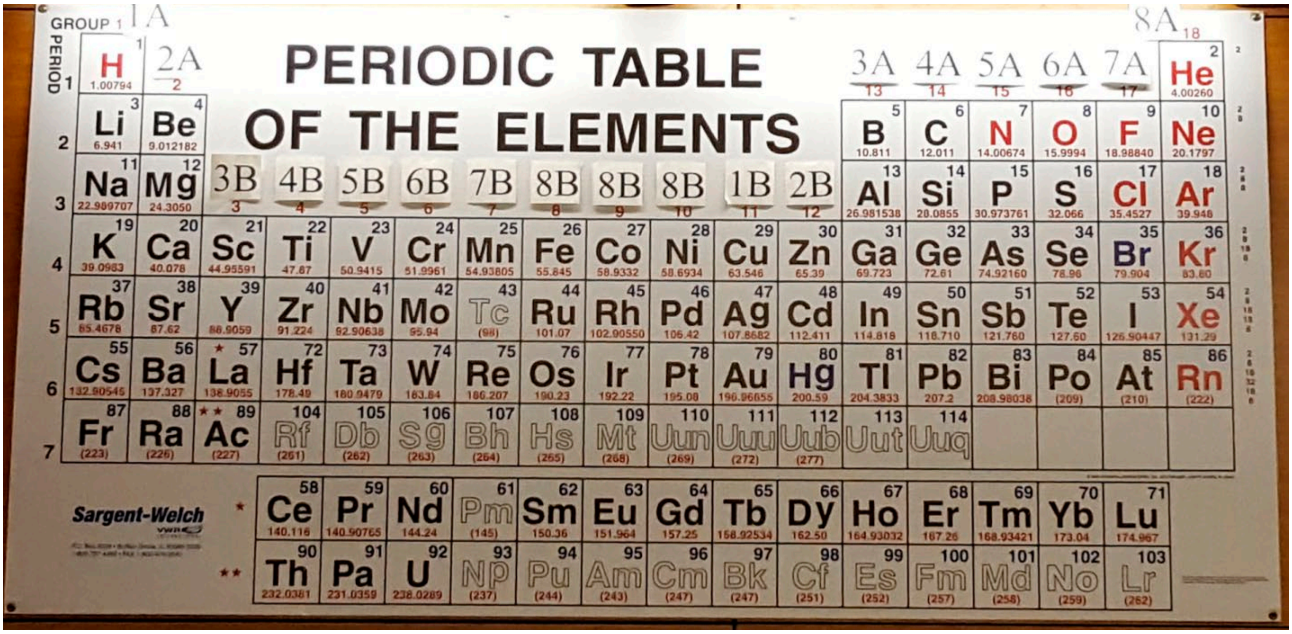


Figure 10. A periodic table wallchart (Sargent-Welch) on which the A/B group numbers have been taped above the 1-18 group numbers (Photo taken by the author at the University of Massachusetts Amherst, June 2016).

miliar group number system. Most textbooks would also need to be revised "because much information about chemical behaviour is usually inferred from the site an element occupies in an 8 group periodic system." Ursula A. Hofacker (? -) concluded that, "a recommendation of the Inorganic Nomenclature Committee to use both forms of the periodic system would be most desirable."[102]

The National Committee of Soviet Chemists strongly objected to the recommendation to drop the A and B sub-group labels and use group numbers 1-18 instead. Unlike the majority of countries, Russia and many members of the Soviet Bloc continued to use the short-form table. The table was considered to be an important part of Russian history, given the role played by Dmitrii Mendeleev in the discovery of the periodic law. The chairman of the National Committee wrote to the IUPAC president noting, "we feel it particularly important to keep table's traditional form … and to reject all groundless attempts to renounce the generally accepted … 8-groups form of periodic table." They also objected to the change on pedagogical grounds.[103]

As these letters were flooding into the chemical news magazines and the IUPAC, the CNIC was well underway with work on a new version of the Red Book. At their 1982 meeting in Paris, they unanimously agreed to the provisional dropping of the A/B sub-group labels. There was also an agreement for a system based on the long-form periodic table.[104] After the publication of the ACS recommended periodic table and the articles in both *Chemical & Engineering News* and *Chemistry International*, the IUPAC became alarmed by "the storm of concern" that ranged "from severe criticism, to tacit approval." The IUPAC president, Chintamani N. R. Rao (1934-), rather unusually wrote to the CNIC expressing his concern and wondering "how the problem will be settled." Further, Kazuo Saito (1923-1998), the president of the Inorganic Division, attended the CNIC meeting in Heidelberg in 1986 – also an unusual event – to impress upon them the importance of the issue.[105]

As most of the objections related to pedagogy, one way to "settle" the problem might have been for the CNIC to consult the IUPAC Committee on Teaching of Chemistry (CTC).[106] However, they apparently did not do so. In a letter to the IUPAC's Executive Secretary, David J. Waddington (1932-), the chair of the CTC, remarked on the "considerable disquiet" regarding the proposed 18-group periodic table. He had "received several unfavourable comments" at the most recent CTC meeting. Members, he said, "were concerned on two counts. One was on the elementary point about consultation within the IUPAC family. The second was on the difficulties foreseen in teaching the new form."[107] If the CTC's objections were made known to the CNIC, they were not enough to change their intentions to move ahead.

After extensive debate, the CNIC acknowledged "the reluctance of some users of the periodic table, mainly teachers" to drop the use of A/B labelling. However, they wished to bring an end to the confusion that was to be found in the literature and in indexing services. While they did not wish to "legislate," they noted that in many countries there was already a tendency to use the long-form table, thereby making the use of group numbers 1-18 easier.[108] As a result of this meeting, Busch, the chair of the CNIC, published an article in *Chemistry International* which laid out their reasons for the recommendation to use the 18-group periodic table. He noted that "it is neither the purpose nor the intent of CNIC arbitrarily to set the format of the Periodic Table to be used in all parts of the world," however, "it is a reasonable mission for CNIC to offer broadly useful solutions when direct conflicts in usage occur."[109]

In response to the many protests, the CNIC continued to state that they were not legislating the adoption of a particular form of the periodic table. Indeed, the new edition of the Red Book contained four periodic tables. The table on the frontispiece was a long-form table using the 1-18 group numbering. An appendix contained a short-form table that used the recommended A/B sub-group numbers, a long-form table that used both systems, and a 32-column table that also used both systems of numbering. The CNIC stated that "common world-wide practice in teaching and research overwhelmingly supports the eighteen-column format," however they "did not wish to deprecate any specific Periodic Table format."[110] Regarding A/B sub-groups, the text stated "this usage is to be avoided."[111] However, three of the four tables included in the appendix used this system.

The new edition of the Red Book was published in 1990 with little fanfare. An article was published in *Chemical & Engineering News* announcing its release[112] but unlike the article in 1985 about the periodic table, it was not followed by months of letters to the editor. That did not mean there was whole-hearted acceptance of the new numbering system. Scientific supply companies began printing periodic tables with group numbers 1-18 but a long tradition of educators modifying commercial products to suit their purposes continued. Much as English chemists had once placed sticky labels over the "wrong" group labels, some have stuck the old group labels orver or above the new 1-18 labels as in Fig. 10. Once again, the CNIC recommended uniformity to end perceived confusion while also leaving the door open for the continuation of difference.

8. CONCLUSION

One of the many letters published in the midst of the controversy over the use of A and B sub-group letters noted, “The progression of scientific thought toward worldwide unification of terms, as evidenced by the acceptance of SI units and IUPAC naming conventions, meets an obdurate foe when faced with the periodic table of the elements.”[113] The IUPAC Commission on Nomenclature of Inorganic Chemistry (CNIC) ran into this obdurate foe in their attempts to further develop a common language for chemistry. As Fernelius had written in his position paper on the naming of elements, “vigilance, vision, and persuasion” was necessary for establishing order out of confusion. The episodes examined in this paper illustrate the persistence of the CNIC in walking the line between a radical unification of chemical terms and the inevitability of differences, a persistence that caused even the obdurate foe to give way.

This line was a difficult one when it came to the names of the elements. As the CNIC discovered when harmonizing the names of the elements after World War II, their perception of what constituted “a good name” was not necessarily welcomed. The lingering use of alternate names for elements 4 and 41 was a case of the inevitability of differences that eventually turned into the acceptance of standardization. The “storm of protest” over the name of element 74 – tungsten or wolfram? – on the other hand was an example of the inevitability of difference not gracefully giving in to the goal of unification.

The CNIC’s insistence on divorcing priority of discovery from the naming of an element, Rule 1.12, engendered more than a storm of protest. In the face of decades of continual protest from Berkeley and Dubna demanding that the traditional right of discoverers be upheld, the CNIC persisted in putting off making decisions they argued were not matters of nomenclature. In response, they developed a systematic nomenclature for elements with an atomic weight greater than 100. Although this system was met with scorn by chemists and physicists alike, the recommendation was welcomed by indexing services such as *Chemical Abstracts* and found its way onto periodic tables worldwide.

The protests that arose of the change of group numbering were perhaps more contentious than those over the naming of synthetic elements. The non-standard use of the A and B sub-group labels were perceived by the CNIC to be a source of confusion, one that could be readily solved by the use of standardized nomenclature. They did not seem to realize the pedagogical importance of the labels, even if they were not standard across the world, and when faced with protest, they did not consult within the IUPAC family. The Committee on Teaching of Chemistry could have been a source of information, if not a partner in how best to approach a change, but even their objections went unheeded. And again, despite the protests that arose, the CNIC was successful in walking the line between radical unification and allowing difference.

On the whole, as these episodes illustrate, the periodic table and the elements were an “obdurate foe” but one that gave way to persistence. Their belief in the power of standardized nomenclature to resolve perceived confusion allowed the CNIC to persevere in the face of protests from multiple directions. In the end, they were responsible for changes to the periodic table and the nomenclature of the elements that advanced the goal of developing a common language for chemistry based on “the existence of a logical, systematic, and generally agreed-upon nomenclature practice.”

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Periodicity Trees in a Secondary Criterion of Periodic Classification: Its Implications for Science Teaching and Communication

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Abstract. In this work, I will present a proposal for introductory courses in chemistry. After the topics of atomic structure, chemical periodicity and chemical bonding, this proposal addresses the study of the periodic system based on triads, which has closed structures called periodicity trees as a secondary periodic criterion. This table was designed from a classical chemical perspective, with the purpose of integrating traditional topics and of supplying a conceptual basis for new ones, and, mainly, to privilege the chemical over the physical approach in the process of teaching-learning chemistry in initial courses.

Keywords. Periodicity tree, chemical element, periodic system, teaching and communication in chemistry.

> *No sólo le costaba comprender que el símbolo genérico "perro" abarcara tantos individuos dispares de diversos tamaños y diversa forma; le molestaba que el "perro" de las tres y catorce (visto de perfil) tuviera el mismo nombre que el "perro" de las tres y cuarto (visto de frente).*[1]
> Jorge Luis Borges

1. INTRODUCTION

> *Borges's quote, presented as an epigraph, is included in the short story "Funes, his memory", and serves as a trigger to the purpose of this work: Not only was it difficult for him to see that the generic symbol "dog" took in all the dissimilar individuals of all shapes and sizes, it irritated him that the "dog" of three-fourteen in the afternoon, seen in profile, should be indicated by the same noun as the dog of three-fifteen, seen frontally.*[2]

Just as the generic symbol 'dog' comprises many different individuals, of various sizes and diverse forms, the generic symbol 'chemical element' comprises a multiplicity of species in the same locker of the periodic tables. For example, one box of the usual periodic tables includes all the isotopes of an element, all the simple ions of all the isotopes of that element, all the ions combined to each other, and therefore all the isotopes of all the elements that make up each combined ion, in turn, in all possible combinations. It furthermore also encompasses all the molecules, from the simplest that the element can form, as oxides or hydrides, going through those of more complex structures, like most organic molecules, to all polymers, both natural and synthetic, in which that element can be part of, etc.[3] In addition, a single locker includes all those species in all possible contexts in which they can be presented, for example, solutions with subtle variations in concentration or pH. The context, although usually neglected, is a however fundamental aspect in chemistry, since small variations, which can be considered insignificant –as the difference between *the dog of three fourteen (seen from the side) with the dog of three fifteen (seen from the front)*– may induce large changes in some particular reactions such as the case of saturated solutions or metastable systems.

Ireneo Funes, the character of Borges's short story, found it hard to comprehend that the generic symbol 'dog' covers many different individuals in size and in shape. By contrast, most students of initial chemistry courses experience no difficulty to approach the complexity of the concept of chemical element, as they simply do not become aware of that complexity, of that conceptual labyrinth. To them, the concept of element coincides with the concept of atom, and an atom is a cluster of protons and neutrons in the nucleus and electrons in the periphery, which are organized in a "quasi-military" way in "decreed" energy levels; in turn, molecules are simply conceived as sums of atoms. The purpose of this contribution is to present an alternative view that could be used in the educational context, in order to help the student to become aware of the complexity involved in the term 'chemical element', and of the importance and limitations of the periodic classification of elements. The acknowledgement of the complexity of this problem and of all the problems derived from the concept of element – basically all chemistry –, far from discouraging the students, should stimulate them to approach the exciting task of studying chemistry.

Let us recall that the standard periodic table (SPT) is organized by a primary criterion, which orders the elements by increasing atomic number, and a secondary criterion, which allows grouping elements in chemically similar families according to the electronic configuration of the last layer. In contrast we suggest the following alternative. After teaching the initial topics of the regular course – atomic structure, periodic table and chemical bonding, the table based on atomic number triads (hereafter called TBT, Table Based on Triads) is introduced, in order to integrate those topics from a purely chemical perspective.[4] The TBT maintains the primary criterion but, as a secondary criterion, it proposes to organize the elements in a series of closed structures called 'periodicity trees' (pT's). The peculiarity of this periodic table is to dispense with all consideration of electronic configurations. This is a fundamental point of the proposal, since it shows an alternative way of organizing the elements without using a concept that, although it is very relevant in chemistry, comes from a physical theory as quantum mechanics.[5,6] Moreover, this approach shakes two common "beliefs" by showing, on the one hand, that the concept of element is not as simple as usually believed, and, on the other hand, that classifications are never unique: there are very different ways of classifying, each useful in its own field or application. In the case of TBT, the secondary criterion of classification is periodicity tree (pT), which focuses on the classification of the elements from a chemical and non-physical perspective: the criterion is based on macroscopic chemical similarities among elements and not on quantum features of atoms (see Sections 4 and 5).

With this goal in sight, the article is structured as follows. The next section provides a brief historical overview on the development of the concept of element. Section 3 sketches the path towards periodic classification. Section 4 describes the proposal of the periodic system based on triads (TBT). By section 5 we will be described focusing on the structures called 'periodicity trees' (pT). Section 6 will introduce the implications in the context of teaching and communication of chemistry; in this section the main proposal of this work will be explained and the treatment of some relevant issues in this context will be discussed. Finally, the conclusions of this work will be presented.

2. THE ROOTS OF THE NOTION OF ELEMENT

From pre-Socratic philosophy to modern times, the concept of element was mainly philosophical, designing the originating principle of everything real: it referred to what is primary, fundamental and persistent, in opposition to what is secondary, derivative and transitory. It was only in the eighteenth century that Antoine Lavoisier (1743-1794) proposed an operational definition of element that had a strong influence up to now: elements are the ultimate product of chemical analysis.

Dimitri Mendeleev (1834-1907) replaced the Lavoisier program, based on the relationship between simple body and compound, by the relationship between element and simple or composite body.[7] Simple body ceases to be an explanatory principle and becomes an appearance. Only elements, hidden in simple and composite bodies and remaining in spite of change, can be an explanatory principle. This motion from the concrete reality of simple bodies to the abstract reality of elements, is what allowed Mendeleev to conceive a general system of elements that goes far beyond a mere grouping of chemical families.[8]

With the advent of quantum physics in the early twentieth century, the atomic theory pervades the field of chemistry, and the concept of element is assimilated to that of atom. However, after the discovery of isotopes by Frederick Soddy (1877-1956) in 1913, elements seemed to "multiply" and the doubts about whether or not there were new elements triggered what Eric Scerri calls as the "periodic table crisis".[9] It is in the context of this crisis that Friedrich Paneth (1887-1958), in 1931 proposes the dual nature of the concept of element, distinguishing between elements as *simple substances* according to their phenomenological manifestations, and elements considered in an abstract sense as *basic substances*, whose only property was no longer their atomic weight, as in Mendeleev's, but their atomic number, in consonance with the new quantum mechanics.[10] For Paneth simple and basic substances are not two descriptions of the same entity, product of an epistemic limitation to be overcome in the future; for him, the very concept of chemical element embodies a double nature. The epistemological status of the basic substance is part of the current discussions about the nature of the concept of element among historians, chemists, educators and philosophers of chemistry. These discussions show that, although there is a broad consensus about the extension of the concept, there are strong disagreements with respect to its intention (cf., for example, Bent, Hendry, Schwarz, Earley, Ruthenberg, Scerri).[11,12,13,14,15,16.]

3. THE ROAD TOWARD A PERIODIC CLASSIFICATION

According to Van Spronsen and Scerri, two notions led to the evolution of the periodic system: the Prout hypothesis and the Döbereiner triads.[17,18] The idea that all simple bodies must derive from hydrogen was formulated by the Scottish physicist William Prout (1785-1850), who noted that many of the atomic weights determined for the elements were integer multiples of the atomic weight of hydrogen. Prout concluded that hydrogen could be the fundamental element, and that all other elements would be formed from this element by a condensation phenomenon. This hypothesis implied that all the elements had to have whole atomic weights, which was in contradiction with many experimental data of the time. Prout's hypothesis played a double role in the history of the classification of the elements: on the one hand, it stimulated research aimed at the exact determination of atomic weights, and on the other hand, it also weakened the tendency to systematize the elements through its phenomenological properties, imposing the primacy of classification by atomic weight.[15]

In 1817 the German chemist Johann Wolfgang Döbereiner (1786-1849) reported that certain elements associated in groups of three, presented chemical similarity and a particular arithmetic relationship: the atomic weight (or equivalent weight) of the second element was almost exactly the average of the other two. He called these groups '*triads*'. For instance, Döbereiner found that selenium in the triad of sulfur, selenium, and tellurium had an atomic weight that was the approximate average of the weights of the other two elements. The importance of this discovery lies in the association of qualitative chemical properties, such as the kind and the degree of reactivity, with numerical properties of the elements. This suggested that there could be some underlying numerical order that could serve to relate the elements to each other in a systematic way. Döbereiner also discovered other triads, such as calcium, strontium and barium, and lithium, sodium and potassium. Other chemists discovered still more triads and began to elaborate tables that tried to relate the triads to each other.[15]

Among the precursors of the periodic system, William Odling (1829-1921) classified the then 45 known elements into 13 groups.[19] Also noteworthy is the contribution made by the British chemist John Newlands (1837-1898), who in 1864 published a table of 24 elements subdivided into five groups.[20] He noticed that in the table there was a repetition of some properties of the elements every certain regular interval. Then he placed the elements in increasing order of atomic weights, giving each one an order number. In 1865 he published another table containing the numbered elements arranged in eight columns.[21] He observed that when counting from any element, the eighth had similar properties. He called this relationship "the law of octaves". In turn, in 1864 the German chemist Julius Lothar Meyer (1830-1895) presented a table of 28 elements, arranged horizontally according to their valence (see also Boeck's article on Meyer in this special issue).[22,23] In 1868 he proposes another periodic table with the atomic weight as criterion of order. This new table had 55 elements arranged vertically in 15 columns, being classified in families located horizontally.[24] By then clearly the ordering of the elements was linked to the atomic weights and the analogy in their chemical behavior, which went beyond Döbereiner's concept of triads but definitely built on it.

When he had to dictate his chemistry course, Mendeleev considered that he lacked appropriate teaching material and decided, like many of his colleagues, to develop his own manual.[25,26] One of the first difficulties that he found was how to organize the huge set of chemical knowledge, accumulated over decades, about thousands of known chemical substances. From the time of Lavoisier, the mostly adopted solution for teaching consisted in relating the properties of a composite substance with the properties of its component *simple* substances.

By contrast, Mendeleev adopted a pluralist position. From his perspective, phenomenal properties are nothing else than external manifestations of more abstract entities, the elements: he considered that elements had a more fundamental status, of a metaphysical nature, and that their only attribute is atomic weight. In this way, Mendeleev introduced a clear differentiation between simple body or simple substance and element. The notion of simple body or substance, which from Lavoisier had become the key concept of chemistry, is thus replaced by that of element, understood in an abstract or metaphysical sense. According to Mendeleev, the simple body is something material, and remains relegated to the world of appearances. The element is the only explanatory principle, the substratum of everything observable. The elements have no phenomenal existence, they are always "hidden" in a simple or compound body. It is that "something" that is conserved in chemical reactions. It is a fundamental reality, clearly abstract, which explains the conservation and permanence of individual properties despite chemical changes.[5]

Mendeleev was a strong defender of the individuality of the chemical elements, and therefore, a critic hostile to the hypothesis of Prout, which he considered contrary to the periodic law. It is on the basis of this conception of element that Mendeleev organized his classification endeavor; reaching that level of abstraction appeared was indeed an essential requirement for a successful classification. He was then able to consider that the properties of simple and compound bodies came as a periodic function of the atomic weights of the elements.[5]

The periodic classification marked the apogee of a chemistry centered on the elements: it recapitulated the facts, organized the laws, systematized the acquired knowledge and motivated the program of the theoretical development of chemistry from the notion of element. It was not the isolated discovery of an isolated individual, endowed with enough knowledge to be in the scientific vanguard of his time; on the contrary, it was the answer to a specific problem of nineteenth-century chemistry, and the culmination of a long history marked by evidence and errors.[5]

In the second decade of the twentieth century, the British physicist Henry Moseley (1887-1915) conducted experiments with discharge tubes, in which the rays collided with metal sheets of different elements. Moseley found that the X-ray spectra so obtained depended on the used metal, and that the lines of the spectra changed uniformly, maintaining a harmonic pattern, when moving from one element to the next of the periodic classification.[27] From his work, a new property was defined: the *atomic number*.[28,29]

In 1913, Niels Bohr (1885-1962) postulated a new atomic model for the hydrogen atom, based on the first quantum theories. Later, other researchers such as Arnold Sommerfeld (1868-1951), Pieter Zeemann (1865-1943) and Wolfgang Pauli (1900-1958) developed the theory and formulated the quantum numbers. The atomic model of Bohr, initially proposed for monoelectronic atoms, was then generalized to any multielectronic atom and the arrangement of electrons in these systems began to be studied, giving rise to the concept of *electronic configuration*, in whose development was fundamental the contribution of other scientists, mainly Charles Bury (1890-1968).[29] It is noteworthy that Bohr's approach was not based on any mathematical basis, nor explicitly resorted to quantum theory to assign the electrons in the different shells, but was guided by the chemical characteristics of the elements to assign them electronic configurations.[14,15]

Chemists accepted the Bohr model, because it provided a surprisingly intuitive version of the concept of atomic number, which indicated the position of the element in the periodic system. This number is equal to the number of electrons, and also to the number of positive charges that characterize the nucleus. Each successive element in the usual periodic table has one more electron that its predecessor, and the periodic changes of the valence observed in the table could be explained by the successive occupation of the orbits. In this way, a research program was initiated, which erased the traditional boundaries between chemical reactions and physical interactions.[31] The present way of teaching chemistry is the consequence of that program.

4. THE PERIODIC SYSTEM BASED ON TRIADS OF ATOMIC NUMBER[32]

As shown in the previous section, one of the early systematisation from which the periodic system was built was the concept of triad concept proposed by

Döbereiner; we regard the concept of triad as one of the pilar of the periodic system. At the beginning of the current century, Eric Scerri reformulated the concept of the triad, by defining them as based on atomic numbers; so, triads resulted from integer numbers.[33,34] Scerri also suggested the use of triads of atomic numbers as a possible secondary criterion for the periodic system. Although in the SPT (and in the representations directly derived from it) there is a large number of triads –which can be increased with the displacement of hydrogen to the group of halogens–, the formation of triads cannot be considered as a secondary criterion of periodic classification since it does not relate systematically to all elements.

In TBT, the primary criterion is given by the increasing atomic numbers, and the secondary criterion is established by the formation of triads of atomic numbers, which in turn form closed structures of 20 elements called 'periodicity trees' (pT's). The representation is based on three factors that act as criteria for the construction of the table: the conception of the elements in their character of basic substances, the triads of atomic numbers, and the chemical information on the behavior of the elements as simple substances.[3]

The fact that the three elements necessarily have similar macroscopic properties is no longer required in TBT, as was the case with Döbereiner. For instance, two of the elements of the triad may belong to consecutive periods with the same length, that is, of the same block, while the third may come from a different block, and thus belongs to a period of different length. In this approach, the elements of the same block have similar chemical properties, and the third element, also called "connecting element", performs the function of linking consecutive blocks. The idea of connecting element only makes sense when elements are considered as basic substances. The branches in the pT's are formed by those connecting elements (see the next section). This way of conceiving triads shows that chemical elements can be organized without appealing to electronic configurations, and without relying exclusively on the macroscopic properties of simple substances. Chemical periodicity can be characterized in a formal and abstract way, but, at the same time, it turns out to be compatible with the empirical knowledge accumulated in chemical experience. This proposal is inspired in the conciliation between the conceptions of element as basic and simple substance, in the sense recommended by Scerri: "Paneth's insistence that the periodic system only classifies elements as basic substances invites the obvious question of how we might learn about these elements, especially as they are said to have no properties. Admittedly atomic number provides an ordering criterion but periodic classification is also about group similarities which are recognized through the properties of elements as both simple substances and as combined simple substances. It is difficult to see how focusing on elements as 'basic substances' can provide any indication of the second dimension of the periodic table, namely the grouping of elements into vertical columns.[35]

In the proposal of TBT, elements are grouped so that all are involved in at least one triad; it is for this reason that formation of triads can be adequately considered as the basis of a secondary classification criterion. The table is structured as follows: (i) periods result from organizing the elements according to the increase in atomic number; (ii) in each period, a new generation of triads is formed, and each generation will have as many triads as the period has (see Figure 1, where all the triads are shown).[3]

The fist 8 periods contain: 1, 1, 8, 8, 18, 18, 32 and 32 elements, respectively. If the series were extrapolated for the construction of the table, the ninth period should contain 50 elements. However, due to anomalies in some elements of the eigth period, a reversal of the sequence is proposed.[3]

Finally, it is interesting to notice that the TPT preserves several aspects present in the Mendeleev classification: the abstract perspective on the nature of elements to allow the structure that classifies them, and also the individuality of the chemical elements as a fundamental and objective feature of nature.

5. PERIODICITY TREES

The system introduced in the previous section is based on the idea that triads manifest the abstract relations between elements, which only make sense at the level of basic substances, but not necessarily in that of simple substances. Thus, each triad in this system should not be thought of individually, but within a pT, that is, a set of nested triads. In other words, each triad is conceived as a part of a tree, in such a way that it becomes meaningful only within this set of relationships. The concept of pT is proposed as an alternative to the traditional concept of group in the SPT.[36]

A pT is a symmetric structure where the elements are related by triads: there are 9 structures of this type (see Figure 2). Since they make up the architecture of the table, they manifest the secondary criterion of classification in TBT.

There are two types of pT: 8 lateral trees of 20 elements, and a central tree also of 20 elements, which is

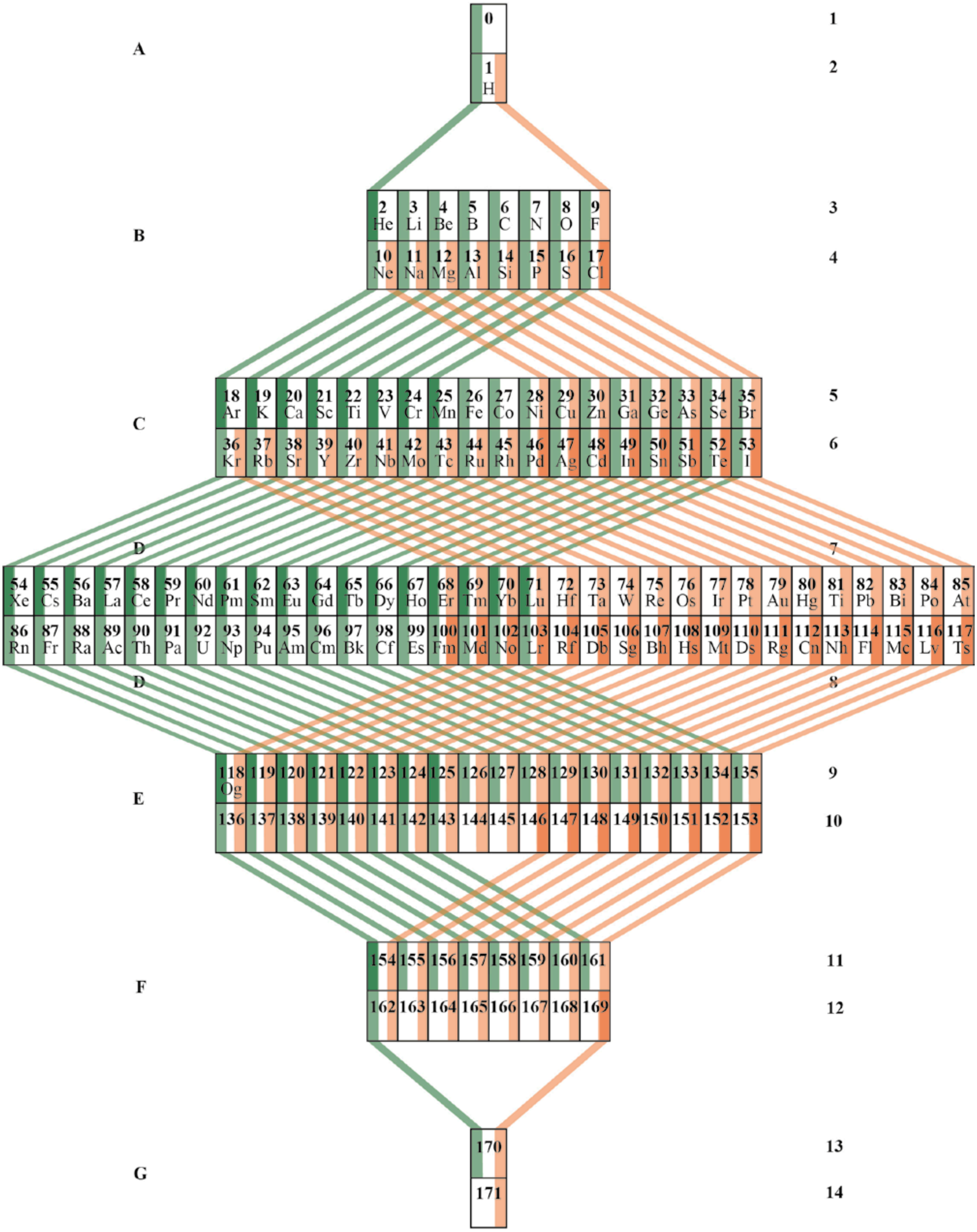

Figure 1. Periodic table bases in triads: in green the triads corresponding to even generations, in orange those corresponding to odd generations. Observe that in each period, a new generation of triads is formed.

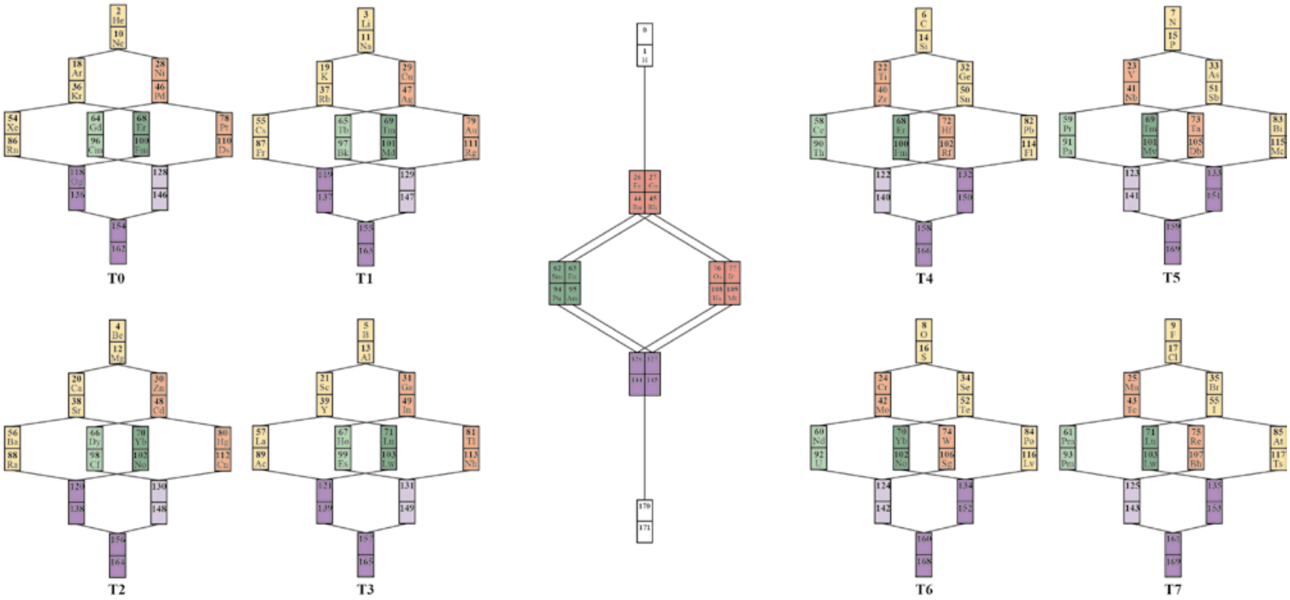

Figure 2. The nine periodicity trees make up the TBT.

formed from the elements not included in the lateral pT's. The *main branch* is the branch that starts with the first two elements and continues with those located at the left in the first 4 trees, and the branch that starts with the first two elements and continues with those located at the right in the second 4 trees. The opposite *complementary branch* is the yellow branch in the first 4 trees, and the orange branch in the second 4 trees (see Figure 2).

The 8 lateral pT's include, as their first element, those elements that start the representative groups of the series A (with the exception of hydrogen, which is a very special element, see next section). Each one of them contains 20 elements, connected through a succession of concatenated triads. In order to give an idea of the structure of the pT's, let us consider the features of the lateral tree T1 and of the central tree.[3]

The tree T0 begins with the triad 2-10-18 (He-Ne-Ar). Then, it continues to the right with the triad 10-28-46 (Ne-Ni-Pd), where Ne acts as a connector element where the first bifurcation occurs. Then, the triads 18-36-54 (Ar-Kr-Xe) and 28-46-64 (Ni-Pd-Gd) follow in the construction. In this way, in the laterals of the tree, the group VIII A of the noble gases appears as a left main branch, and the third column of group VIII B of the STP appears as a right complementary branch in the same structure.[37]

In turn, in the one of the central branches of the tree, the first lanthanide (Gd) is included, in the next generation the triads 36-68-100 (Kr-Er-Fm) and 46-78-110 (Pd-Gd-Cm). The first actinides (Fm and Cm), and the second lanthanide (Er) appear. The next generation is composed of the triads 54-86-118 (Xe-Rn-Og) and 64-96-128 (Kr-Er-Fm), which complete the elements known up to the present in T0. The tree continues with triads formed some hypothetical elements: the triads 100-118-136 (Fm-Og-136) and 96-128-146 (Cm-128-146), then the triad 118-136-154 (Og-136-154) comes, and finally the triad 146-154-162 which closes the tree.[3]

The pT's T1 to T7 are constructed by following the same procedure, by adding 1 to the number of each element. In turn, the central pT includes the elements not contained in the lateral pT's, beginning by 26 and 27 (Fe and Co). The central tree allows to reconstruct the first 2 columns of the SPT by means of triads. The central tree also includes the first 2 elements (0 and 1) and the last 2 (170 and 171).[3] Figure 3 shows the complete TBT.

6. IMPLICATIONS FOR THE TEACHING AND COMMUNICATION OF CHEMISTRY

In higher secondary education and university courses of chemistry of introductory level, the teaching of the periodic relationships among chemical elements generally follows the study of the electronic structure of atoms and precedes the basic concepts of chemical bond. In this way, the most frequent strategy (without considering the different possible approaches whose analysis is not the purpose of the present work) begins by study-

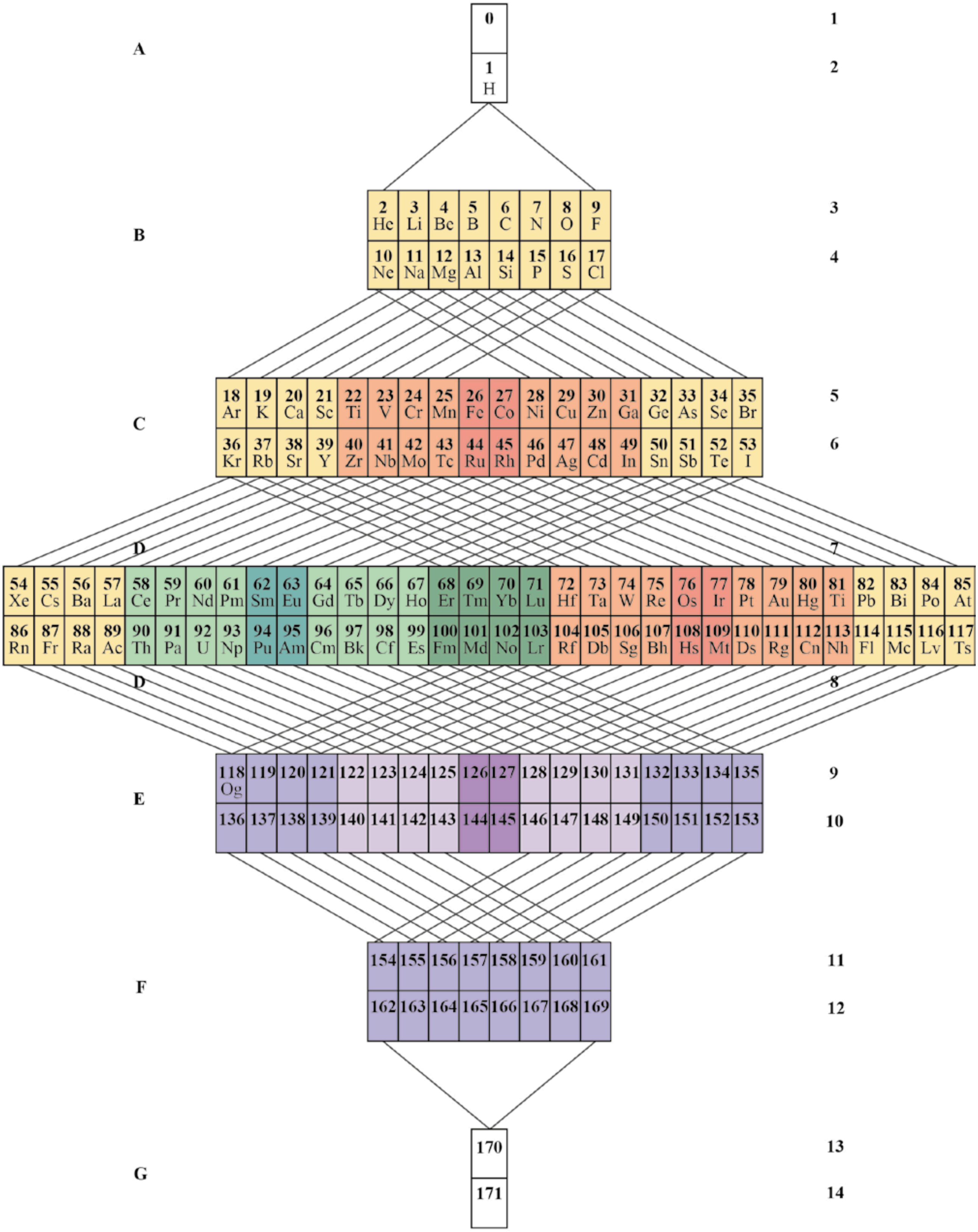

Figure 3. Periodic table based in triads, in the same color the elements that must present relations of periodicity.

ing the electromagnetic radiation and the atom from the quantum-mechanical point of view, on the basis of the uncertainty principle, an introduction to the wave functions, the quantum numbers and the characteristics of the atomic orbitals. Then, the chemical periodicity is approached from the point of view of the quantum numbers and the electronic configurations of the neutral atoms, the electronic configurations of the ions, and the variation of the periodic properties, such as ionization energy, electronic affinity, and atomic and ionic radio. After this, covalent and ionic bonds, the rule of the octet and its exceptions, the Lewis structures, the load distribution, and the formal charge are introduced. Finally, the theory of repulsion of valence orbitals and an introduction to the theory of molecular orbitals are explained.[38]

This way of presenting the topics in chemistry courses is the result of the uncritical acceptance, by most of the current chemical community, of the quantum tools as potential solutions and comprehensive explanations of all the problems and challenges posed by chemistry. This, in turn, derives from the great influence of the so-called "dictum" of Dirac: "The fundamental physical laws necessary for the mathematical theory of a large part of physics and the totality of chemistry [are] completely known from quantum mechanics."[38] In recent years, many works in the field of the philosophy of chemistry addressed the problem of reduction, focusing on logical, ontological, epistemological and historical aspects and questioning the validity of Dirac's dictum. The present work is part of this trend: it is based on the assimilation of new philosophical research, or rather, the part of that new research that is relevant to chemistry.[40]

From this perspective, I propose, as a didactic strategy, to teach the periodic system on the basis of TBT and the concept of pT, immediately after the treatment of the notions of atomic structure, chemical periodicity and chemical bond.[41] It is important to introduce TBT after chemical bond, and not in conjunction with the standard study of chemical periodicity, in order to emphasize the chemical approach over the physical one. This table can be used as a tool to integrate the preceding topics, and in this way to consolidate their conceptual bases; this facilitates the approach to the later topics with a fundamentally chemical approach, and not, as usually happens, from a physical perspective.

The TBT, given its foundations, might have been contemporary to the Lewis's proposals at the first decades of the last century, since it is conceptually independent of the quantum-mechanical description of the atom. In fact, for the elaboration of TBT, I relied on a *deliberate anachronism*, by "rewriting" the periodic system with an approach that rescues the essential aspects of the chemical perspective of the late nineteenth and early twentieth centuries. At that time, chemistry boasted of being an active, autonomous, and academic science, self-reliant.[42]

On this basis, I tried to accommodate the later developments of the discipline from a chemical perspective, that is, from a classical way of understanding chemistry. This view does not intend in any way to conflict with the quantum perspective, whose study is fundamental especially for university students of chemical-based careers. The aim here is to complement and enrich that physical point of view, and to reassess the chemical approach over the physical for the process of learning chemistry in the initial courses. The concepts and aspects that can be enriched by this proposal are: (1) the concept of chemical element; (2) the concept of "valence shell" and, in a certain sense, also the treatment of the notion of electronic configuration; (3) the relations between the groups of the series A and B of the SPT, which appear naturally in the pT's; 4) the concept of metal element; (5) the debate about the elements difficult to be classified according to the standard view; and (6) some considerations on the foundations of the periodic system under discussion. While the latter issues are still debated among specialists, the four first are integral to the teaching of chemistry from the secondary school on. I will expand briefly on each of them in the subsequent sub-sections.

6.1 The concept of chemical element

It is very common that students, especially in the initial courses of chemistry, but also in the advanced courses, consider the concept of element as equivalent to the concept of atom.[43] The concept of element is even introduced in terms of its electronic configuration, as if there were almost nothing else than electronic configuration as relevant for chemistry. Every element is usually represented in terms of the closest noble gas, to which the missing part of the electronic configuration is added. Thus the chlorine element, for example, is usually represented as [Ne] $3s^2$ $3p^5$. More than an individual entity, a chemical element is considered the result of the sum of elementary particles, which in some sense (perhaps not too indirect) implies an allegorical return to the hypothesis of Prout. This view equates the concept of the element to that of the atom, and the concept of molecule to that of a simple set of atoms; chemistry is thus understood as the study of the interactions between molecules in those terms. Such a view is a barrier that prevents students from understanding the high relevance of the context in chemistry. For instance, it is common that students conceive regulatory systems of pH as something alien to the solution they are regulating, something external to the solution: the multiplicity of chemical interactions involved are not usually analyzed; they are perceived as a kind of thermostat in a refrigeration system. Similar situations occur when studying solutions in states close to the saturation point, heterogeneous systems, etc., in which the importance of context is crucial. Students are exclusively anchored in the perspective of the individual, or of the form, instead of taking into account the perspective of matter or stuff, specific of chemistry.[44,45]

The distinction between simple substance and basic substance is not perceived, except in exceptional cases. Thus, it can be said that the practice and teaching of chemistry, in some sense, has brought the chemical teaching back to the conceptual framework previous to the work of Mendeleev. Our proposal (or the TBT) aims at contributing to recover the distinction between simple and basic substance, and to emphasize the importance of context in chemistry. This would help the student to become aware of the complexity of the concepts of element, compound, basic substance and simple substance.

6.2 The concept of "valence shell"

In general, the traditional approach to explain the place of elements in groups and periods of SPT is based on describing sequentially the electronic configurations by means of combinations of quantum numbers. As a consequence, the valence shell (the outermost shell of an atom, containing the electrons that can be transferred to or shared with another atom), which is the relevant notion for chemists, appears at the end of this sequential process. Therefore, students commonly direct their effort in memorizing the sequence of the diagram of construction (*Aufbau* principle, Madelung Rule), and lose sight of the importance of the valence shell. They do not interpret, for example, the reason why the sublevels *s* and *p* are "mixed" to form the valence shell of the so-called elements of the *p*-block in the SPT, among many other difficulties. Moreover, since they arrive to the valence shell after a long procedure, errors are frequent.

In the approach of the TBT based on pT's, in the 8 lateral pT's the number of electrons in the valence shell coincides with the tree number (except in tree T0 and in the complementary branches of T1 and T2). In Figure 3, it is possible to observe that, in trees 3 to 7, the number of electrons in the valence shell of the elements that make up the main and complementary branches (which in the SPT integrate the groups A and B, see next sub-section) coincides with the number of the tree. For instance, in tree T4, the elements C, Si, Ge, Sn, Ti, Zr, Pb and Hf have 4 electrons in their last shell (adding the *s* with the *p* or *d* as appropriate). Moreover, in neutral atoms the number of internal electrons can be computed by subtracting the number of electrons in the valence shell from the atomic number; so, the diagram of construction is applied only to the internal levels.[45] This strategy introduces the electronic configurations of the elements "in reverse", that is, from the valence shell to the inner shells, emphasizing the concept of valence shell, one of the most relevant in chemistry.[47] Moreover, the frequent errors in the application of the construction diagram remain confined to the inner shells, with few chemical consequences, at least at the level of teaching.

It is also important to note that TBT, based on a simple arithmetic relationship such as the triad, allows the student, once the logic of generation of triads is interpreted, to easily locate each element, by its atomic number in its corresponding pT, know the number of electrons in the valence shell, and make inferences about its chemical behavior. For example, with the logic of generation of triads, the elements of any tree can be reconstructed. And once the elements are located in the corresponding trees, it is possible to make inferences about the chemical behavior of the elements and the relationships between them; this is particularly important to relate the elements of the series A and B (see the next sub-section).

This way of introducing the concept of valence shell actually recovers Lewis's structures, with all their didactic virtues. Lewis used cubes to represent atoms, in such a way that the electrons of the valence shell in the 2nd period of the SPT are placed in the 8 vertices of the cube. The practice in the formation of the Lewis structures is particularly productive –but often underestimated– in representing chemical bond, becoming a useful resource for the student who begins the study of chemistry. In fact, this practice allows representing chemical bond in a "classical" way, with the union of 2 points, and not with a line, as currently recommended. Now, if the number of electrons in the valence shell can be obtained in the TBT without relying on electronic configurations, the student can concentrate his attention on those electrons and use Lewis's structures to analyze chemical bonds.[48]

6.3 The relations between the elements of the same groups of the series A and B

In the first tables of Mendeleev, the series A and B do not appear. In later Mendeleev's tables, those series are distinguished, with the relationships between the elements belonging to them.[49] Precisely due to the fact that the series A and B cannot be explained in quantum-mechanical terms, they have disappeared from the contemporary tables, and its use is explicitly discouraged by IUPAC.[50] However, this strategy hides important chemical analogies between elements. Some of these relationships are very relevant, and usually go unnoticed by students, especially those linking groups 2 and 3, such as the chemical similarity between Mg and Zn, and between Al and Sc. Other similarities regarding reactivity naturally arise among Ti, Si and Ge, among V, P and As, and among Cr, S and Se, among others.

The TBT based on pT's recovers the classification in series A and B in a natural way since it represents the elements the series A by the lateral branches of the pT's, and the elements of the series B –the so-called 'transition metals'– by the complementary branches of the trees. It is also interesting to notice that, in general, the elements belonging to the main branch and those of the complementary branch in a lateral tree have the same number of electrons. The exceptions of this regularity are T0, T1, and T2. However, these exceptions are the manifestations of chemical particularities of the involved elements. For instance, in T0, Pd and Pt (belonging to the complementary branch) are not very reactive, but their reactivity is a degree greater than the almost zero reactivity of noble gases (belonging to the main branch); in this way, the less reactive metals are related with the less reactive non-metals in the same tree.

6.4 Metallic elements

Traditionally, it is taught that the essential feature of transition metals is that their *d* sub-level remains incomplete; this allows explaining the variation of the periodic properties between these elements. However, this explanation produces in the student the false idea that the metallic elements are very similar to each other and even that they are "essentially equal". By contrast, the chemical differences between these elements, which are all part of the B series in the SPT, are clear within the TBT, because the transition metals appear in the different pT's that constitute the table.

Lanthanides and actinides, also known as internal transition metals, are traditionally presented as having an incomplete sub-level *f*. So, even more intensely than in the case of transition metals, students have the idea that they are all alike, an idea that persists even in advanced courses. It is true that internal transition metals are chemically very similar to each other, but ignoring their differences leads the students not noticing very chemically important elements, such as Ce, Pr, Nd, and Dy in the first series, and U, Np, and Pu in the second series, for instance. In the present proposal, although internal transition metals appear all together in the TBT, they belong to different pT's which clearly expresses their differences.

6.5 Classification of elements

The TBT provides a criterion about the relative position of the elements that are difficult to be classified, a topic currently under discussion in the studies on the foundations of the periodic system. While these topics do not appear in the teaching program, these discussions can nevertheless be interesting and informative if presented in introductory chemistry courses.

The first debate refers to the position of H and He. Hydrogen as membership of group 1 is under discussion: the question is whether it should be placed with alkaline elements or with the group of halogens in the SPT. It has also been proposed that H must appear floating on the top of the table due to its peculiarities.[51] According to TBT, the particularity of H is manifested by the fact that it belongs to the central tree, and it is the single member of its period. Nevertheless, H is connected with the rest of the TBT through its participation in two triads (0-H-He and H-F-Cl). The central position of H in TBT thus naturally manifests the importance and the multiple aspects of its chemical behavior.

In the case of helium, the discussion is whether it must be included in the group of the noble gases (for its chemical properties) or in group II with the alkaline earths (for its valence electrons). If we evaluate the question from the standpoint of the TBT there can be no doubt: He belongs to the triad He-Ne-Ar, which integrates the main branch of T0. This position characterizes He as a noble gas, in agreement with the SPT.

In addition to the positions presented, about this controversy, other alternatives have been proposed, presented with interesting arguments and discussions.[52,53,54,55,56]

Another controversy is related to the position of the elements of group 3 of the SPT. In particular, the disagreement refers to which elements have to be placed under Sc and Y: some tables place the pair La and Ac, and others the pair Lu and Lr.[57,58,59,60,61] The TBT shows that, in a certain sense, both pairs are "below" Sc and Y. This is particularly evident in the T3: Sc and Y form a triad with La; but, on the other hand, Y forms a triad with Lu and Lr (see Figure 4). In this way, the structure of trees leading to interconnected triads allows to conclude that there are good reasons for the two solutions,

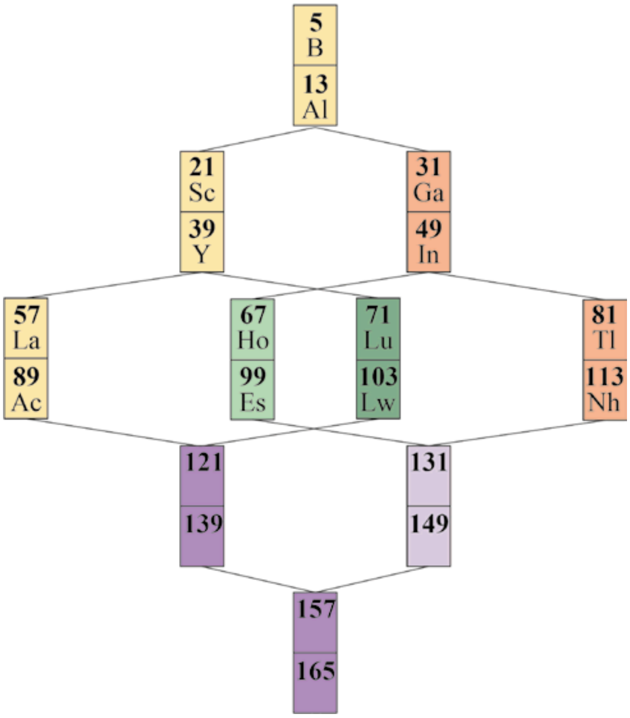

Figure 4. The periodicity tree 3.

although both are partial manifestations of a more complex relationship.

6.6 Other considerations about the foundations of the periodic system

At present, other points are debated: the existence of the element 0, the existence of a final element, and the multiplicity of possible representations, among others. Though not compulsory, a basic presentation of these topics in introductory courses might be interesting and motivational for students. It also invites them to think more deeply about the periodic system and the elements.

The TBT allows accommodating the element 0, which forms a triad with hydrogen and helium and initiates the system of triad generation. This element is conceived as an undifferentiated substance, which in a certain sense persists in all the elements: the neutron might be conceived as an empirical manifestation of the element 0. In this aspect, the TBT agrees with some recent views, such as that of Philip Stewart, who proposed a representation of the periodic system in spiral form, known as “chemical galaxy”: the chemical element number zero is placed in the center of the galaxy, and its “atoms” are the neutrons.[62,63,64] The idea of element 0 sounds strange if chemical elements are considered only as simple substances, but is natural when elements are viewed also as basic substances. In the TBT, which admits the double nature of elements, the element 0 is defined in a theoretical way by following the same progression that orders all elements: it is the element with zero electrons and zero protons, and one of its manifestations as a simple substance is the neutron, which corresponds to the element with atomic number 0, mass number 1 and null electronic configuration.

Regarding the existence of a final element, a point that is left open in SPT, the proposal of TBT takes a definite position. On the basis of the conjecture that leads to the reversal of the growth trend in the central period, the periodic system has a final element with number 171. This view suggestively agrees with some very recent quantum-mechanical model.[65,66]

Finally, the TBT represents a favorable contribution to acknowledging the multiplicity of possible representations for classifications of the elements. In fact, it is based on a secondary criterion completely different from that used in the SPT, and this fact allows it to highlight different features of the classification. As Jorge Luis Borges asserts in his short story “The analytical language of John Wilkins”: “… it is clear that there is no classification of the Universe not being arbitrary and full of conjectures. The reason for this is very simple: we do not know what thing the universe is.”[67]

7. CONCLUSIONS AND FINAL THOUGHTS

The presentation of the periodic system in the introductory chemistry courses usually follows the teaching of the atomic structure, and the relations of periodicity among elements are based on the combination of the corresponding quantum numbers. This way of teaching often leaves out, or confines to a secondary place, the chemical perspective about elements. Moreover, as Bernadette Bensaude-Vincent stresses, Mendeleev is usually presented as a precursor of those theories, ignoring that, far from being a prophet, he was a chemist of his time, who reorganized the body of existing knowledge around the concept of element, and not around merely empirical properties of substances.[5] After describing how the historical roots of the periodic system were erased by the quantum understanding of elements and the reorganization of the periodic system through the atomic number instead of the atomic weight, this paper presents a proposal for teaching the periodic system differently, based on analyzing the chemical relationships among chemical elements on the basis of the TBT. This table, being conceived from a chemical perspective, can be a plausible option to integrate not only the study of the periodic system, but also the concepts of element, atom, molecule, mole, as well as the concepts of valence shell, chemical bond, and reactivity, among others. This novel perspective offers an approach very different from that offered by the currently predominant physical viewpoint.

Of course, the quantum mechanical perspective is nevertheless important in higher courses, and clearly it must be studied in the first courses to be able to address those challenges. However, basing teaching exclusively on the physics perspective leaves aside the chemical view of the elements, and this causes great difficulties in the understanding of many chemical topics; in this way, the perspective of classical chemistry turns out to be merely anecdotal. But this is paradoxical, especially when the objective is precisely to train professionals in chemistry. Indeed the nowadays way of teaching the classification of the elements is not only disconnected from the historical development of the periodic system, it is also disconnected from a large part of the practice of chemistry.

The TBT highlights the chemical perspective of the second half of the nineteenth century, and goes beyond the mere historical interest. That was a chemistry which, as Isabelle Stengers expressed "not only achieved its status as an autonomous science, but the science of the avant-garde, science queen, positive science model , illustrating a conception in the effective practice of pragmatic and empirical science.[41] The TBT aims to rescue that spirit, and from that position seeks to assimilate and structure the chemical knowledge about chemical elements. In particular, the aim is to recover both the individuality and the dual meaning of the concept of a chemical element, beyond of the idea of atoms and molecules as constituents of matter. On this basis, this work looks towards the future for teaching, but also, to forthcoming theoretical and empirical research in the realm of chemistry. A future full of challenges and full of difficulties, whose approach will bring us successes, but also errors, unforeseen difficulties, failures and unforeseen complications. In short, a future that is worth living.

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4. A. Zambon, *Found. Chem.* **2018,** 20 (1), 51.
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48. In my teaching practice, I devised a strategy of teaching the formation of Lewis structures by combining cubes and icosahedrons (that, with their 12 vertices, allow representing the electrons of the metallic elements) with molecular models of balls and sticks and with pencil and paper exercises.
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Compounds Bring Back Chemistry to the System of Chemical Elements

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Abstract. The periodic system of chemical elements was historically devised by assessing order and similarity relationships among the elements from their compounds, that is, using the accumulated results of chemical practice and knowledge. However, the current approach to the system is based on an ontology of isolated atoms where similarities, especially, are addressed through resemblances of electronic configurations. Here we show how the historical approach can be combined with computational tools for data analysis to build up the system based on the compounds reported by chemists. The approach produces well-known similarities of chemical elements when applied to binary compounds. The results come from the analysis of 4,700 binary compounds of 94 chemical elements, whose resemblances are quantified based on the elements they form compounds with and the proportions of those combinations. It is found that similarities do not always correspond to columns of the conventional periodic table and that besides robust similarities such as those of alkali metals, halogens and lanthanoids, there are other mixed similarities involving transition metals and actinoids, some of which were already known for a long time. These similarities are described. Finally, the advantages and disadvantages of the electronic and the compound approach to the system are discussed. It is concluded that the current data availability and computational facilities make possible to think of a periodic system closer to the chemical milieu of compounds, bringing chemistry back to the system.

Keywords. Compound, substance, periodic system, chemical space, similarity.

INTRODUCTION

While some of the formulators of the periodic system[1] were after numerical relationships among atomic weights,[2] Julius Lothar Meyer (1830 –1895) and Dmitri Ivanovich Mendeleev (1834-1907) were especially interested in systematizing chemical knowledge.[3] They sought to highlight relationships

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[1] According to van Spronsen (reference 1), there were at least six formulators: Alexandre-Emile Béguyer de Chancourtois, John Alexander Reina Newlands, Julius Lothar Meyer, William Odling, Gustavus Detlef Hinrichs and Dmitri Ivanovich Mendeleev.

[2] This is especially visible in Newlands' and Odling's approaches. See references 2 and 3, respectively.

[3] The importance of textbook writing in the process of formulating the periodic system for Meyer and Mendeleev has been stressed by Gordin (reference 4) among other historians.

among chemical elements. The two relations supporting their sketches were similarity and order,[5] which built up a system for chemical elements; where "system" is understood in the ample sense of a set of related objects,[6] in this case chemical elements.[4]

The providers of order and similarity were in fact chemical compounds. Atomic weights, which constituted the order criterion; were determined by finding the smallest common weight of large numbers of compounds containing the reference element in question.[7] Similarity was based on resemblance in the composition of substances. As Mendeleev stated it in 1905: "if CO_2 and SO_2 are two gases which closely resemble each other both in their physical and chemical properties, the reason of this must be looked for not in an analogy of sulphur and carbon but in that identity of the type of combination, RX_4, which both oxides assume".[8] He concludes: "The elements, which are most chemically analogous, are characterized by the fact of their giving compounds of similar form RX_n".[8]

Gathering together chemical compounds constitutes a *chemical space*, which spans all energetically stable atomic ensembles.[5] By chemical space we designate all material species chemists experiment with, ranging from substances that can be stored in "bottles" such as liquids, solids or gases, to atomic clusters held together by van der Waals interactions. Throughout history, chemists have explored such a space by synthesis or extraction of new compounds. As chemists report their findings of new substances in the scientific literature, a suitable proxy for knowing how fast the exploration of the space has been carried out is the rate of reports of new chemical substances. We recently demonstrated that the chemical space has been historically explored in an exponential fashion with an annual growth rate of 4.4%,[10] indicating that about every 16 years chemists have doubled the number of substances since 1800, which was the starting point of the study reported in reference 10. This magnitude can be better expressed by the fact that the new substances reported in 2015 amount to the total of those reported between 1800 and 1950, i.e. the production of 2015 is equivalent in magnitude to the production of 150 years of new substances.[6]

This rapid growth poses a challenge to the periodic system and raises different questions: what was the chemical space in the 1860s when the system was formulated? What is the current chemical space and how does it affect the periodic system? We recently explored the space in the 1860s and found that several of the classes of similar elements known at that time could actually be obtained by analyzing the resemblance of the elements through their compounds through our approach, confirming the fact that Mendeleev and Meyer had indeed mapped the chemical space of their time.[13] In the current paper we analyze the question of the relationship between the current space and the periodic system and the implications for teaching the system.

CLASSIFYING THROUGH THE CHEMICAL SPACE

A classification of the chemical elements based upon the known chemical space up to 2011 was reported in 2012[14] through the analysis of 4,700 binary compounds,[7] which accounted for 94 chemical elements (Figure 1).[8] By binary compounds we mean substances made of two elements, e.g. water, ammonia and methane, but not sulfuric acid and fullerene, for instance.

Following the Mendeleevian approach to similarity of chemical elements, which states that two elements are similar if they form compounds with common elements in similar proportions, Leal et al.[14] formalized the notion as follows: For a given set of compounds the elements and proportions of combination of each element x are gathered in the neighborhood of the element x, called N_x. For example, if only $BeCl_2$, $MgCl_2$, $BeBr_2$ and $MgBr_2$ are the substances considered, the neighborhoods are: $N_{Be}=\{Cl2/1, Br2/1\} = N_{Mg}$ and $N_{Cl} = \{Be1/2, Mg1/2\} = N_{Br}$, which shows the similarity between Be and Mg and between Cl and Br, respectively.[9]

With the neighborhoods for each of the 94 elements, the similarity of every couple of elements was calculated

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[4] Interestingly, little emphasis has been made on the periodic system as an actual system. What we stress in reference 5 is that order and similarity are the structure keepers of all possible periodic systems.

[5] As later discussed, by atomic ensembles we mean substances, which may be transient ones. Moreover, in most extreme cases the ensembles do not necessarily require the presence of chemical bonds. More on the chemical space is found in reference 9.

[6] The idea of assessing chemistry growth through the frequency of reports of new substances was initiated by Schummer (reference 11). Quantitative studies of scientific growth began with Solla Price (reference 12), who analyzed the growth of scientific literature in different disciplines. Chemistry was found to be the most rapid growing discipline in terms of published abstracts.

[7] These compounds are a representative sample of the space by 2011, as $4{,}700 > \sqrt{12{,}060{,}017}$, where 12,060,017 is the number of known substances by 2011. Details of the annual production of new compounds are reported in reference 10.

[8] The elements analyzed are: H, Li, Be, B, C, N, O, F, Na, Mg, Al, Si, P, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Ra, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, and Es.

[9] In general, for a compound $x_a y_b$, the neighborhood of x is given by $\{xa/b, yb/a\}$.

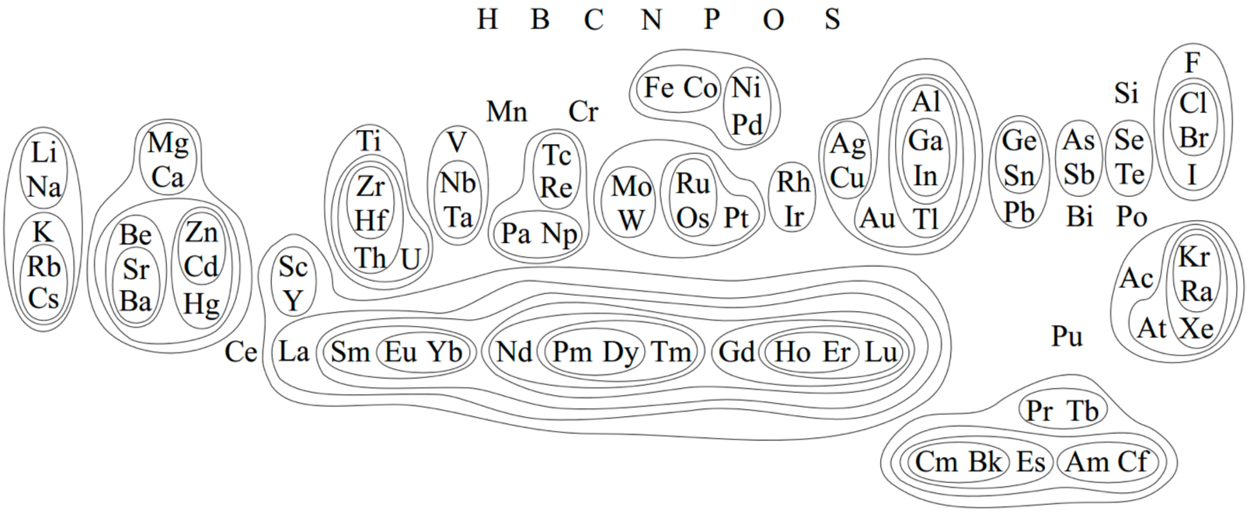

Figure 1. Most relevant similarity classes for 94 chemical elements obtained by analyzing binary compounds. Elements are spread on the plane trying to keep their positions as those depicted in the current middle-form periodic table while at the same time spatially indicating nearness in .behavior, expanding on the traditional grid. Sets and subsets group elements by similarities. Pairs of similar elements are denoted by subsets of two elements. Whenever a subset belongs to a larger subset, this indicates a hierarchical similarity. For example, Rb and Cs are similar elements, which in turn hold a more relaxed similarity regarding K.

as the commonalities of their neighborhoods. In general, the more common neighbors two elements have, the more similar they are (see Appendix 1 for details). This is exemplified with the following compounds:[15] HF, B_2H_6, B_5H_9, $B_{10}H_{14}$, from which the neighborhoods of the elements involved are: N_F= {H1/1}, N_H= {F1/1, B2/6, B5/9, B10/14}, N_B = {H6/2, H9/5, H14/10}. Thus, according to these compounds, hydrogen is more similar to boron than to fluorine, for there are more commonalities with the former than with the latter.

Once the similarities for all pairs of elements are calculated, clusters of similar elements are built up, for example through hierarchical cluster analysis. This technique looks for the most similar pair of elements and group them together in a first cluster. The new cluster is then included as a new object, where the similarities of the two members of the cluster regarding all the other elements are averaged.[10] In this setting, the most similar couple of elements is found, which may be made either of two elements, or of the cluster of the first merging and a third element. A new cluster is then formed and the process iterates until all elements have been merged.[11]

The outcome of the classification through hierarchical cluster analysis is a nested system of similarity classes that establishes the hierarchy of classes from which the classificatory technique takes its name. In the next section, we discuss the results of applying this methodology to the 4,700 binary compounds.

SIMILARITY LANDSCAPES: FROM CLASSIFICATION TO SYSTEM

The hierarchy of similarity classes for the 94 chemical elements studied in Leal et al.[14] can be depicted either as a classification tree, as in reference 14, or as a similarity landscape as in reference 15. In the current section, we present a simplified version of the similarity landscape (Figure 1).

Hydrogen is the most dissimilar element, which indicates that other elements combine very differently than hydrogen does. Other dissimilar elements are carbon, oxygen, sulfur, boron, phosphorus, and nitrogen (top of Figure 1).

There are well-known classes of similar elements, e.g. alkali metals and halogens, with opposite chemis-

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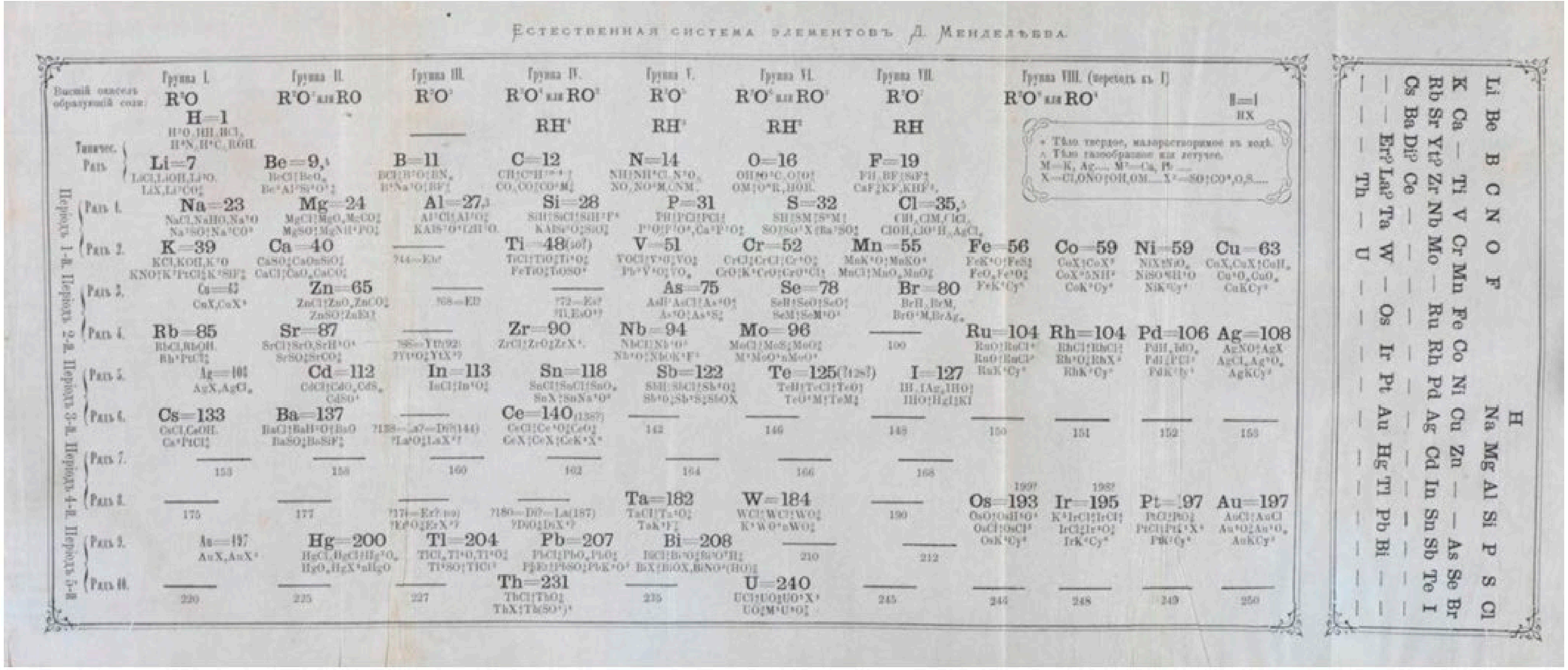
[10] Merging elements into a cluster and calculating the similarity of the cluster regarding the other elements is equivalent to finding the distance from an object to a set. There are different ways to find such a distance and the selected here of averaging the similarity of the elements of the cluster is called group average methodology. Other approaches are, for instance, the complete linkage, where the similarity of the cluster to the other elements is based on the similarity of the most dissimilar of the elements of the cluster. Further details on these and other grouping methodologies are found in reference 15.

[11] Particular details of the clustering process are found in reference 15.



Естественная система элементовъ Д. Менделѣева.

Высшій окиселъ образующій соли:	Группа I. R^2O	Группа II. R^2O^2 или RO	Группа III. R^2O^3	Группа IV. R^2O^4 или RO^2	Группа V. R^2O^5	Группа VI. R^2O^6 или RO^3	Группа VII. R^2O^7	Группа VIII. (переходъ къ I) R^2O^8 или RO^4			
				RH^4	RH^3	RH^2	RH				H=1 HX
	H=1										
Типичес. Рядъ	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19				
Рядъ 1.	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5				
Рядъ 2.	K=39	Ca=40	— ?44=Eb?	Ti=48(50?)	V=51	Cr=52	Mn=55	Fe=56	Co=59	Ni=59	Cu=63
Рядъ 3.	Cu=63	Zn=65	— ?68=El?	— ?72=Es?	As=75	Se=78	Br=80				
Рядъ 4.	Rb=85	Sr=87	— ?88=Yt?(92)	Zr=90	Nb=94	Mo=96	— 100	Ru=104	Rh=104	Pd=106	Ag=108
Рядъ 5.	Ag=108	Cd=112	In=113	Sn=118	Sb=122	Te=125(?128?)	I=127				
Рядъ 6.	Cs=133	Ba=137	— ?138=La?=Di?(144)	Ce=140(138?)	— 142	— 146	— 148	— 150	— 151	— 152	— 153
Рядъ 7.	— 153	— 158	— 160	— 162	— 164	— 166	— 168				
Рядъ 8.	— 175	— 177	— ?174=Er?(170)	— ?180=Di?=La(187)	Ta=182	W=184	— 190	Os=193 (199?)	Ir=195 (198?)	Pt=197	Au=197
Рядъ 9.	Au=197	Hg=200	Tl=204	Pb=207	Bi=208	— 210	— 212				
Рядъ 10.	— 220	— 225	— 227	Th=231	— 235	U=240	— 245	— 244	— 248	— 249	— 250

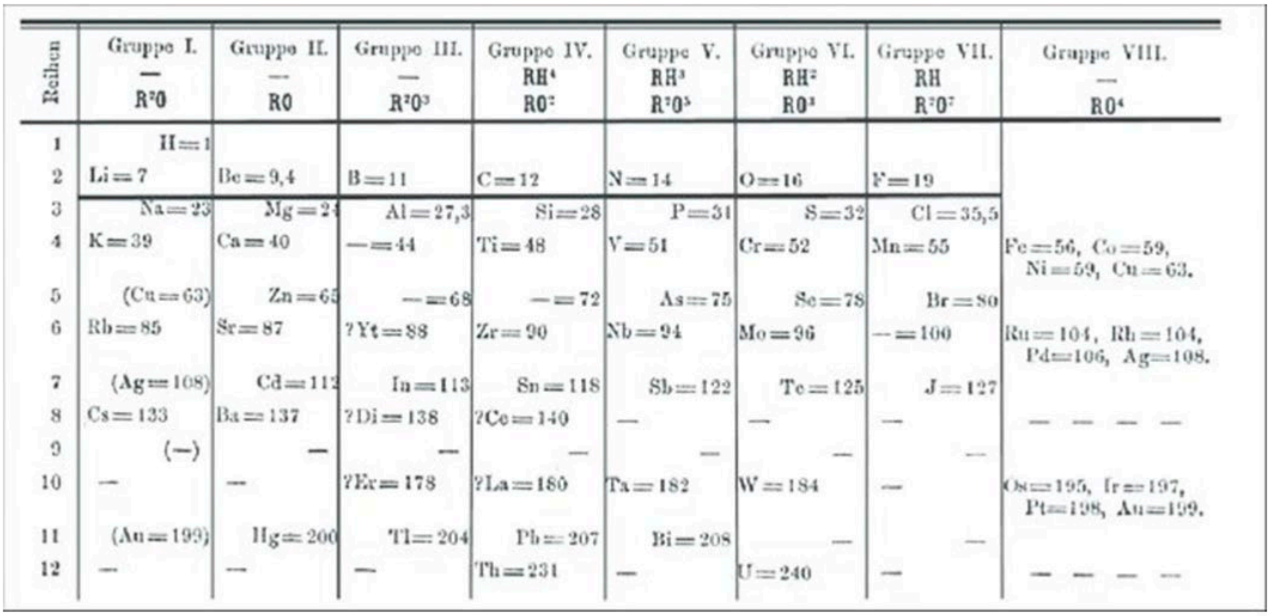
Періодъ 1-й. Періодъ 2-й. Періодъ 3-й. Періодъ 4-й. Періодъ 5-й.

* Тѣло твердое, малорастворимое въ водѣ.
△ Тѣло газообразное или летучее.
M=K, Ag.... M^2=Ca, Pb ....
X=Cl,NO³,OH,OM.... X^2=SO⁴,CO³,O,S....

										H						
Li	Be	B	C	N	O	F				Na	Mg	Al	Si	P	S	Cl
K	Ca	—	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	—	—	As	Se	Br
Rb	Sr	Yt?	Zr	Nb	Mo	—	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
Cs	Ba	Di?	Ce	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	Er?	La?	Ta	W	—	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	—	—
—	—	—	Th	—	U	—	—	—	—	—	—	—	—	—	—	—

A

Figure 2a. Mendeleev's periodic tables by 1871. A) Folding table in his textbook, D. I. Mendeleev, *Osnovy khimii (The Principles of Chemistry)*, Obshchestvennaia pol'za: St. Petersburg, Part II, 1871.[16]



Reihen	Gruppe I. — R^2O	Gruppe II. — RO	Gruppe III. — R^2O^3	Gruppe IV. RH^4 RO^2	Gruppe V. RH^3 R^2O^5	Gruppe VI. RH^2 RO^3	Gruppe VII. RH R^2O^7	Gruppe VIII. — RO^4
1	H = 1							
2	Li = 7	Be = 9,4	B = 11	C = 12	N = 14	O = 16	F = 19	
3	Na = 23	Mg = 24	Al = 27,3	Si = 28	P = 31	S = 32	Cl = 35,5	
4	K = 39	Ca = 40	— = 44	Ti = 48	V = 51	Cr = 52	Mn = 55	Fe = 56, Co = 59, Ni = 59, Cu = 63.
5	(Cu = 63)	Zn = 65	— = 68	— = 72	As = 75	Se = 78	Br = 80	
6	Rb = 85	Sr = 87	?Yt = 88	Zr = 90	Nb = 94	Mo = 96	— = 100	Ru = 104, Rh = 104, Pd = 106, Ag = 108.
7	(Ag = 108)	Cd = 112	In = 113	Sn = 118	Sb = 122	Te = 125	J = 127	
8	Cs = 133	Ba = 137	?Di = 138	?Ce = 140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er = 178	?La = 180	Ta = 182	W = 184	—	Os = 195, Ir = 197, Pt = 198, Au = 199.
11	(Au = 199)	Hg = 200	Tl = 204	Pb = 207	Bi = 208	—	—	
12	—	—	—	Th = 231	—	U = 240	—	— — — —

B

Figure 2b. Mendeleev's periodic tables by 1871. B) as in his Table II in his publication, D. Mendeleev, *Die periodische Gesetzmässigkeit der chemischen Elemente*, Ann. Chem. Pharm. 1871, 8 (Supplementband).[17]

tries and ways of combining with other elements. This was noted and detailed by Mendeleev in the table published in his second volume (1871) of *Principles of Chemistry*[16] (Figure 2a), where it is explicitely written that alkali metals combine with oxygen in a 2:1 ratio (R^2O using Mendeleev's notation). In contrast, halogens do it in a 2:7 fashion (R^2O^7). This table, among several other commonalities, shows that alkali metals form hydroxides of the form XOH, being X an alkali metal. One of the commonalities for halogens in this table is that they form compounds RH, where R is a halogen. The table was then simplified to the second table of Mendeleev's 1871 paper on the periodic system[17] (Figure 2b), where only the general formulae for oxides and hydrides remain, but the particular details of the table in Figure 2a are omitted.[12] In our work on the periodic system of 1869 using the known chemical space at that time, we found additional commonalities for alkali metals, e.g. $XAsO_4$, X_2CO_3, X_2SO_4, XNO_3, XCl, and XI.[13] For halogens, we found RC_2H_3O.

Finding alkali metals and halogens as classes of similar elements with the sample of compounds analyzed in reference 14, which include not only oxides and hydrides, indicates that the commonalities of the members of these families extend to most of their combinations with other elements, not only to those with oxygen and hydrogen.

Delving into the details of each of these classes, alkali metals can be divided into two sub-clusters, one of light metals: lithium and sodium and a second of heavier ones: potassium, rubidium, and strontium. Halogens follow a nested similarity structure, chlorine and bromine being the most akin halogens, with some resemblance to iodine. Fluorine is the most dissimilar halogen. The explanation of the strong dissimilarity of fluorine is based upon its small atomic size. This is part of the so-called *singularity principle*, which states that the chemistry of the second period elements is often different from the latter members of their respective groups.[18] Such principle is generally evident in the lack of similarities of carbon, oxygen and the other elements mentioned above and shown at the top of Figure 1.

Alkali-earth metals appear together with group 12 metals. This cluster of eight elements was recognized by Mendeleev as early as 1871 and is characterized by a 1:1 ratio of each element in the cluster with oxygen (RO and R^2O^2 in Mendeleev's 1871 periodic table (Figure 2)). As for alkali metals and halogens, this similarity class indicates that its elements combine in a similar fashion not only with oxygen but also with other elements (more details to be found in reference 14). In the study of the

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[12] As suggested by Brigitte Van Tiggelen during the revision of the current paper, this is an early evidence of how the simplification of the table through its dissemination started to leave aside valuable chemical information.

system of 1869 using the known chemical space, other resulting commonalities were RF_2, RCl_2 and RS.[13]

Another cluster of similar elements is the couple of selenium and tellurium, which constitutes the only case of similarity among chalcogens.[13] All other chalcogens constitute single classes. Likewise, arsenic and antimony are the only cluster including pnictogens.[14] This lack of vertical similarity for groups of the periodic table indicates differences among elements members of each group. Although it is true that most chalcogens have RH^2, RO^3, and R^2O^6 combinations as stated by Mendeleev (Figure 2),[16,17] the sample of substances used in Leal et al.[14] shows that there are other combinations disturbing this similarity put forward in 1871.[15] On the other hand, the already discussed singularity principle makes oxygen behave differently in comparison with the other chalcogens, combining with other elements in a rather different way as its homologues do. The same argument applies for pnictogens, with nitrogen behaving differently, but still with RH^3 and R^2O^5 combinations, as noted by Mendeleev (Figure 2).[16,17]

Other clusters of similar elements are the trio of vanadium, niobium and tantalum, today labeled as group 5 and recognized by Mendeleev as a set of elements having relations RH^3 and R^2O^5.[16,17] Interestingly, the quartet of ferrous metals: iron, cobalt, nickel, and palladium, which are members of the group VIII for Mendeleev[16,17] and the old IUPAC group numbering, or VIIIB in the CAS numbering, forms a cluster.[15] This cluster indicates that these elements have indeed commonalities in terms of the compounds they form, for example RO^4 and R^2O^8.[16-17] In the current group numbering of the periodic table, group VIII corresponds to groups 8 to 10, which include nine elements. The results of Leal et al.[14] actually show that resemblances among these elements are not only restricted to iron, cobalt, and nickel: the trio ruthenium, osmium, and platinum is another case.[16] By considering larger clusters, it is found that ruthenium, osmium, and platinum also have certain resemblance with molybdenum and tungsten.

Interestingly, the pair of similar elements rhodium and iridium, traditionally considered as part of platinum metals,[17] do not appear closely related to the other platinum homologues as usually stated but loosely connected to some lanthanoids and actinoids.

Titanium, zirconium and hafnium, forming group 4 of the current periodic system, constitute a cluster of similar elements, which holds similarity ties with the actinoids thorium and uranium. These transition metal-actinoid resemblances were noted by Seaborg as early as 1945[20] and are based on similarity of combination with other elements where the +4 oxidation state of the metal is the commonality.[18]

The resemblance of transition metals zirconium and hafnium was explained by Goldschmidt through the *lanthanoid contraction*, which is currently understood as the spatial shrinking of lanthanoid atoms as a consequence of the filling of 4*f* shells that contracts 5*p* and 6*s* shells. This contraction makes that Zr^{4+} and Hf^{4+} have roughly the same ionic radii when six-coordinated.[22-24]

As we remarked in our previous work[15], even if the zirconium and hafnium resemblance is known, in some theoretical communities, it is considered an exception caused by "anomalous cancellation of relativistic effects" for elements of the 5th- and 6th-rows of the system.[24,25] In the study by Leal et al. mentioned earlier,[14] it was found that out of the 17 possible pairs of 5th- and 6th-row elements that belong to a group, there are five other pairs sharing similarities: niobium and tantalum; molybdenum and tungsten; technetium and rhenium; ruthenium and osmium; and, finally, rhodium and indium. The first two couples here listed were discussed by Huheey and Huheey on the basis of the very close radii for 5th- and 6th-row species.[23] This resemblance was also discussed in terms of similar oxidation states.[26]

Our work uncovered a cluster of elements belonging in group 13, but which excludes boron. Here, gallium and indium are the most similar elements, which then have resemblance relations with aluminum and finally with thallium. Interestingly, this quartet turns out to be similar to gold and to a lesser extent to the couple of coinage metals cooper and silver.

So far, we have discussed clusters that are only a few elements in length, but there are also larger clusters corresponding to elements that are very similar in terms of the compositions they form. These are the lanthanoids and actinoids. It was found that lanthanoids are more similar among themselves than actinoids. This is caused by a dominant +3 oxidation state, which has been explained on electronic grounds.[15]

Remarkably, rare earths constitute a large cluster of similar elements that groups together scandium and

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[13] Group 16 of the conventional periodic table.

[14] Group 15 of the conventional periodic table.

[15] In reference 13 we found that another commonality for chalcogens is XNH_5, being X a chalcogen.

[16] According to Rayner-Canham, ruthenium and osmium become similar as each forms compounds where the +8 oxidation state is favored. The commonality of these two elements with platinum stems mainly from compounds where the +4 oxidation state of the metal is present. Details in reference 19.

[17] By platinum metals is understood: ruthenium, osmium, rhodium, iridium, palladium, and platinum.

[18] Schwarz recently discussed the similarity of early actinoids with some transition metals of the 6th-row of the periodic system (details in reference 21).

yttrium and is relevant to an ongoing IUPAC discussion about the elements that should be recommended as belonging to group 3 of the periodic system.[27] Part of the question is whether scandium and yttrium should be grouped together with lanthanum or with lutetium. The results here discussed show that lanthanum should be placed in group 3 as the element holds similarities with 11 lanthanoids and scandium and yttrium. In contrast, lutetium is more akin to lanthanoids and not so much to scandium and yttrium.[14,15]

In contrast with the strong similarities among lanthanoids, actinoids are tied by a more diverse repertoire of combinations because of a more ample set of available oxidation states that vary from +2 to +6. This has been explained on quantum chemical grounds and is known as the actinoid contraction, which is more irregular than the lanthanoid contraction.[21,26]

Resemblances between transition metals and *f*-elements are not specific to lanthanoids. Actinoids also keep some of these similarity ties, for example with zirconium, hafnium, technetium and rhenium. In particular, uranium is similar to titanium, zirconium and hafnium (group 4) and also to thorium. Similarities of these sorts have been reported by Rayner-Canham and studied by Schwarz and Rich.[18,28]

An actinoid worth mentioning is plutonium, which holds similarities with other actinoids[19] along with lanthanoids terbium and praseodymium. It has been argued that plutonium particularities stem from its peculiar electronic properties resulting from the changing roles of the 5*f* orbitals, which, for example make it equilibrate four oxidation states in solution, something not reported for any other chemical element.[31]

MENDELEEV RETRIEVED – AND MUCH MORE

We have underlined the central role of compounds as providers of order and similarity relationships for the elements in Mendeleev's approach to the periodic system. Using this argument, we analyzed the results of chemical similarity of chemical elements through a sample of their known binary compounds in the early years of the 21st century. The results show that several of the well-known similarities of chemical elements are recovered through this method based on the composition of compounds.

Regarding the similarities obtained, and contrary to the general message of current textbooks,[30] *resemblances are not always vertical on the periodic table*. Besides the well-known vertical similarities of the alkali metals, halogens, aluminum-group and copper-group, horizontal resemblances were detected such as those of 4th-row platinum metals, lanthanoids, actinoids. To which mixed similarities can be added, e.g. lanthanoids and scandium and yttrium (rare earths); and actinoids with some transition metals. Interestingly, Mendeleev had noted as early as 1869 that "in certain parts of the system the similarity between members of the horizontal rows will have to be considered, but in other parts, the similarity between members of the vertical columns."[31] Hence, chemically speaking, similar elements are close to each other on the table but vertical proximity is not the only and most relevant similarity scheme.

The results here discussed agree with the classification of elements presented in specialized chemical books such as the classic *Chemistry of the Elements*,[32] where the classification is the basis for the distribution of the material presented in the book. It is worth noting that the same pedagogical aim rooted on a chemical system was sought for by Meyer and Mendeleev when writing their respective chemistry textbooks.[4] This presentation of chemical knowledge is therefore expected from books rooted in chemical information, which contrasts with the current simplistic approaches of introductory chemistry textbooks, based on electronic resemblance of free atoms. We have also shown how quantum chemistry concepts can be used to make sense of the similarity results obtained through compounds.

It has been claimed that the motivation for developing a periodic system was to make sense of the large amount of information about compounds and their reactions that had been gathered by mid 19th century.[4,13] However, the exponential growth of chemical substances made it difficult for 19th century chemists to assess similarities through all known compounds, even if efforts of gathering chemical information in a systematic fashion had begun during that time as evidenced in the different editions of the famous *Gmelins Handbuch der anorganischen Chemie* and *Beilsteins Handbuch der organischen Chemie*, which by 1869 included more than 11 thousand substances.[13] These handbooks plus the *Patent Chemistry Database* are now available in digital form in *Reaxys*™, a large electronic database that is updated on regular basis from material published in more than 15,000 scientific journals and patents. Another database gathering chemical information is *SciFinder*™. Therefore, the method here presented can be computationally applied to those databases in order to shed light on the similarity structure of the chemical space at a particular historical period of the available chemical space.

19th century approaches to similarity, the growth of

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[19] Curium, berkelium, einstenium, americium, californium, and actinium.

the chemical space, combined with the emerging atomistic ontology at the end of the century and the advent of quantum mechanics at the beginning of the 20th century, led to analyze and assess similarities among chemical elements through resemblances on the energetic distributions of valence shell electrons.[33] This is the root of the current over-emphasized textbook introduction to the periodic system through electronic configurations of free atoms.[34] However, as some authors have remarked,[34,35] these configurations are rather dissimilar to those of the bounded atoms present in compounds, which are the actual relevant species for chemistry.

ELECTRONIC AND COMPOUNDS: TWO APPROACHES TO A SYSTEM OF THE CHEMICAL ELEMENTS

The approach discussed in the current paper therefore constitutes an alternative way to introducing the periodic system to students, with more chemical "flavor" than what has become the traditional electronic approach.[15] "Compound" is the fundamental concept of chemistry that is part of the bulk level by Nelson for describing chemistry.[38] By bulk level, we mean the approach to chemical education based on compounds and chemical reactions, often performed at chemistry laboratories with bulk matter or material that consists of large numbers of atoms, molecules, or ions. We have indeed currently two options to approach the study of the periodic system and its teaching.

The first approach, the *electronic approach*, now largely in use in chemical education and practice, requires possible molecular ensembles as input to calculate properties. However, current quantum chemical approaches are not able to systematically treat chemical species with the same levels of theoretical accuracy to end up with properties that can be compared leading to classifications of elements. This poses an interesting and worthwhile challenge to quantum chemistry which is computationally difficult, for the number of compounds populating the chemical space is extremely large:[20] even the simplest quantum chemical methods would require too much time to finally end up with values for various material properties.

To make matters worse, in teaching, the electronic approach cannot be introduced as here described because the periodic system is normally presented in the first year of chemistry studies, where quantum chemistry concepts are still to be developed and taught. One could, however, approximate the approach using quantum chemical results of isolated atoms in their ground state energy, which brings back the problem of a "fantasy chemistry"[21] far from the chemistry of bonded atoms forming compounds with electronic configurations different from those of isolated atoms.

The second approach to the study of the system and its teaching is the *compound approach*, discussed in this paper, which requires managing the rapidly growing chemical space, currently recorded in electronic databases. Here, obtaining similarity classes of chemical elements requires formulas of the compounds reported and the application of classification algorithms, whose complexity, in general, does not depend on the size of the compounds nor on their number of elements. It is, in this sense, independent from both size and electronic theories, which is its advantage compared to the electronic approach.

In teaching, the compound approach would require knowledge on how to operate on the chemical space, which, as noted by Schummer,[37] requires data analysis techniques to make sense of the information stored in databases. One can hope that sooner or later, chemical databases will include the possibility of running data analysis studies on the cloud in such a way that clicking on "give me the system of elements" button, one can retrieve the shape of the system constructed with the available chemical knowledge.[22]

FUTURE PERSPECTIVES: MAPPING SIMILARITIES AND CREATING CHEMICAL SYSTEMS

For now, a more realistic approach to the systems from the compounds is through random samples of the space, easy to handle in personal computers.[23] Another option is to run projects with enough computational facilities, able to store the complete chemical space at a given time and to process its information. This approach is currently followed in our research group, whose ini-

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[20] Up to March 2019, for example Reaxys reported 31,134,633 chemical species.

[21] Expression taken from Peter Schuster at the Mathematics in Chemistry Meeting (Leipzig 2016), when objecting classification results of chemical elements not meeting well-known similarities.

[22] Actually, the technicalities of the "button" should read "give me the system of elements according to the available chemical space for period *p* (a range of years) using the merging methods *A*, *B*, ..." A very recent instance of how data analysis techniques applied to chemical information are making their path in current chemistry is the publication of the first chemistry book written entirely by a machine (reference 38). It contains a survey on lithium-ion batteries based on 150 papers published between 2016 and 2018.

[23] A similar approach was followed by Schummer when analyzing the growth of chemical compounds at the end of the 1990s. Details in reference 10.

tial results have analyzed the temporal evolution of the growth of the chemical space since 1800 up to 2015. A third option to apply the compound approach is through classification of the compounds of the space in such a manner that one can select representative compounds of the classes to run similarity studies. This approach requires further research on the chemical space and on its mathematics. Further work to develop appropriate tools in this direction is currently carried out in our research group.

Even if we are advocating for a more data-driven approach to the system of elements through their compounds, it is not free of subtleties. It brings to the surface another fundamental question of chemistry. What is a chemical compound? Strikingly, as noted by several authors,[39,40] even its fundamental role in the edifice of chemistry, there is no consensus on what this concept is.

At first glance, it looks like the compound approach to chemical similarity here discussed cannot stand the test of time, for it relies on compounds, which are especially scarce for the heavy elements. Moreover, for these elements the few compounds that are obtained are synthesized in a one-atom-at-a-time fashion, which is different from the bulk process of the traditional chemistry.[15,41] This sparks not only a clash of chemical traditions, but also the mixture of two different ontological levels for types of compounds. By contrast, the computational methods that operate on chemical databases overcome these problems, for it is actually based, beyond compounds, on their mathematical generality, i.e. their composition and stoichiometry, not on their mode of existence or acquisition. Both composition and stoichiometry can be extracted from either bulk or atomic aggregate compounds; it does not matter whether the substances have been synthetized through wet-lab techniques, or in a one-atom-at-a-time fashion, or even estimated through quantum chemical approaches.[42]

We have shown that a sample of the current chemical space is the natural source of information about similarity among chemical elements. These similarities, when combined with the traditional order of elements by atomic number, provide what we see as the current structure of the periodic system. This methodology is nothing else than Mendeleev's methodology applied to the current chemical space, now assisted by computational tools of data analysis. Applying the same pedagogical motivation that was the hallmark of Mendeleev has produced results that ought to be introduced in contemporary chemistry classrooms together with the electronic understanding of elements in order to bring chemistry back into the periodic system.

APPENDICES

Appendix 1: Similarity calculation

If N_x and N_y are the neighborhoods of elements x and y, respectively; the similarity $s(x, y)$ between x and y is calculated as $s(x, y) = |N_x \cap N_y|/|N_x \cup N_y|$, where $|X|$ represents the number of elements in the set X. Thus, $0 \leq s(x, y) \leq 1$ and values close to one indicate similar elements, whereas those close to zero, very dissimilar elements.

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