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Editorial

Setting the Table: A Retrospective and Prospective of the Periodic Table of the Elements

Mary Virginia Orna[1], Marco Fontani[2]

[1] *ChemSource, Inc., 39 Willow Drive, New Rochelle, NY 10805, USA*
[2] *Dipartimento di Chimica "Ugo Schiff", Università degli Studi di Firenze, via della Lastruccia, 13 Sesto Fiorentino (FI) Italy*
E-mail: maryvirginiaorna@gmail.com, marco.fontani@unifi.it

Abstract. The major theme of this special issue volume is "The History of The Periodic Table, the Discovery of the Elements, and of the Materials that Changed the Course of History: The Development of the Periodic System and Its Consequences." After a brief chronological retrospective on the development of the periodic table, each paper contributed to this volume will be summarized, with some editorial comments.

Keywords. Ordering Elements, Periodic Table, History, Understanding Chemistry, Mendeleev Sesquicentennial.

INTRODUCTION

This year we celebrate the 150th anniversary of the periodic system (1869-2019), indisputably "one of the most significant achievements in science, capturing the essence not only of chemistry, but also of physics and biology;[1] ...[the] table it gave birth to hangs in every chemistry classroom in the world and is one of the field's most recognizable symbols. But the solid squares and familiar patterns of today's table mask one of its fundamental characteristics: 'the' periodic table does not exist"[2] and when 'the' table really came into being is a matter of debate. Some would place its beginnings in 1860 at the Karlsruhe Congress, where some 140 European scientists from 11 European countries and Mexico gathered to debate the chaos surrounding fundamental definitions and measurements in chemistry.[3] This was probably the most inconsequential conference ever held in the sense that very little was actually resolved on site. On the last day of the conference, the Italian chemist, Stanislao Cannizzaro (1826-1910) of the University of Genoa, described his teaching method regarding the importance of atomic weight. Thanks to one of his colleagues, the conferees went home with a reprint of Cannizzaro's paper published two years earlier in the Italian chemical journal, *Il Nuovo Cimento*, in 1858.[4] The paper stressed the importance of Avogadro's hypothesis which, taken to its logical conclusion, was critical in determining the atomic weights of the elements.[5] By their own admissions, it was this document that inspired the creation of Dmitri Mendeleev's (1834-1907) and Julius Lothar Meyer's (1830-1895) periodic tables.[6] But realizing that we stand on the shoulders of the giants of the past, we cannot forget that it was Antoine Laurent Lavoisier (1743-1794) who, toward the end of the 18th century, published the first credible list of elements upon which all future chemical endeavor was based.[7] From there, it was a matter of intellectual stepping stones that led us to the creation of the periodic table – a perfect illustration of how science makes progress.[8]

PATHWAY TO THE PERIODIC TABLE

Departing from Lavoisier, the first such stepping stone was John Dalton's (1766-1844) revival of the Greek concept of atom in 1805, taking it a step beyond by quantifying relative atomic weights based on hydrogen with a weight of one. What follows is elucidated in much greater detail in Eric Scerri's very helpful paper, "The Discovery of the Periodic Table as a Case of Simultaneous Discovery".[9] In 1829, Johann Döbereiner (1780-1849) discerned a relationship among "triads" of elements in which the central member's atomic weight was the average of those of the other two. He also discerned similarities in their chemical and physical properties, but not all of the known elements fit into his groupings.[10]

A German chemist, Leopold Gmelin (1788-1853), chemist and son of the prominent chemist Johann Friedrich Gmelin (1748-1804), professor at the University of Heidelberg, among other things, worked on the elements' classification. In 1843 he established the basis for expanding Döbereiner's classification system.[11] In addition to those of Julius Quaglio (1833-1899) and Heinrich Adolf Baumhauer (1848-1926), his table is believed to be one of the earliest precursors to the periodic table.[12]

According to Eric Scerri,[13] among Mendeleev's competitors "there was a Danish chemist and mineralogist Gustavus Hinrichs who fled to the United States when he was a young man. He set up a very interesting and rather original periodic system which was arranged like spokes of a bicycle". Hinrichs stated his ideas as early as 1855 and published it in his book *Programme der Atommechanik* in 1867.

In 1862, shortly after the Karlsruhe Congress, geologist Alexandre-Émile Béguyer de Chancourtois (1820-1886) proposed classifying the elements on a cylindrical three-dimensional form arranged in order of Cannizzaro's atomic weights. His resulting "*vis tellurique*" clearly showed periodic trends in the elements.[14] In 1864, William Odling (1829-1921), an attendee of the Karlsruhe Congress and a strong proponent of Cannizzaro's view, published a table containing 57 elements and noted proportional numbers of the elements as seen in successive rows.[15] We can reckon that Béguyer de Chancourtois' and Odling's contributions were giant steps along the way to the development of the periodic table and the latter occurred almost simultaneously with John Alexander Reina Newlands'(1837-1898)[16,17] promulgation of his "law of octaves" in which he arranged the known elements in order of atomic weight, assigned to each an ordinal number (!), and correctly predicted the existence of the then-unknown element germanium. This was a major advance, especially the almost prescient divination of the number 8 before any hint of the existence of electrons or electronic configuration.[18] But we are not there yet.

In 1862, Julius Lothar Meyer published a table containing 27 elements. He classified the elements into six chemical families according to their valences – a first-time conceptual advance in arranging the elements according to their combining power. He published an updated table containing 50 elements two years later, and also predicted the possibility of yet undiscovered elements, but gave no details. Meyer's evolution of thought was brought to a head by his 1870 publication in Liebig's *Annalen*[19] in which he plotted the molar volumes of the elements as a function of atomic weight that clearly showed periodicity. However, since Dmitri Mendeleev had published his table in 1869, a long drawn-out priority dispute arose from which Mendeleev eventually arose the victor – some say because of his longevity: he outlived Meyer by twelve years. Both scientists were honored for their mutual "discovery of the periodic relations of the atomic weights" with the Royal Society of London's Davy Medal in 1882.

MENDELEEV'S DISCOVERY

So, who really discovered the periodic table? The question seems moot since the IYPT was promulgated for 2019, the 150th anniversary of Mendeleev's publication, not Meyer's nor anyone else's. Our own opinion would be to answer "all of the above." We all stand on each other's shoulders. Our ideas come from somewhere and someone else. Mendeleev was indebted to those who went before, most notably Cannizzaro, but also those others who stepped into the roiling sea of elemental chaos and attempted to put some order into it.

The standard version for Mendeleev's discovery reads something like this: on a single day, February 17, 1869 (according to the Julian calendar then in use in Russia), he produced his first variant, which he called an attempt at a system of elements based on their atomic weights and chemical similarity, written on the back of a letter received from a friend. From there he proceeded to two incomplete rough drafts, arranging the elements horizontally so that those closest in atomic weight would fall under one another in the same column. His methodology was to make a card for each of the 63 then-known elements, including its symbol and chief properties, and then arrange the cards by playing a "game" of "chemical solitaire" that led to the full draft table of the elements.[20] Igor Dmitriev, Director of the Mendeleev Museum and Archives at Saint Petersburg State University, takes issue with this version. He claims that Mendeleev discovered the periodic law in the process of writing his textbook, *Principles*, by following a non-linear, complicated, and difficult pathway that occurred in stages involving an enormous amount of work and the reconciliation of often incorrect and contradictory information. In his thinking, Mendeleev denied the existence of sharp boundaries, which almost forced him to construct an initial arrangement of elements that contained three major divisions, or structural blocks, arranged from left to right:

Typical metals	Intermediate elements "with a less sharp chemical character"	Typical non-metals

Working with at least five variants of the above structure, Mendeleev was able to confirm in his own mind his two major hypotheses: the causal dependency of the elements' properties on their atomic weights, and the periodic nature of this dependence. It was on the basis of these two fundamental concepts that he drew up the table we are familiar with today, and that he allowed room for yet-undiscovered elements whose properties he uncannily predicted[21] (Figure 1). Note the question marks for elements that would be expected to have atomic weights of 45, 68, and 70. According to Dmitriev, his table did not spring full blown "from the head of Zeus" all in one day.[22]

So, one hundred and fifty years later, we are still struggling with "the" table – or some variant of it, of which there are hundreds. Although the typical classroom-style table has become an icon, with its 18-column main body and two rows of f-block elements arranged in order of increasing atomic number, it does not satisfy the demands placed on it by the development of quantum mechanics and atomic physics. Now we know that one of Mendeleev's principles, that of the causal relationship of the elements to atomic weight, is not the logic that dictates the arrangement. There is also the challenge of reconciling an order based on chemical properties vs. an order based on electron configuration.

A TABLE FOR EVERYONE

As a result of these problems, there is no one standard periodic table. Some chemists prefer a table based strictly on adherence to atomic number as the organizing principle, leading naturally to a 32-column arrangement, favored by Eric Scerri.[23] Another 32-column table, the so-called left step table, devised by Charles Janet (1849-1932) in 1928, based strictly on atomic orbital and electron-filling order, is getting more attention these days.[24] Janet's table follows the Madelung Rule, which Janet intuited before Erwin Madelung (1881-1972) ever even published it! Some scientists think it may be a solution to the f-block-Group 3 dispute.[25,26] For futurists, the 172-element table devised by University of Helsinki theoretical chemist Pekka Pyykkö, is based strictly on calculated electron configurations, effectively bypassing the current placement questions.[27] Carnegie Mellon chemist Paul Karol takes another tack when viewing his crystal ball: he bases his predictions about future synthesis, measurement, and determination of chemical properties of new elements on qualitative, rather than theoretical, considerations.[28]

Consensus has it that there are enough periodic tables to go around for everyone. We can all have our own favorite table. As for us, what works best is best; what is comfortable, like a pair of old slippers, is the favorite.

			Ti = 50	Zr = 90	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104,4	Pt = 197,4
			Fe = 56	Ru = 104,4	Ir = 198
			Ni = Co = 59	Pd = 106,6	Os = 199
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	J = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

Figure 1. Mendeleev's 1869 Table as published in the *Russian Journal of Chemistry*, **1869**, *1*, 60 and in the *Zeitschrift für Chemie*, **1869**, *12*, 405-406.

THIS SPECIAL ISSUE

Here is a brief glimpse of the delightful and informative essays that make up this special issue.

Initially, John Emsley takes up the theme of the volume in the title of his paper, "The Development of the Periodic System and Its Consequences." Of the many hundreds of forms of the periodic table that have been proposed, one has come to the forefront: that approved by the International Union of Pure and Applied Chemistry (IUPAC). In his lead-off paper, The Development of the Periodic Table and its Consequences, Emsley traces the 250-year old story of how chemists arrived at it in the first place.

Next, father and son team of Jürgen Heinrich and Alexander Maar discuss the periodic table from the standpoint of its universality in many different senses: geographical, historical, pedagogical and philosophical, as well as what we deem "universal" in virtually every field of human endeavor, from poetry to pop culture to science fiction.

Although the periodic table as we know it had its genesis in the latter half of the 19th century after many tentative "baby steps" along the way toward the concept of the elemental universe as an ordered one, Professor Ferdinand Abbri puts his finger on the driving force for order: the feverish discovery of elements in Scandinavia over the course of the 18th century. The figure of Jöns Jacob Berzelius dominates these efforts through his own vision and classification of substances, influencing the course of scientific thinking throughout the first half of the 19th century.

Orna and Fontani in "Mendeleev's Family," point out that Dmitri Mendeleev himself now occupies a well-deserved place within the periodic system under the title of "mendelevium," element 101, and that, by this attribution, he belongs to a special "family," the actinides. How this family was uncovered, grew, and developed is the topic of their essay.

To be credited with the discovery of an element is a singular honor awarded to only a chosen few. But "discovery" is not a simple issue in terms of priority recognition, neither in the distant past nor the recent present. Professor Helge Kragh explores some of the controversies arising over priority disputes with respect to their reasons and their scientific implications.

Carl Auer von Welsbach (1858-1929) was a world-famous entrepreneur, discoverer, inventor and experimental chemist. In this issue, his work in the field of the rare earths and related elements is described using source material from the archives of the Auer von Welsbach Museum (founded in 1998) heretofore not accessible to the general public. From 1880 to 1882, Auer von Welsbach studied with Robert Bunsen in Heidelberg, specializing in the field of spectral analysis. Using this method, he discovered praseodymium and neodymium in 1885 and ytterbium and lutetium in 1905. Gerd Löffler shows how his three great discoveries in addition – the incandescent mantle, the metal filament lamp, and pyrophoric flint – were the basis for his ongoing exploration of the chemical and physical properties of the lanthanides and actinides.

Since one of the great unifying principles of all science is embodied in the periodic table, an examination of the many extant written documents leading up to its creation and improvement is a rich and rewarding activity. Professor Gregory Girolami reviews and assesses the value of some of these works, spanning a time frame from Boyle and Lavoisier to just before Mendeleev.

The chapter by Seth Rasmussen, "A Brief History of Early Silica Glass: Impact on Science and Society," follows the evolution of silica glass from the wide variety of glass vessels developed in the Roman period to improvements in glass quality through new composition formulae and production techniques that reached their culmination in the borosilicate glasses of the 20th century. The virtually perfect glass for use as chemical glassware would not have been possible without the expansion of our knowledge of new elements via the periodic system.

In 1907, four years after Dmitri Mendeleev's death, St. Petersburg State University, where he lived and worked for forty years, set up the Mendeleev Museum and Archives. Mendeleev's own personal effects form the basis of this remarkable museum, which is well worth a visit. "Mendeleev at Home" describes the contents of the museum, embellished by personal photographs taken during a visit in 2007. This short contribution at the end of this special issue aims to convey the atmosphere in which the most iconic of scientific icons was conceived and developed.

CONCLUSION

We can conclude in no better fashion than to quote the inimitable Peter Atkins for his view of the unique character of the periodic table. "The periodic table is arguably the most important concept in chemistry, both in principle and in practice. It is the everyday support for students, it suggests new avenues of research to professionals, and it provides a succinct organization of the whole of chemistry. It is a remarkable demonstration of the fact that the chemical elements are not a random clutter of entities but instead display trends and lie together in families. An awareness of the periodic table is essential to anyone who wishes to disentangle the world and see how it is built up from the fundamental building blocks of chemistry, the chemical elements… for it is a part of scientific culture."[29] And no matter how many areas of chemistry the periodic table has influenced, we can never forget that it was a chemist who provided physicists with the key to unlock the structure of the atom, to perceive its essentially orderly arrangement both physically and mathematically, and to literally give birth to the field of atomic physics. Given the achievements of the past 150 years, we cannot even conceive of the developments to be made over the next 150 years using the periodic table as a tool and guide.

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