Various forms of the periodic table including the left-step table, the regularization of atomic number triads and first-member anomalies

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Abstract

The relative virtues of 8- and 18-column periodic tables are discussed, followed by a brief mention of a 32-column table. Next, the left-step periodic table, as first introduced by Janet, is presented, as are the various attractive features of this representation. The advantages include what is termed here as the regularization of atomic number triads and a better rationalization of first-member anomalies. The distinction between simple substance and element is also explained as is the significance of this issue to the left-step table. Finally, I respond to some recent criticisms of previous work that I have published on atomic number triads of elements. It is becoming increasingly acknowledged that the discovery of the periodic table took place at the hands of at least six individuals working independently in different parts of the world (Scerri, *A Tale of Seven Scientists*, Oxford University Press, New York, 2016). In the intervening 150 or so years since the most well known of these tables were published, by Dmitri Mendeleev, at least 1000 periodic systems have appeared either in print form (Van Spronsen, *The Periodic System of Chemical Elements. A History of the First Hundred Years*, Elsevier, New York, 1969; Mazurs, *Graphic Representations of the Periodic System during One Hundred Years*, University Alabama Press, Alabama, 1974) or more recently on the Internet (Leach, https://www.meta-synthesis.com/webbook/35_pt/pt_database.php).

There is a huge variety of systems in terms of how chemical periodicity can be represented, be it in tabular form, in cyclic or circular shapes, as a series of interconnected levels or in 3-D formats, to name just a few of the possible variations. The present article will be concerned with tabular forms which have tended to predominate, especially in the context of chemical education.

Variation in tabular forms of the periodic table

Strictly speaking a periodic table, as opposed to a periodic system in general, is displayed in tabular or 2-D form. Such tables have undergone a gradual evolution since the publication of the earliest tables of pioneering discoverers such as John Newlands, Julius Lothar Meyer and Dmitri Mendeleev, from Britain, Germany and Russia, respectively, who generally presented their systems in the form of eight columns or groups.[1]

As many historians of science and chemical educators realize, an 8-column table actually provides some advantages over what has become the conventional or 18-column table (Fig. 1), which is encountered in almost all textbooks and wall charts [5, 6]. The elements in the same group of an eight-column table, such as Mendeleev's table of 1871 as shown in Fig. 2, all share the same maximum valency or combining power such as is the case with carbon, titanium, silicon, zinc, tin, etc. Each group of this periodic table is further divided into two subgroups, A and B. The properties

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[1] This was not exclusively the case, however. For example, both Mendeleev and Meyer published periodic tables of an extended format such as Mendeleev's 17-column table of 1879 [7], and Lothar Meyer's 15-group table of 1868 [8]. It should also be remembered that the group of noble gas elements had not been discovered at this time, which would explain why Mendeleev's extended table consisted of 17 rather than 18 columns.

Group #

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Fig. 1 Conventional 18-column periodic table. This version, with a 15 element wide f-block is sometimes designated as the IUPAC table

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	—	— — —

Fig. 2 Mendeleev's eight-column or short-form periodic table of 1871 [9]. As the reader may note, the elements Cu, Ag and Au are each placed into two groups in this early periodic table by Mendeleev, a feature that he later corrected

Fig. 3 An element line based on increasing order of atomic weights of the elements, from hydrogen to iron, known in the nineteenth century, before the noble gases had been discovered

of elements within a subgroup resemble each other more markedly, but they differ from those of the elements of the other subgroups. For example, lithium and potassium, etc., of subgroup IA have close resemblance of properties, but they have hardly any resemblance to the coinage metals (Cu, Ag and Au) of subgroup IB. Furthermore, from a modern perspective, the group number for the A subgroups in an eight-column table, which incidentally is still used in some countries such as Russia, corresponds directly to the number of outer electrons that atoms of the element in question possess. In an 18-column table, the International Union of Pure and Applied Chemistry (IUPAC)-approved group number does not immediately correspond to the number of outer electrons, except in the case of groups 1 and 2, among the 18 groups or columns.[2]

Nevertheless, an 18-column table reflects the greater similarity between certain elements that occurs within a single group of the 8-column table. For example, the elements vanadium, niobium and tantalum have more in common with each other in terms of chemical and physical properties than they do with the elements nitrogen, phosphorus and arsenic.

Another way to appreciate the move from an eight- to an eighteen-column table is the following. Chemical periodicity essentially consisted of first arranging the elements in a one-dimensional order or sequence on the basis of increasing atomic weight or, in modern terms, increasing atomic number, in what is sometimes termed an element line (Fig. 3). Let us assume that we are working with atomic weights, in the era when the noble gases had not yet been discovered.[3] Here then is what the element line would have looked like.[4]

Fig. 4 A short-form, or seven-column, periodic table of all elements from hydrogen up to and including manganese as it would have looked in the late nineteenth century

This one-dimensional sequence could then be converted into a 2-D, or tabular, form by cutting the line after regular intervals and pasting each strip obtained underneath each other, to reflect chemical similarities within vertical columns. One possible result of such a move is the beginning of an eight-column table as shown in Fig. 4.

The next element in this sequence, following manganese, is iron. However, it would have been incorrect to place iron below H, Li, Na and K since it shows no resemblance whatsoever to these elements.[5] Mendeleev solved this problem by creating an entirely new and miscellaneous eighth group into which he placed iron and the three subsequent elements of Co, Ni and Cu, as shown in Fig. 2.[6]

On moving to a 17-column table, as Mendeleev did in some of his published versions, or an 18-column table as we are obliged to do in modern terms, we can remove the need for this rather anomalous group VIII with its four elements per each space in some cases. These elements, which constituted the original 'transition elements', since they represented an interruption to periodicity, are placed very

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[2] Of course, this is more a consequence of the IUPAC style of numbering the groups of the periodic table which has now been generally adopted than the mere fact that there are 18 columns in a medium-long-form table. The older European and American systems for labelling groups also featured 18 groups, but consisted of a number from I to VIII followed by a letter A or B. The precise assignment was carried out differently in the European and American systems however, such that an element such as Ge would be said to be in group IVA in the US system and in group IVB in the European one.

[3] I am also assuming that the element scandium had already been discovered for the purposes of this reconstruction.

[4] The analogous argument can be made using atomic number to order the elements and with the inclusion of the noble gas elements. The outcome is the same in that certain elements need to be excluded from the main body of the table to maintain periodicity among the remaining elements.

[5] Similar issues might be seen to arise for earlier elements such as manganese being placed in the same group as fluorine and chlorine, although there are some genuine similarities between these elements. For example, chlorine and manganese form the analogous compounds of $KClO_4$ and $KMnO_4$, respectively.

[6] I am not claiming that Mendeleev actually took this path in arriving at his periodic table. What I am carrying out here is an ahistorical reconstruction but one that I believe to be helpful in the context of this article. Readers interested in more historically accurate accounts of Mendeleev's path to the periodic table can consult Bensaude-Vincent [10], Gordin [11] and Dimitriev [12].

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54

Cs 55	Ba 56	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	Nh 113	Fl 114	Mc 115	Lv 116	Ts 117	Og 118

Fig. 5. Thirty-two-column or long-form periodic table

successfully as new groups in the modern table and in the current 18-column periodic table (Fig. 1).

Although the 18-column table is now very deeply entrenched in the popular imagination, as well as in chemical education, as being 'the' periodic table, it too seems to relegate certain elements, namely the f-block elements, instead of integrating all the elements together fully. This last issue can easily be resolved by expanding the periodic table further to form a 32-column periodic table in which every single element appears in order of increasing atomic number and no elements are separated or excluded from the main body of the periodic table (Fig. 5).

I put it to the reader that this form of the periodic table is intellectually and scientifically more satisfactory than our traditional 18-column table and that it would represent a clearer way to teach the periodic table to students of chemistry and other allied sciences. The only drawback would appear to be a pragmatic one, in that the table is almost twice the width of the 18-column version and that each element space and element symbol would have to be about half the size of how it appears in the 18-column table in order for it to fit into the same space.[7]

The left-step periodic table

Having argued for the superiority of the 32-column periodic table as compared with the 18-column table, I now turn to another 32-column table which shows a couple of major variations. This is the left-step table that was first proposed by the French engineer Charles Janet as early as 1930, and which is being increasingly discussed as a candidate for being the optimal periodic table, or perhaps the most fundamental periodic table [13–21].

The left-step table is obtained from the 32-column table shown in Fig. 5 by following two simple steps. First of all, the element helium is moved to the head of group 2 of the table on the basis of its having two electrons and therefore being analogous to the elements of group 2, all of which possess two outer-shell electrons in their atoms.

Secondly, the entire s-block is disconnected from the left edge of the table and moved to form its right-hand edge, to produce the table shown in Fig. 6.

This form of the table has a number of advantages from a more fundamental or physics-oriented point of view. First of all, as already mentioned in terms of its electronic structure, helium can be regarded as an s-block element. The left-step table simply emphasizes this point by actually placing helium in group 2 of the table. It would be possible to just place He in group 2 of the table. The left-step table goes further by relocating the entire s-block to the right side of the table.

Secondly, this format shows considerably more regularity than the conventional 32-column table of Fig. 5. This greater regularity is immediately obvious from the shape of the left-step table. Moreover, the left-step table removes what may appear to be an anomaly in the conventional 32-column table, namely the fact that, whereas all period lengths are repeated in the form 8, 8, 18, 18, 32, 32 in the numbers of their respective elements, the first very short period of

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[7] One can of course continue this process of expanding the periodic table. In fact, if, or perhaps when, element 121 is synthesized, it will become necessary to expand even the 32-column table to accommodate the first of the elements whose atoms contain a g-electron at least in a formal sense. Accurate predictions suggest otherwise in that the first element with a g-electron is expected to be element 125 according to some estimates [22].

Charles Janet's Left-Step Periodic Table

f															d										p						s	

																															1 H	2 He
																														3 Li	4 Be
																				5 B	6 C	7 N	8 O	9 F	10 Ne	11 Na	12 Mg
																				13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	19 K	20 Ca
													21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	37 Rb	38 Sr
													39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	55 Cs	56 Ba
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Rc	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	87 Fr	88 Ra
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og	119	120

Fig. 6 Left-step periodic table of Charles Janet, who prepared various different periodic tables, although he is now remembered for this version. Table drawn by Jeries Rihani and reproduced with his permission

two elements does not repeat. Meanwhile, the left-step table shows that all period lengths, including the very short two-element period, are repeated.

Perhaps most importantly, the left-step table more faithfully represents the order of electron occupation as summarized in the Aufbau scheme and more particularly in the Madelung or $n+l$ rule whereby orbitals are occupied in the order of increasing values for the sum of their first two quantum numbers n and l as shown in Fig. 7. In the left-step table, each of the diagonal lines in the Madelung diagram represents a distinct period.

Finally, there is an argument in favour of the left-step table that depends again on rendering the periodic table more regular, but now in the sense of regularizing atomic number triads to which I will return shortly after a section explaining the historical development and current status of triads of elements.

Having outlined at least some of the advantages of the left-step table, I now turn to one possible disadvantage depending on one's perspective. From the narrow perspective of placing the greatest emphasis on chemical properties, the placement of helium among the alkaline earth elements appears to be something of a travesty. After all, as many authors including myself have argued, chemistry is not completely reduced to quantum mechanics, and so we are not obliged to accept the notion that electronic structure is the most important criterion for arriving at an optimal periodic table [23].

On the other hand, as I have also stressed in a previous article, we should also not allow the "tyranny of the chemist" to dictate the best form of the periodic table [24]. What is

intended by this expression is that the periodic table is the domain of chemists, because they were the ones who discovered it, and as a result the periodic table should be primarily and fundamentally dictated by chemical, rather than physical, properties. Of course, the table was discovered on the basis of chemical similarities, but this does not necessarily justify the need to continue to anchor all of one's considerations on the dictates of chemical properties, that are clearly not as fundamental as the properties that are concerned with quantum physics.
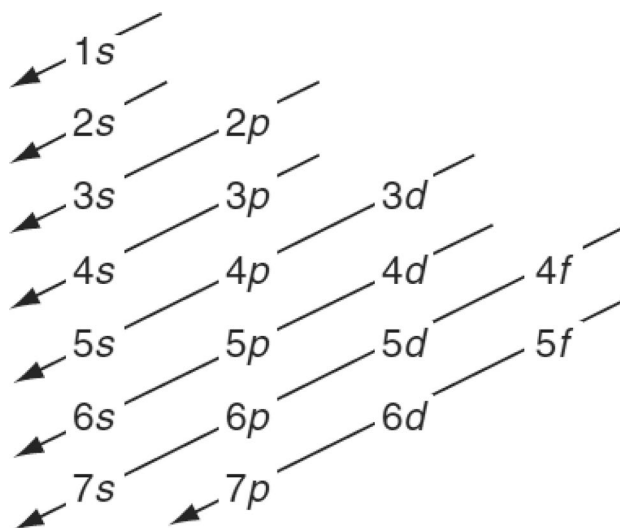

Fig. 7 The Aufbau scheme states that orbitals are filled in order of increasing energy, and Madelung rule gives the order of orbital occupation as following increasing values of $n+l$ quantum numbers

$$S\ (32)$$

$$As\ (75) \qquad Se\ ? \qquad Br\ (80)$$

$$Te\ (127.5)$$

$$(32 + 75 + 80 + 127.5)/4 = 79$$

Fig. 8 Mendeleev's method for calculating the weight of selenium

Triads of elements

A triad of elements consists of a group of three elements, one of which has an atomic weight which is approximately the average of the other two elements. In addition, the same one element shows chemical and physical properties that are approximately intermediate between those of the other two elements. The classic example of a triad consists of lithium, sodium and potassium. Their atomic weights, using the same values that appear on Mendeleev's table of 1871, or Fig. 2, are Li (7), Na (23) and K (39). At this level of accuracy, the atomic weight of sodium appears to be exactly the average of the two flanking elements, although this is the result of using approximate values. At the same time, as is well known, the element sodium shows intermediate reactivity when small pieces of the three metals are placed into a container of water, for example.

The discovery of triads belongs to the German chemist Wolfgang Döbereiner, who published his findings in 1829 [25]. The history of triads of elements has been a somewhat chequered affair. Some chemists pushed the idea to extremes in an attempt to discover numerical patterns to connect the various elements. One such example was Ernst Lenssen, another German chemist, who claimed to have discovered 20 triads and even triads of triads [26]. The approximate nature of triads and their association with numerology in some quarters led to their being criticized by other chemists, including quite notably Dmitri Mendeleev (Fig. 8). Nevertheless, Mendeleev himself appeared to have used the basic idea upon which triads are founded, when he explained how the atomic weight of an element such as selenium, whose value was known at the time, could be calculated [9]. As Mendeleev pointed out, the value predicted by taking the average of these four flanking elements is 79, which

compared rather well with the then known experimental value of 78 for the atomic weight of selenium.

Be that as it may, the more correct ordering criterion for the elements was found to be atomic number rather than atomic weight, following the contributions of Van den Broek and Moseley [27].

Returning to the notion of triads of elements, it emerges that, if we now use atomic numbers, the value of the 'middle element', as it were, is precisely the average of the atomic number of the two flanking elements such as in the case of Li (3), Na (11) and K (19), and it could not be otherwise since atomic number corresponds to the number of protons in the nucleus of any particular atom, which can only take on integral values. Indeed, the philosopher of science Imre Lakatos cited the case of triads as an example of a scientific concept that made a 'come-back' in the sense that, after initially having been refuted, its validity became re-established after the discovery of atomic number [28].

But not all three groups of elements in a single column of the periodic table represent a triad, either using atomic weights or atomic numbers. For example, the elements sodium (11), potassium (19) and rubidium (37) clearly do not form a valid triad. It turns out that every other vertical triad is a valid triad, meaning half of all conceivable triads on the periodic table. The explanation for this outcome is well understood. It is a direct consequence of the phenomenon of period doubling, meaning that the lengths of periods occur in pairs such as 8, 8, 18, 18 and 32, 32. For example, the elements chlorine, bromine and iodine form one of the originally discovered triads. This is the case because the distance or interval between chlorine and bromine consists of 18 elements, as does the interval between bromine and iodine. Atomic number triads are therefore a direct consequence of the phenomenon of period doubling. The only period length that does not appear to occur as a pair is the very first short period of two elements. This anomalous feature is removed in the left-step form of the periodic table.

Atomic number triads and the left-step table

Having rehearsed the topic of triads and, in particular, atomic number triads, we may now return to highlight another advantage in the left-step periodic table as compared with the conventional 32-column periodic table, or for that matter the ubiquitous 18-column table.

For example, valid triads, in the case of the 18-column table, occur when the second and third element in a triad fall into periods having equal lengths, such as the example of chlorine, bromine and iodine. The same is true for all valid triads in all other p-block groups and also those in the d-block and even potential triads involving as yet undiscovered elements in the f-block of the table. However, the

Fig. 9 Atomic number triads in a 32-column periodic table shown as blue, green and brown strips. Whereas triads in the p- and d-blocks involve cases where the second and third elements fall into periods of equal lengths, in the case of the s-block, triads require the first and second elements to be in periods of equal lengths. An example in the p-block of Si, Ge and Sn is highlighted, as is an example from the s-block consisting of Li, Na and K. The boxes that are fully filled represent elements that belong to two triads simultaneously, such as K, Ca or Ar

elements in the s-block of the conventional 18 or 32 column tables appear to be anomalous, in that it is the first and second elements that must fall into periods having equal numbers of elements. For example, the first triad mentioned in the present article, consisting of lithium, sodium and potassium, features the first two members of the triad, lithium and sodium, which belong to periods of eight elements, while potassium, the third member, belongs to a period of 18 elements. Why, one might ask, is the s-block showing such anomalous behaviour when compared with the other three blocks of the table (Fig. 9)?

If we now return to the left-step table, it becomes clear that absolutely all valid triads, in the entire periodic table, occur when the second and third elements fall into periods of equal lengths (Fig. 10). I believe this form of regularization of the triads is a further point in favour of the left-step table as providing the most fundamental table that is available at present. It should be noted that in this instance there is no appeal to physics or the reduction of chemistry to physics but only to the humble notion of triads of elements which have their origins some 50 or so years before the periodic table was even discovered.

Yet a third anomaly in the standard periodic table is also removed on focusing on the left-step table. In the conventional format, shown either as 18 or 32 columns, the first member of each group is not part of an atomic number triad, with the exception of groups 2 and 18. For example, Be, Mg and Ca do form an atomic number triad with the inclusion of the first member of the group, beryllium.

$$(_4Be + {}_{20}Ca)/2 = {}_{12}Mg.$$

Once again, this anomaly disappears in the left-step periodic table as seen in Fig. 6, since beryllium is no longer the first member of group 2. The first three elements in the modified group 2 are now He, Be and Mg, which no longer form a valid triad with the result that group 2 is no longer anomalous in this respect. At the same time, the anomaly

TRIADS

The 2nd and 3rd elements occur in periods of equal length

	f		d		p		s	
							1 H	2 He
							3 Li	4 Be
				5 B	6 C	7 N	8 O	9 F	10 Ne	11 Na	12 Mg
				13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	19 K	20 Ca

21 Sc, 22 Ti, 23 V, 24 Cr, 25 Mn, 26 Fe, 27 Co, 28 Ni, 29 Cu, 30 Zn | 31 Ga, 32 Ge, 33 As, 34 Se, 35 Br, 36 Kr | 37 Rb, 38 Sr

39 Y, 40 Zr, 41 Nb, 42 Mo, 43 Tc, 44 Ru, 45 Rh, 46 Pd, 47 Ag, 48 Cd | 49 In, 50 Sn, 51 Sb, 52 Te, 53 I, 54 Xe | 55 Cs, 56 Ba

57 La, 58 Ce, 59 Pr, 60 Nd, 61 Pm, 62 Sm, 63 Eu, 64 Gd, 65 Tb, 66 Dy, 67 Ho, 68 Er, 69 Tm, 70 Yb | 71 Lu, 72 Hf, 73 Ta, 74 W, 75 Re, 76 Os, 77 Ir, 78 Pt, 79 Au, 80 Hg | 81 Tl, 82 Pb, 83 Bi, 84 Po, 85 At, 86 Rn | 87 Fr, 88 Ra

89 Ac, 90 Th, 91 Pa, 92 U, 93 Np, 94 Pu, 95 Am, 96 Cm, 97 Bk, 98 Cf, 99 Es, 100 Fm, 101 Md, 102 No | 103 Lr, 104 Rf, 105 Db, 106 Sg, 107 Bh, 108 Hs, 109 Mt, 110 Ds, 111 Rg, 112 Cn | 113 Nh, 114 Fl, 115 Mc, 116 Lv, 117 Ts, 118 Og | 119, 120

139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152

189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202

Fig. 10 Atomic number triads on a left-step periodic table. All valid triads occur when the second and third elements are in periods having equal lengths. The s-block triads cease being anomalous. In the f-block, the presumed triads involve elements that have yet to be synthesized. The g-block elements 121–138 inclusive, as well as elements 171–188 inclusive, have been omitted due to space limitations. Table drawn by Jeries Rihani and used with his permission

whereby the noble gases do feature a triad which includes the first member is removed because group 18 now features the first three elements of Ne, Ar and Kr, which does not constitute a triad.

There is even a fourth anomaly which can be successfully removed by appealing to the left-step table. As is well known, the first member of main group elements generally shows anomalous chemical behaviour [29, 30]. For example, beryllium in group 2, boron in group 3 and nitrogen in group 15 all show chemical properties which are rather different from those of their fellow group members.

According to Rayner-Canham, who summarizes some of the causes of this so-called uniqueness principle [31],

- Second-period elements have exceptionally small atomic radii.
- Second-period elements exhibit a maximum of four bonding electrons.
- The non-metallic elements have an enhanced ability to form multiple (π) bonds.

According to Kutzelnigg [32],

The essential difference between the atoms of the first and higher rows is that the cores of the former contain only s-AOs, [s atomic orbitals], whereas the cores of the latter include at least s- and p-AOs [p atomic orbitals]. As a consequence, the s and p valence AOs of first row atoms are localized in roughly the same region of space, while the p valence AOs of higher row atoms are much more extended in space. This has the consequence that for the light main group elements both lone-pair repulsion and iso-valent hybridization play a greater role than for the heavy main group elements. Furthermore, this implies that single bonds between first row elements are weak and multiple bonds are strong, whereas for the second or higher row elements single bonds are strong and multiple bonds weak.

In the left-step table, the first member of group 2 now becomes helium, which is indeed extremely anomalous in comparison with the alkaline earth elements that lie below it. As a result, the typical chemist's objection to placing helium among the alkaline earth elements can be countered by supposing that this represents an extreme case of first-member anomaly. Finally, theoretical analyses of first member anomalies have also been given by Kaupp [33] as well as Wang [30] among others.

Proposal for an enhanced uniqueness effect for the first elements

In this section, I will focus more specifically on the notion that first members of the main groups of the periodic table are not members of triads, regardless of whether one considers atomic weights or atomic numbers.

For example, the 1*s* orbital is very special due to the following points:[8]

i. The 1*s* shell is the only orbital of all (nearly) neutral atoms and molecules that 'sees' an attracting unscreened point centre; the 2*sp* shell 'feels' a slightly screened atomic attraction centre Z-1s^2; the higher shells 3*sp* or 3*d*4*s* or 4*sp*, etc., 'feel' a strongly shielded atomic core.

ii. There is no other orbital energetically close to the 1*s*, so 1*s* is single and is neither easily polarized nor hybridized (such as 2*s*2*p* or 3*d*4*s*, etc.) nor is there any strong 2*s*–2*p* two-electron configuration mixing (that is the big difference, from the quantum-theoretical point of view, of $1s^2$ and $2(sp)^2$). In other words, 1*s* is alone, but for any $n > 1$, the *ns* orbitals are not alone and hybridize.

iii. The overlap of 1*s* is very special: H-1*s* binds to transition metal (TM) atoms with TM-$(n − 1)d,ns$, while most other ligands such as Cl, OH_2, CN, etc., bind with TM-$(n − 1)d$. In contrast to all other atoms, the proton can easily be inserted in the electron density distribution of other atoms or ligands, while all other atoms have occupied core shells, and the Pauli principle causes Pauli repulsion and restrains that interaction.

The proposal for an enhanced uniqueness effect for the elements H and He gains further support from a fact that Bent and also Jensen have stressed in the literature, namely that the anomalous behaviour of the first member of groups decreases as one moves from the s-block to the f-block. Jensen had this to say in an article written 35 years ago [34]:

> While it is true that H is unique relative to other IA elements, this is really a reflection of a systematic variation in the periodic table which shows that the elements in the first row of any new electronic block tend to show abnormalities relative to the elements in later rows of the same block, and that the degree of divergence decreases in the order s-block >> p-block > d-block > f-block.

The 'much greater than sign' following the mention of s-block elements is especially relevant for the proposal of an enhanced uniqueness effect which would further support placing the element He at the top of group 2 rather than its traditional position at the top of the noble gases.

The relationship between quantum mechanics and the periodic table

A more general objection that is sometimes raised against the left-step table is that the periodic table was discovered in the domain of chemistry and consequently that chemists have a right to design a periodic table that serves their concerns. The fact that helium has two electrons in a single shell and therefore seems analogous to the elements in group two, which have two outer-shell electrons, is generally dismissed on the grounds that electronic configurations do not always reflect chemical behaviour [35].

Quantum physics has succeeded in almost completely explaining the periodic table by appealing to first principles.[9] If the time-independent Schrödinger equation is solved for the hydrogen atom, it emerges that three distinct quantum numbers are required to specify each of the solutions. Furthermore, the relationship between the three quantum numbers that characterizes the solutions can also be rigorously derived. To these three quantum numbers one must add a fourth quantum number or spin. On combining the possible values of these four quantum numbers, one can predict that successive electron shells contain 2, 8, 18, 32, etc., electrons.

This outcome is surely not a coincidence but a sign that the periodic table fundamentally reduces to quantum mechanics.[10] If one accepts that this is the case, there should be no undue alarm at the notion of wanting to make the current periodic table more regular as required by the underlying physical theory. Similarly, there should be no concern over the desire to regularize the manner in which atomic number triads appear on the periodic table. Even more elementary perhaps is the wish, on the part of some periodic table scholars, to place helium into the alkaline earth elements because of their analogous electronic configurations (two electrons in He as compared with two outer-shell electrons in the alkaline earth metals).

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[8] I thank Eugen Schwarz for bringing these points to my attention.

[9] In earlier articles, I pointed out the lack of a complete reduction of the periodic table, but as I have also stressed, this does not imply that I am in any way attempting to diminish the current achievements that have been obtained through a reductive approach [41].

[10] See Scerri [42] for a recent account of the extent to which the periodic table reduces to quantum mechanics.

A final word concerning 'elements' and simple substances

Much has been written in recent years by philosophers of chemistry about the distinction between abstract 'elements' and elements in the form of simple substances [36]. Briefly put, the abstract element is a bearer of properties but devoid of any properties, apart from atomic weight which serves to characterize it.[11] Meanwhile, an element as a simple substance is the manifestation of the element that can be extracted, and represents the final stage in the decomposition of any compound. An element as a simple substance can be identified with the manner in which Antoine Lavoisier, the founder of modern chemistry, defined elements, namely as the final stage of chemical decomposition. This often-forgotten distinction was at the heart of Mendeleev's thinking about the periodic table. Furthermore, Mendeleev believed that the periodic table was primarily a classification of abstract elements rather than simple substances [9]. One of the features of abstract elements as discussed by Mendeleev is that these entities have no properties as normally conceived, and are characterized just by their atomic weights, which remain invariant throughout any chemical reactions.

There has been a great deal of debate as to how this notion should be interpreted. Some authors like Paneth [37], who was the person responsible for reviving this question in the philosophy of science, have insisted that one should not attribute a microscopic interpretation to this notion. For example, commenting on an article by the chemist C. Hell, Paneth writes,

> "According to the second definition", the article continues, "the concept of element coincides with that of atom, and serves mainly to designate and individualize the latter more closely"; "the atoms are the true elements of bodies", a statement which is not, in my opinion, correct. The atomic theory can, it is true, contribute enormously to—indeed, may be necessary for—visualizing how the basic substances persist in simple substances and compounds; but the concept of basic substance as such does not in itself contain any idea of atomism.

Some, including Ruthenberg, emphasize the transcendental nature of abstract elements, which are also alluded to by Paneth [38, 39]. The term transcendental is used in the sense of transcendental realism, referring to the alleged unobservability of elements as basic substances. Meanwhile, Hendry has criticized the tendency of some authors to think of this view of elements as being somehow transcendental in the sense of being literally metaphysical, meaning beyond the physical realm [40].

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[11] In modern terms, abstract elements are characterized by their atomic numbers.

In previous writings, I have tended to agree with the Mendeleev–Paneth–Ruthenberg approach, especially when it comes to the question of whether one should adopt a microscopic approach to understanding abstract elements. My reason for doing so was largely because Mendeleev was against atomic theory. But it now occurs to me that this may not be sufficient grounds for retaining the view that elements in the abstract sense should only be interpreted macroscopically. Clearly, Mendeleev held incorrect views on many subjects, including his doubting radioactivity, the existence of the electron, ionization theory, valence theory when it was first proposed, the importance of triads, atomic substructure and so on. In addition, this view would be consistent with the opinion expressed earlier about chemists not having sole custody of the periodic table.

I am therefore changing my mind about my opposition to a microscopic interpretation of abstract or basic elements. Clearly, atoms do not have any properties as such. Atoms of gold are not yellow coloured, nor are they malleable or in possession of any of the usual macroscopic properties that one associates with the element gold. A microscopic view of abstract elements is consistent with the notion that the abstract elements do not have macroscopic properties and avoids the obscure appeal to transcendentalism and what may lie beyond the physical realm. Stated in other words, it is proposed that the quantum–mechanical atom is the scientific concept that most closely corresponds to the philosophical abstract element.

Finally, let me return to the question of the left-step periodic table. If the more fundamental basis for the classification of elements lies with the abstract elements, then it should not matter that helium does not share any macroscopic properties with the alkaline earth elements. Similarly, the elements in group 17 of the periodic table are grouped together because of their atomic properties such as electronic configurations, not because their macroscopic properties are similar since they consist of two gases (F_2 and Cl_2, a liquid Br_2 and a solid I_2). Conversely, the atomic properties of helium and the alkaline earth elements are analogous in that they involve having two electrons in He and two outermost electrons in the alkaline earth metals.

A brief commentary on a recent article on triads

In a recent article, the historian of chemistry, William Jensen, has given a critique of the concept of triads which I will attempt to identify in what is to follow [43]. Jensen launches into a critique of Döbereiner by declaring that, to a modern reader, Döbereiner's article is,

…a mess in that it contains inconsistent data, inconsistent symbolism, and a failure to state its underlying assumptions.

Needless to say, some of this criticism may be justified, but one could comment similarly about many scientific discoveries when they were first conceived [1]. Jensen's dislike for triads seems to overshadow the fact that their discovery can be interpreted, in retrospect, to mark the very first hint of chemical periodicity as I have previously suggested [44]. Whatever inconsistencies Döbereiner may have committed can be forgiven in view of the fact that his triads marked the start of the hugely influential development of the periodic table.

Jensen proceeds to lament the fact that other chemists of that era, including Ernst Lenssen, indulged in what he terms the "triad fad". Having illustrated a high failure rate among Lenssen's proposed triads, Jensen further states that,

> these abysmal results would have been sufficient to consign the triad concept to the dustbin of history, but rather remarkably, in recent years it has once more been revived by two well-known authors on the periodic table (p. 38)

Since I am one of these authors, along with the late Henry Bent, I feel somewhat compelled to respond in order to clarify my own use of triads. First of all, I should stress that, in attempting to search for new triads, it was never my intention to predict which elements may be chemically analogous, as Jensen claims. As I have explained above, I was attempting to correct what I regard as anomalous aspects of the modern periodic table.

Given that the periodic table has been almost completely explained by quantum mechanics, it is perhaps to this theory that one should look for ways to resolve any remaining discrepancies. One can point to important precedents of this kind, such as when physics came to the rescue of the periodic table by providing the criterion of atomic number in place of atomic weight, that chemists had previously been using to order the elements [44].

Jensen also states that it would be circular to use triads to find chemically significant triads. As I implied earlier, I am not aware that I have ever claimed to do so. What Henry Bent and I have claimed, is that a more regular periodic table, which accords better with quantum mechanics, can be obtained while also producing new triads. Of course, I cannot speak more specifically for Bent, but my own purpose for doing so was not to obtain chemically analogous elements, but a by-product of attempting to find a more regular periodic table. In my earlier publications [45], which Jensen cites, I did attempt to solve the long-standing problem of the placement of hydrogen by suggesting that it should be placed into the halogen group. I also pointed out that doing

so would result in the creation of a new triad, namely H, F and Cl.

But this is clearly not a case of using triads to obtain chemically analogous elements as Jensen is implying. It is rather an attempt to resolve the question of the placement of hydrogen, which is already known to be analogous to the halogens in many respects, and a desire to support this view by appealing to triads. In any case, this particular example, the only one in which I claimed to have created a new triad, is now entirely academic, since I have withdrawn this proposal in a more recent book [6]. I no longer believe that hydrogen should be placed among the halogens but have returned to fully supporting the left-step periodic table as first proposed by Charles Janet in which H remains in group 1, while He is placed in group 2. In the first edition of this book, and until quite recently, I had proposed considering the formation of a new atomic triad to settle the question of the placement of hydrogen. Here is what I wrote in the second edition while withdrawing my earlier claim:

> However, appealing this proposal might seem, I now think that it may represent a mistaken strategy. My reason for saying so is that the first members of groups of elements are never members of triads and there is no reason to believe that a group such as the halogens should represent an exception (139–140).[12]

Conclusions

This article has traced the historical development of the periodic table by essentially focusing on 8-, 18- and 32-column presentations. I have also attempted to mount a case for considering the left-step periodic table as the most fundamental form of the periodic table. One of the supporting arguments is that the left-step table serves to regularize the way in which atomic number triads are displayed. The conventional 18- and 32-column table show irregularities, in having triads for the s-block elements consisting of the first- and second-member elements in periods of equal lengths, whereas in the case of all other blocks (p, d and f), valid triads have the second and third elements in equally long periods. Further support for the left-step table was provided in the form of the proposed 'enhanced uniqueness' of the first period in the table, which supports the accommodation of helium into group 2. The other supporting arguments for the left-step table that were reviewed were the greater agreement with the Madelung rule, which summarizes the

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[12] To be precise, He, Ne and Ar do form an atomic number triad in the conventional format of the periodic table, although I believe this to be a false triad for reasons discussed elsewhere in the present article. I thank a reviewer for making this point.

order of orbital occupation as well as the fact that all period lengths are repeated.

Finally, it was suggested that the traditional opposition to such a placement relies too heavily on the macroscopic properties of the elements in group 2 and those of helium. According to the alternative, and more fundamental, understanding of the concept of an element, the periodic table is primarily concerned with abstract elements. This conception of an element, which has sometimes been termed as 'element as basic substance', should be associated with the properties of atoms of the elements rather than macroscopic properties. If one accepts this premise, the well-known configuration of the helium atom, with its two electrons, is more in keeping with placing it in group 2, which consists of atoms whose outer shells likewise contain two electrons, than it is with keeping it in the noble gas group.

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