# The location and composition of Group 3: A follow-on examination

René Vernon Canberra, Australia Charles Sturt University rene@webone.com.au ORCID 0000-0003-0108-6646

*Keywords:* Actinides; electron configurations; first member anomaly; Group 3; IUPAC; lanthanides; periodic table; triads

#### Abstract

This article is a follow-on to the author's 2021 arguments on the location and composition of Group 3, a topic which continues to attract interest (Cotton 2022; Neve 2022). In three parts I examine the matter via (a) a critique of the provisional report of the IUPAC Group 3 project (Scerri 2021a); (b) a critique of "In praise of triads" by Scerri (2022a); and (c) electron configuration arguments. The provisional report of the IUPAC Group 3 project is found to lack objectivity; the scientific basis of triads and the notion of a fundamental periodic table are challenged; and electron configuration arguments support Group 3 as Sc-Y-La-Ac.

# Contents

PART A: A critique of the 2021 provisional report of the IUPAC Group 3 project	PART C: Electron configurations and the group 3 question
Précis	Précis
Historical background	Background
Replacing a compromise table with a compromise table?	Historical context The start of the f-block and blocks generally
The popularity of tables showing	Solid state electron configurations
group 3 as Sc-Y-La-Ac	Cation configurations
Rarity of the 32-column form of periodic table	Earlier arguments
What next?	Incumbency
Role of IUPAC	Predominant differentiating electrons
Coda	The f-block filling sequence The lanthanoid contraction
PART B: A critique of "In praise of triads"	The most important orbital in a chemical sense
by Eric Scerri (2022a)	Electron configuration analogy
Précis	Coda
Introduction	
Valid and false triads	Conclusion
Henry Bent's views on periodic tables	References
Consistency with quantum mechanics	Acknowledgements
The premise of chemists as the "owners" of the periodic table	Appendix
(Ir)relevance of chemical properties	
The most fundamental form of the periodic table?	
Coda	

# PART A: A critique of the 2021 provisional report of the IUPAC Group 3 project

#### **Précis**

In this part I critique some grounds relied on by Scerri (2021a) in suggesting that IUPAC could perhaps make a ruling that Group 3 of the periodic table should be composed of Sc-Y-Lu-Lr. My concerns have to do with the philosophical meaning of "compromise"; the popularity of periodic tables instead showing group 3 as Sc-Y-La-Ac; and the rarity of the 32-column form of periodic table. IUPAC has further evidenced a long-standing reluctance to issue guidance on the use of any particular form of periodic table, including the table appearing on its own web site. The provisional report of the IUPAC Group 3 project lacks objectiveness on these bases. IUPAC could nevertheless issue some carefully worded guidance to address the situation.

# Historical background

In this section I enumerate some key dates concerning the periodic table in a IUPAC context.

In 2009 Leigh clarified that the periodic table appearing on the IUPAC web site, which features a 15-wide f-block and shows Group 3 as Sc-Y-Ln-An (Fig. 1), is neither an IUPAC-recommended nor IUPAC-approved periodic table, and is agreed within IUPAC only (Leigh 2009).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Н																	He
2	Li	Be											В	С	N	0	F	Ne
3	Na	Mg											AI	Si	Ρ	S	CI	Ar
4	к	Ca	Sc	Ti	v	Cr	Mn	Fe	Со	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Мо	Тс	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Те	I	Xe
6	Cs	Ва	Ln	Hf	Та	W	Re	Os	lr	Pt	Au	Hg	TI	Pb	Bi	Ро	At	Rn
7	Fr	Ra	An	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	FI	Мс	Lv	Ts	Og
				La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu
				Ac	Th	Ра	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure 1. Layout of periodic table appearing on the IUPAC web site

Earlier, in 1988, and on behalf of the Inorganic Chemistry Division of IUPAC, Fluck (1988, p. 436) wrote that the (unofficial) IUPAC table "is a compromise" between the La form and the Lu form of periodic table. In the 32-column version it can show either lanthanum or lutetium in group 3 according to the perspective of interest at the time.

In 1990 the IUPAC Commission on the Nomenclature of Inorganic Chemistry noted that it was neither their intent, nor their purpose to, "arbitrarily to set the format of the Periodic Table to be used in all parts of the world." (Leigh 1990, p. 280)

In 2008, Jensen expressed incredulity as to the basis for the IUPAC form of table, in which the 30 lanthanoid and actinoid elements are treated as degenerate members of group 3 of the d-block. He wrote:

IUPAC or not, I can hardly believe that a modern inorganic chemist would advocate such an antiquated interpretation of these elements, unless, as noted above, they have lost all contact between the underlying premises of their periodic table and the facts of chemistry. (Jensen 2008, p. 1492)

In 2009 and 2013 IUPAC again made it clear that they were not interested in mandating any particular form of periodic table; the 2013 decision extended their disinterest to the composition of particular groups. (IUPAC 2009, p. 7; IUAPC 2013, p. 11)

In 2015 IUPAC nevertheless set up a project with the objective of delivering a recommendation in favour of the composition of group 3 of the periodic table as consisting of either:

- the elements Sc, Y, Lu and Lr, or
- the elements Sc, Y, La and Ac. (IUPAC 2015)

The impetus for the IUPAC Group 3 task group was that, "students and instructors are typically puzzled by the fact that published periodic tables vary in the way Group 3 of the periodic table is displayed."

In 2021 my article on "The location and composition of group 3 of the periodic table", in support of Sc-Y-La-Ac, was published in this Journal (Vernon 2021).

In 2021 the IUPAC group 3 project delivered a provisional report concluding that, "There is no objective means to adjudicate between group 3 consisting of Sc, Y, La and Ac or as Sc, Y, Lu and Lr." They went on to say that:

...IUPAC should make a ruling on the question which in the final analysis is one of convention rather than one that can be decided on objective scientific grounds. (Scerri 2021a, p. 31)

The Lu form was however mentioned as a half-way solution. As noted in the provisional report:

Perhaps a compromise could be reached on...[a Sc-Y-Lu-Lr table] since it achieves three desiderata. First, it displays all the elements in order of increasing atomic number. Secondly, it avoids splitting the d-block into two highly uneven portions, and thirdly, it depicts all the blocks of the periodic table in accordance with the underlying quantum mechanical account of the periodic table which calls for 2, 6, 10 and 14 orbitals to occur in the extra-nuclear electronshells. (Scerri 2021a, p. 33)

Finally, the provisional report stated that it was intended as, "a call for feedback or suggestions from members of IUPAC and other readers."

Subsequently, Neve (2022) wrote: "Evidence of [a] cold reception of the IUPAC panel working hypothesis is already manifest in the work of several scholars."

As at May 2023, after more than two years, IUAPC has taken no further action with respect to the provisional report.<sup>1</sup>

# Replacing a compromise table with a compromise table?

The report suggested the desirability of adopting a "compromise" table, showing group 3 as Sc-Y-Lu-Lr. Such a table was reckoned to combine objective factors as well as interest dependence (Scerri 2021a, p. 32).

There are three issues to do with the notion of a compromise table: (i) how is one compromise better than another i.e. the IUPAC-style table(?); (ii) a compromise fully satisfies no one; and (iii) what kind of compromise is it when one "side" does all the conceding?

Subsequent advice was received from the editor of IUPAC's Chemistry International, as follows:

<sup>&</sup>lt;sup>1</sup> An anonymous reviewer of the first iteration of this tranche wrote, "There is certainly no need now to reopen this... certainly since the established task group did not see a need for it." In fact, the established task group suggested what they referred to as a compromise solution which, as noted, IUPAC has not acted upon. The statement there is "no need to reopen this" does not follow since it was never officially closed in the first place, there being no final report nor pronouncement from IUPAC.

I have consulted with Division II former officers who have in length followed the project which ultimately only ended with a provisional report. As it happened, the task group could not provide a way forward to the project, and the ongoing debate is an ample illustration of that. In consequence, the Inorganic Chemistry Division is for now considering the matter closed. (Meyers F 2023, pers. comm., May 5)

First, as noted, the table appearing on the IUPAC web site, with its 15-wide f-block and group 3 shown as Sc-Y-Ln-An had already been referred to by IUAPC as a compromise table (Fluck 1988, p. 436).

Second, such an approach lacks rigour as, by its very definition, a compromise fully satisfies no one. Group 3 is the least studied group in the periodic table, so why is so much energy wasted on arguments over its composition, when the question is inevitably informed by the context at hand, at the time?

Like Schrödinger's Cat, the question does not need to be answered until, and unless, it comes into focus (Scerri 2021c, p. 374). At that time the answer crystallizes according to the viewer perspective, whether that is, for example, a chemist interested mainly in vertical trends or an educator concerned with electron configurations (whether idealized or real, gas phase, standard state or ionic).

Henry Bent (2006), who was an aficionado of the left-step table (with group 3 as Sc-Y-Lu-Lr), advised that using more than one table is a step to perfection (Bent 2006, p. 119) and to use whichever table is best suited for the task at hand (Bent 2006, pp. 151, 158).

Echoing Fluck (1988), Philip Ball (who was a member of the IUPAC Group 3 project team) said, "...there's room for more than one periodic table: Chemistry is about compromise." (Lemonick 2019).

Lemonick (2019) similarly referred to some prevarication by Restrepo, another member of the IUPAC Group 3 project team:

...Restrepo encourages scientists to think beyond just one table. 'There's a lot of discussion about if this table is good or bad, if this shape is better or worse,' he says. He prefers to focus on the periodic system rather than on the table. In a sense, he says, the system is like a sculpture, and the tables are shadows cast by lights shone from different angles. He says that allows chemists to find the periodic table or tables that are most useful to them, whether they're looking for new elements or trying to understand properties in detail.

Third, I do not understand what kind of compromise it is in which one "side" (the Lu form) "concedes" nil, at the expense of the other side/s (the La form; the IUPAC form) doing all the conceding.

The La side concedes the Lu form may be more appropriate in some situations; the Lu side concedes the contrary. Students come away enriched by being able to walk and chew gum at the same time. Fernelius, a long-time member of the IUPAC's Commission on Nomenclature of Inorganic Chemistry, put the situation this way:

The choice of one form of the periodic table as the 'official' or the 'best' is a mistake. Users of the periodic table should be encouraged to know several forms and to use that one that best suits the use at hand. (Fernelius 1986, p. 266)

Notwithstanding, and out of the blue as it were, the Lu form apparently leapt to the head of the pack in the compromise stakes.

# The popularity of tables showing group 3 as Sc-Y-La-Ac

"In the majority of textbooks and wall-chart periodic tables, La is located in the d-block directly below Y." (Scerri 2021c, p. 377).

A survey of 193 textbooks undertaken by the IUPAC Group 3 project (Wong & Scerri 2019) found that the Sc-Y-La-Ac form of table had steadily declined in popularity since the 90's but maintained a plurality; the IUPAC style of periodic table in which the f block was 15 elements wide had steadily increased in popularity since the 80's; and the Sc-Y-Lu-Lr form of table showed a decline in popularity from the 00's to the 10's (Fig. 2).

# Rarity of the 32-column form of periodic table

A further concern is that the provisional report relied on the 32-column form in order to highlight the split d-block that arises when



**Figure 2.** An IUPAC-commissioned survey of university textbooks on how group 3 of the periodic table is shown.

group 3 is Sc-Y-La-Ac (Fig. 3) Yet the survey of 193 textbooks found just eight examples of the 32-column form. That is to say, it appears that effectively no one is concerned about a split d-block given the rarity of the 32-column form.

Reger, Scott and Ball (2010, p. 295) had earlier queried the impact of the 32-column form:

Perhaps the correct shape of the [32-column] periodic table should...have...a split d block. We avoid these structures by splitting the f block off from the rest of the periodic table. This also has the advantage of being able to print a legible periodic table on a single piece of paper.

They show La below Y in the rest of their book.

If a convention is needed there already is one in that the most common form is Sc-Y-La-Ac. Even so, no mention was made of the results of the survey in the provisional report.

Seemingly, for the IUPAC group 3 project, Sc-Y-La-Ac was objectively the wrong convention.

#### What next?

As mentioned, the IUPAC Group 3 provisional report (which appeared early in 2021) wrote that, "Perhaps a compromise **could** [emphasis added] be reached on...[a Sc-Y-Lu-Lr table]." (Scerri 2021b).

On the other hand, in a subsequent March 2022 public lecture given at the University of New Hampshire, Eric Scerri, chair of the IUPAC Group 3 project, instead said that, "We suggested...it **should** [emphasis added] be...lutetium and lawrencium in group 3." (Scerri 2022)

That is to say there is discrepancy between what the provisional report says—with its use of "could"—and what Scerri believes the project team suggested, with his use of "should".

1	2															3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Н																															He
Li	Be																									В	С	Ν	0	F	Ne
Na	Mg																									Al	Si	Ρ	S	CI	Ar
К	Са															Sc	Ti	۷	Cr	Mn	Fe	Со	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr															Y	Zr	Nb	Мо	Тс	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Те	Ι	Xe
Cs	Ва	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu	Hf	Та	W	Re	Os	lr	Pt	Au	Hg	TI	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	FI	Мс	Lv	Ts	Og
	s								f											(	1							k	)		
_																															
S	d	f	р																												
1	2	3															4	5	6	7	8	٩	10	11	12	13	14	15	16	17	18
Ч	2	U															7	J	U	'	U	0	10		12	10	14	10	10		Но
- 11	Ba																									D	C	N	0	E	No
	De																									D	C C		0	г 01	ive
Na	Mg																									AI	SI	Р	S	CI	Ar
K	Са	Sc															Ti	۷	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y															Zr	Nb	Мо	Тс	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Те	Т	Xe
Cs	Ва	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu	Hf	Та	W	Re	Os	lr	Pt	Au	Hg	TI	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	FI	Мс	Lv	Ts	Og
	s	d							1	f											d							F	)		

**Figure 3.** 32-column table with group 3 shown as Sc, Y, Lu, Lr (top); 32-column table with group 3 shown as Sc, Y, La, Ac and split d-block (bottom). In both tables, the s-block is split into two highly uneven portions due to the placement of He over Ne.

Scerri added the IUPAC appears to have sat on its hands with respect to the provisional report:

I'm afraid that we...this has not been resolved...it's been left hanging and I'm afraid it's, this is just a personal opinion which i hesitate to say publicly, but i think they're copping out...IUPAC is afraid of a Pluto situation or something like it where a major change to the periodic table occurs and everybody freaks out and says no no you've destroyed my favourite periodic table." (Scerri 2022, 53:05–53:16; 54:11–54:41)

Scerri concurrently tabled an email from another member of the IUPAC Group 3 project team who wrote, "It may even be premature to do anything right now"; the other member added:

Students will always be annoyed when the answer is not 'yes' or 'no' but 'on one hand...' However, there is value in learning that is how things are in real life. (Scerri 2022, 54:23)

As noted, IUPAC has taken no further action with respect to the provisional report since it appeared at the start of 2021. This is consistent with an observation made by Robinson (2018, p. 279):

Seeming attempts of the IUPAC in the second half of the twentieth century to mandate the use of a specific form of the table were met with such outrage from chemical educators that they decided it was too controversial to dictate the use of any specific form.

#### **Role of IUPAC**

The current confusion for students and teachers as to why the IUPAC table has a 15-element wide f-block, whereas other authors show lanthanum or lutetium under yttrium and an associated 14-element wide f-block, arises from a lack of carefully worded IUPAC guidance rather than because it has not formed a view as to the composition of Group 3.

With respect to the IUPAC Red Book, such guidance could usefully address the matter:

The periodic table on the insider cover is the form agreed and used within the IUPAC, rather than being IUPAC recommended or approved. In this instance, the lanthanoids are shown as a 15-element wide series in light of their chemical similarities.

Different forms of the periodic table may be more or less appropriate in particular contexts. For example, a 14-element wide lanthanoid series may be more appropriate to better bring out the concept of an f-block. Such a series could start with, for example, lanthanum or cerium depending on the context.

IUPAC does not recommend or approve any particular format of periodic table or system, nor does it mandate the composition of Groups (Vernon 2021, p. 160).

Such IUPAC guidance is long overdue and its lack has caused needless confusion, and continues to do so. Is something of this kind too much to expect?

#### Coda

The provisional provisional report of the IUPAC Group 3 project lacks objectiveness given (i) the existence of two "compromise" tables, and the philosophical meaning of "compromise" whereby no party is fully satisfied; (ii) the popularity of periodic tables showing group 3 as Sc-Y-La-Ac; and (iii) the rarity of the 32-column form of periodic table. It is apparent that there is an inconsistency between what the report states and the view of the chair of the project; at least one project member does not appear convinced. More than two years after the provisional report of the IUAPC group 3 project was published it is not surprising that IUPAC has left the report abeyance given its shortcomings. That said, IUPAC shares a role in any confusion surrounding the Group 3 issue on account its failure to issue clarifying guidance, as suggested.

\* \* \*

# PART B: A critique of "In praise of triads" by Eric Scerri

# **Précis**

In this part I critique some grounds relied on by Scerri (2022a) in support of the left step periodic table as a more general or most fundamental form of periodic table the relevance of this arrangement being that it shows Group 3 as Sc-Y-Lu-Lr. My concerns have to do with: the determination of which triads are valid or "false"; the late Henry Bent's support for the left step table; supposed consistency with quantum mechanics; the premise of chemists as the "owners" of the periodic table; and the (ir)relevance of chemical properties. Finally, in looking for a most fundamental periodic table, I suggest Scerri is conflating the notion of the theory underlying the periodic table with the treatment of the periodic table as a classification.

# Introduction

Scerri refers to the left step periodic table as "a more general…version of the periodic table" and "the most fundamental form of the periodic table" on the basis that it is a more regular table (Scerri 2021c, pp. 293, 297, 288). In a related manner he has elsewhere referred (or alluded) to the left step form as the "best" possible or "optimal" periodic table,<sup>2</sup> and one that shows the greatest degree of regularity (Scerri 2021c, pp. 390; 402–403); and "perhaps the most fundamental periodic table" (Scerri 2022b, p. 4). Assigning so many superlatives to the left step form results in some difficulties with Scerri's arguments, as will be seen.

<sup>&</sup>lt;sup>2</sup> Scerri has referred to the optimal periodic table as "the one which best represents the facts of the matter concerning chemical periodicity" (Scerri 2019, p. 127). Subsequently he opined that "It becomes increasingly clear that there may not be any such thing as one optimal table in a purely objective sense. The question seems to depend on what criteria are considered and, most importantly perhaps, on whether one favours chemical or physical criteria or general didactic considerations" (Scerri 2020, p. 12).

The "more regular" aspect refers to (i} triads; (ii) period lengths; and (iii) consistency with quantum mechanics. Triads are vertical sets of three elements, the middle of which has the average atomic number of the other two elements. A classic example is that of lithium [3], sodium [11] and potassium [19]. Figures 4 and 5 show the occurrence of triads in the conventional and left step forms of the periodic table. The regularity of triads in the left step table is apparent. Without exception, each triad consists of elements whose second and third elements belong in equally long periods. The first members of each column are seen to not be members of triads. The period lengths in the conventional table (Fig. 4) are 2-8-8-18-18-32-32 whereas those in the left step table uniformly repeat as 2-2-8-8-18-18-32-32. The quantum mechanics aspect refers to the fact one can rigorously predict that successive electron shells contain 2, 8, 18, 32... electrons based on the values of four quantum numbers (Scerri 2022a, p. 297).

Period																			
length																			
2	1																		2
-	н																		He
0	• 3	• 4												5	6	7	8	9	10
0	Li	Be												В	С	Ν	0	F	Ne
0	11	12												13 •	14 •	15 •	16 •	17	18 •
0	Na	Mg												AI	Si	Р	S	CI	Ar
10	19•	20•	21 •		22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
10	K	Ca	Sc		Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
19	37	38	39		<b>°</b> 40	<b>°</b> 41	<b>°</b> 42	•43	•44	<b>°</b> 45	•46	<b>°</b> 47	<b>°</b> 48	•49	•50	•51	•52	•53	•54
10	Rb	Sr	Y		Zr	Nb	Mo	Тс	Ru	Rh	Pd	Ag	Cd	In 💧	Sn	Sb	Те		Xe
22	55	56	57	58-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
52	Cs	Ba	La	Ce-Lu	Hf	W	W	Re	Os	lr	Pt	Au	Hg	TI	Pb	Bi	Po	At	Rn
22	87	88	89	90-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
52	Fr	Ra	Ac	Th-Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	FI	Mc	Lv	Ts	Og

**Figure 4.** Periodic table with bar bells spanning atomic number triads. The shaded triads, except for Sc-Y-La, are mentioned in this article.

# TRIADS



Figure 5. Left step periodic table showing the regular occurrence of triads.

#### Valid and false triads

To focus support on the left step periodic table and the regularity of its triads Scerri argues that "classic" triads appearing in the convention table such as Li-Na-K (Fig. 4) are false triads. Before I examine the basis for this assertion, he refers to said triad in the following terms (Scerri 2022a, p. 286):

The explanation...is that the interval between the first and second member of the triad is equal to the interval between the second and third member or, in other words, it captures the essence of chemical periodicity.

This and similar triads of elements that were originally found, represent a very significant discovery which paved the way for what is perhaps one of the major discoveries ever made in chemistry, namely that of the mature periodic table. It goes without saying that the periodic table is *the most central icon and organizing principle in the whole of chemistry*. [italics added]

For convenience, in the rest of this article I will refer to the preceding italicised passage of words as the CIOP paradigm.

The reasoning advanced by Scerri for why the Li-Na-K triad, and other well-known triads, such as Be [2] Mg [12], Ca [20] and He [2], Ne [10], Ar [18], are false is that, in his view, a triad is valid only if it consists of elements whose second and third elements belong in equally long periods (Scerri 2022a, p. 287). In this way triads in the left step table occur in a regular fashion.

This argument lacks substance since there is no basis to regard uniform regularity in the appearance of triads, or a periodic table, as being a fundamental requirement. Thus, Stewart (2018, p. 75) observed that, "Triads are a consequence of the structure of the system and cannot at the same time be its cause". As Scerri acknowledges:

One must beware of imposing beauty or regularity on nature where it might not actually be present. Too many proponents of alternative tables seem to argue about the regularity in their representation and forget that they may be talking about the representation and perhaps not the chemical world itself. (Scerri 2021c, p. 387)

In the case of undoing the classic He-Ne-Ar triad Scerri relies on the well-known phenomenon of the anomalous or abnormal behaviour of the first members of each group. Here, the degree of divergence between the elements in the first row of any new electronic block relative to the elements in later rows of the same block decreases in the order s-block >> p-block > d-block > f-block. He argues that:

The "much greater than sign" following the mention of s-block elements...support[s] placing He at the top of group 2, rather than its traditional placement at the top of the noble gases (Scerri 2022a, p. 296).

However, helium is already quite anomalous compared to neon. Thus, helium is an s-block element whereas neon is a p-block element. Helium has two outer electrons whereas neon has eight. Helium has an abnormally small atomic radius since its 1s subshell has no inner analogue and therefore experiences no electron repulsion effects, unlike the 2s, 3p, 4p and 5p subshells of heavier elements. Even though helium is located at the top of the noble gas group, and could be expected to be the most electronegative of all elements it is expected to have an electronegativity less than that of neon (Allen 1989; Nagel 1990; Grochala 2012; Grandinetti 2013; Rahm, Zeng & Hoffmann 2018). These four properties make helium sufficiently abnormal compared to neon.

It is further interesting to note that the left step form with helium over beryllium introduces its own anomaly in that no element in period 1 (H, He) is part of a triad whereas this is not the case for all periods thereafter. In contrast, all periods of the conventional table have at least one element that is part of a triad.

#### Henry Bent's views on periodic tables

Scerri mentions the late Henry Bent's support for atomic number triads (Scerri 2022, pp. 286–288). Bent was an avid supporter of the left step periodic table.

Since the premise of Scerri's article is to, in part, rely on triads as a basis for supporting the left step table as the most fundamental form, it is relevant to note Bent repeatedly observed there is no "best" periodic table (Bent 2006, pp. 108, 127, 151, 170, 175, 183, 191). Using more than one table is a step to perfection (Bent 2006, p. 119). Use whichever table is best suited for the task at hand (Bent 2006, pp. 151, 158). Bent further asserted that the left step table and conventional table complement one another (Bent 2006, p. 164).

#### Consistency with quantum mechanics

The arrangement of the left step form is said to be more congruent with quantum physics, in that its period lengths of 2, 8, 18, 32 etc. can be derived from the four quantum numbers. Scerri writes (Scerri 2022a, p. 297):

Quantum physics has succeeded in *almost* [italics added] completely explaining the periodic table by appealing to first principles. If the time-independent Schrödinger equation is solved for the hydrogen atom it emerges that 3 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 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 rigorously 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. 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.

The conventional table, on the other hand, has an apparent anomaly in that all period lengths (2, 8, 8, 18, 18, 32, 32) repeat apart from the first very short period with just two elements and which "rather mysteriously fails to repeat" (Scerri 2022a, pp. 293, 295). This is not the case in the left step form where all periods repeat uniformly (2, 2, 8, 8, 18, 18, 32, 32).<sup>3</sup>

However, there is no basis to regard regularity in period lengths as necessarily being a fundamental requirement.<sup>4</sup> The delimitation of elements into periods is arbitrary. According to Stewart (2018a, p. 111): "The Greek *periodos* means simply 'coming around'. The sequence of elements is a continuum and there are different ways—at least six published—of cutting it up into repeating sections."<sup>5</sup>

In the conventional table the cuts or period breaks follow each noble gas (including helium) these being characterised by closed valence shells and large energy gaps above their outer electron shells (Cao et al. 2021, p. 3).

The left step form introduces its own irregularities since helium is positioned above beryllium and the rest of the alkaline earth metals none of which have a large energy gap above their outer shells nor closed valance shells.

<sup>&</sup>lt;sup>3</sup> Scerri notes that, "The lengths of successive periods have not yet been strictly deduced from...[quantum] theory" and adds, "but not everybody agrees with this claim." (Scerri 2021c, pp. 254, 277). See also Scerri (2021b, p. 412, note 5). The length of periods in the left step table =  $2 \lceil n/2 \rceil^2$  and in the conventional form =  $2 \lceil (n+1)/2 \rceil^2$ .

<sup>&</sup>lt;sup>4</sup> Several authors have nevertheless expressed their personal preferences for regularity (or symmetry) in the arrangement of the periodic table, to no avail, as summarized in the appendix to this paper.

<sup>&</sup>lt;sup>5</sup> Echoing Stewart, and nigh on a century ago, Sommerfeld (1923, p. 61) wrote: "Concerning the arrangement of the periodic system in our table, it cannot fail to be recognised that it is in many ways arbitrary...As is self-evident from the cyclic character of the system, the table may be split at any vertical row and then joined at the former edges."

A further observation is that the order of blocks in the left step table is f-d-p-s which corresponds, in reverse order, to the angular momentum quantum number values l = 0, 1, 2, 3. The latter sequence is further consistent with the average distance of an electron from the nucleus, namely s > p > d > f (Scerri 2021c, p. 389).

That said, there are three other sequences of blocks which show the same order, namely dpsf, psfd and sfdp (Filippov & Gorbunov 1993) differing only with respect to how the continuous sequence of elements is cut into repeating sections.

The more pertinent consideration is that the periodic table, as a classification, is intended to show an approximate repetition of the physical and chemical properties of the elements (and their compounds), rather than being unduly concerned with suppositions of quantum mechanical regularities. The CIOP paradigm provides an affirmation of this question.

The blocks in the conventional s-f-d-p table appear in that order so as to have the metals on the left and nonmetals on the right.<sup>6</sup> Helium appears over neon on chemical grounds rather than, in the left step table, over beryllium on electron configuration grounds. The focus is on pragmatic chemical utility.

More generally, the conventional form of periodic table strikes a balance between order and regularity and the sometimes "Most of the properties important to a chemist are explained by two trends: an increase in ionization energies and a decrease in atomic radii from left to right along the rows of this [sfdp] configuration" (Filippov & Gorbunov 1993, p. 1626).

messiness of chemistry. Imyanitov (2016, pp. 153–154) refers to these two poles as follows:

If one seeks for the maximum chemical utility...[one] should opt for the more 'unruly' tables. If one seeks maximum elegance and orderliness above all...[one] should favor the more regular representations.

The basis for Scerri's support of the left step form as the most fundamental periodic table seems to be inconsistent with the conception of the periodic table expressed in the CIOP paradigm. Scerri elaborates the central role of the conventional table as follows:

[The conventional table] embodies the physics and chemistry of the elements as simple substances as well as basic substances. At the same time, the medium-long form stops short of adopting a fully reductionist approach that puts the highest premium on electronic configurations, which would commit one to the placement of helium among the alkaline earths. (Scerri 2021c, p. 403)

Akin to a last hurrah Scerri (2021c, p. 402) suggests that:

An optimal classification can be obtained by identifying the deepest and most general principles that govern the atoms of the elements, such as the [popular]<sup>7</sup> n + l rule, and by basing the representation of the elements on such principles.

While this rule is consistent with the arrangement of the elements in the left step form, it has (as yet) no first principles quantum mechanical derivation. In 1969, now over a half-century ago, the absence of such a derivation was described as being, "perhaps remarkable" (Löwdin 1969, p. 332). Going further, Cao et al. (2019, p. 16) suggest that, "the left step design of Periodic Tables appears to be non-derivable from physics."

<sup>&</sup>lt;sup>6</sup> With the usual exception of hydrogen, a non-metal, appearing on the left.

<sup>&</sup>lt;sup>7</sup> Cao at al. (2019, p. 16)

# The premise of chemists as the "owners" of the periodic table

Scerri goes on to seek to change the rules of the game by assigning ownership of the periodic table to the chemists and holding them responsible for the lack of traction of the left step form. He asserts:

The mere fact that the periodic table was discovered by chemists,<sup>8</sup> does not necessarily imply that only they should have the last word when it comes to grouping the elements together. (Scerri 2022a, p. 287)

...and follows this up:

What I would like to propose here is that the fact that the periodic table was first discovered by chemists does not give them the right to dictate what should be regarded as the most fundamental form of the periodic table. (Scerri 2022a, p. 297)

Per contra, no entity has claimed ownership of the design of the periodic table nor has an official body endorsed any particular design. Anyone or any official body is free to use or endorse any form of periodic table according to their preferences. It so happens that chemical educators and chemists have developed a periodic table that best suits their own uses.

#### (Ir)relevance of chemical properties

In his article praising triads Scerri (2022a, p, 287) states that, "I do not believe<sup>[9]</sup> that chemical properties should be regarded as the main criterion for the classification of elements."

Rather than this or that belief, one can turn to Mendeleev for an explanation of the periodic law and the associated table on the basis of the relationship between atomic weight (now atomic number) and chemical and physical properties. More specifically he wrote that it was atomic weight that served as the departure point for the discovery of the periodic law and that a law expressed a relationship between variables; atomic weight was the first variable, and chemical and physical properties were the second:

It is not only in the forms of the compounds that we observe a regular dependency when the elements are arranged according to...atomic weights but also in their other chemical and physical properties.

It would be more correct to call my system 'periodic' because it springs from a periodic law, which may be expressed as: The measurable chemical and physical properties of the elements *and their compounds* [italics added] are...[an approximate] periodic function of the atomic weight of the elements. (Mendeleev 1871, 1871a, in Jensen 2005, pp. 45, 116).

Since it is now understood that the chemical (and physical) properties of the elements, and their compounds, are largely a periodic function of atomic number, I do not understand the need for Scerri's denigration of chemical properties in classifying the elements. Indeed, taking account of these properties is consistent with what Scerri (2021) wrote in his review of Rayner-Canham's book, *The Periodic Table: Past, Present, Future:* 

As philosophers we have a natural tendency to concentrate on generalities and not to get too involved in the specifics and the details. Above all else, this new book reminds us that such an approach needs to be tempered by a detailed knowledge of the exceptions and features that go against the simplified generalities which we so cherish.

<sup>&</sup>lt;sup>8</sup> Presumably such chemists are experts having knowledge of chemistry and applying it in order to advance chemistry (Schwarz WHE 2023, pers. comm., 4 Jun)

<sup>&</sup>lt;sup>9</sup> The relevance of personal belief to the scientific method, in which scientific truth is determined through the rigorous examination of empirical evidence, replication of experiments, critical peer review, consensus building within the scientific community, and the continuous evolution of scientific knowledge, is not apparent.

As Poliakoff (2011) said:

In the end, I think that one should remember that Mendeleev devised the periodic table for a textbook to help rationalize the mass of facts in inorganic chemistry...For me, the periodic table remains a tool to help reduce the complexity, not a metaphysical truth that has a correct form yet to be discovered.

A further consideration is that the left step form interrupts: (a) the regularity of patterns that characterise the conventional periodic table i.e., metals on the left and nonmetals on the right (with the usual exception of hydrogen); and (b) the horizontal and diagonal trends that characterize the elements in their most stable forms at or near ambient conditions.

#### The most fundamental form of the periodic table?

On three occasions in his article Scerri refers to the left step form as the "most fundamental" periodic table (Scerri 2022a, p. 297).

While the word "fundamental" appears several times in the article he does not clearly elaborate the meaning of this term in a periodic table context.

Now, if the periodic table was a theory rather than a classification then it would be reasonable to seek the most accurate, valid or perhaps "fundamental" theory.

However, as Scerri refers to it in his article (Scerri 2022a, pp. 287, 298), the periodic table is instead a classification.<sup>10</sup> This does not exempt it from greater objectivity; classifications evolve over time in light of new information or interpretations of facts.

The closest he comes to explaining the "most" fundamental nature of the periodic table is in his conclusion, on the basis of treating the elements as abstract substances, bereft of any property other than atomic number. Scerri writes:

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 group 2 that consists of atoms whose outer shells likewise contain two electrons than it is with the noble gas elements. (Scerri 2022a, p. 299)

His references to elements as being abstract or basic substances means that, for example, carbon exists as a simple substance in the form of its allotropes such as graphite and diamond whereas carbon as a basic substance is the atomic form of carbon found in its compounds such as CO<sub>2</sub>. The focus is on the atomic number of carbon rather than the differing physical, chemical, and electronic properties of its allotropes. "A basic substance is an abstract concept indicating matter devoid of properties.<sup>11</sup> It is what remains of elements in its compounds." (Restrepo 2019)

The nub of Scerri's argument then rests on the observation that Mendeleev said the periodic table was primarily based on the elements as basic (or abstract) substances. As Scerri mentions:

This often-forgotten distinction was at the heart of Mendeleev's thinking about the periodic table and who believed that the periodic table was primarily a classification of abstract elements rather than simple substances. (Scerri 2022a, p. 298)

<sup>&</sup>lt;sup>10</sup> Scerri (2010, p. 70) refers to the periodic table as, "the supreme example of a scientific system of classification." And later: "Recall that the periodic table...is not a theory, at least for the vast majority of authors." (Scerri 2012, p. 283) <sup>11</sup> Aside from atomic number, and possibly electronegativity (Leach 2013)

Conversely, and as noted, what Mendeleev wrote (1899; 1901, in Jensen 2005, p. 200) was that it was atomic weight that served as the staging ground for the discovery of the periodic law and that a law expressed a relationship between variables, with atomic weight being the first of these, and chemical and physical properties the second. More specifically, Mendeléeff (1905, Volume 2, p. 24, note 11) opined that mass and valence were the most important properties since it was their periodicity that formed the substance of the periodic law.

In treating the elements as basic substances one is still obliged to consider the similarities among and between their physical and chemical properties<sup>12</sup> and those of their compounds in order to inform the arrangement of the periodic table (Vogt 2021, p. 10610). Jensen puts the situation this way:

What all of this means is simply that the periodic table is a true natural classification based on the simultaneous consideration of as many property-atomic number maps as possible. Since none of these maps exhibits perfect periodicity, the result is the best "averaged" representation and one which is consequently imperfect with regard to any single property considered in isolation, be it maximum oxidation state or electronic configuration. In short, the table should combine the best features of both the traditional chemical table and the more recent electronic configuration tables. (Jensen 1986, p. 498)

Clearly, arguments that rely on the elements only as basic substances are not necessarily reliable or useful. As further noted by Scerri (2021c, p. 132) the level at which a science operates is a question for its practitioners and the deepest most fundamental bases are not necessarily the best for all purposes.<sup>13</sup>

# Coda

Scerri appears to be contradicting his own advice in arguing for regularity at the expense of the chemical world itself.

Several of the grounds upon which he bases his support for the left step table do not appear to withstand scrutiny. The scientific basis upon which triads are either valid or false is not apparent. While Henry Bent was a fan of the left step table he advocated using whichever table was suited to the task at hand. The division of periods is arbitrary, depending on the perspective of interest. While quantum mechanics (perhaps) almost provides an underlying explanation of the periodic table it is not necessarily the basis for the classification of the elements. That chemists choose to design a periodic table according to their own requirements does not translate to ownership of the periodic table. Anyone or body is free to choose a design according to their particular interests. The periodic table is the most general representation of the entirety of chemistry yet Scerri deprecates the relevance of chemical properties.

As a classification rather than a theory, I contend there cannot be a "most fundamental" periodic table, as Scerri is seeking. The periodic table, as Mendeleev designed it and chemists and chemical educators have developed and used it, is focused on a pragmatic blend of chemistry- and physics-based considerations rather than being unduly concerned about philosophical nuances (involving the elements as basic or abstract substances) and the need for yet more regularity.

<sup>&</sup>lt;sup>12</sup> In their most stable form at or near ambient conditions

<sup>&</sup>lt;sup>13</sup> A case in point is the periodic table appearing in the IUPAC web site, which has a 15-wide "f-block" in light of the similarities among the lanthanide elements La–Lu, rather than a 14-wide block consistent with the precepts of quantum mechanics (Scerri 2021a, p. 33)

# PART C: Electron configurations and the group 3 question

# **Précis**

Twelve arguments based on or associated with electron configurations of the d or f block elements, absent of any other considerations, support (a) cerium-thorium and lutetium-lawrencium as the first and last dyads of the f-block; and hence (b) Group 3 as Sc-Y-La-Ac, on regularity grounds. The least common form of periodic table with Group 3 as Sc-Y-Lu-Lr does not accommodate the impact of the delayed appearance of the first f electron.

# Background

As noted in Part A, a recent provisional report from the IUPAC project tasked with making recommendations about the constitution of group 3 of the periodic table suggested that "perhaps" the group "could" be composed of Sc-Y-Lu-Lr in order to avoid splitting the d-block into two portions (Scerri 2021a). Such a split occurs in the rarely seen 32-column form of periodic table when group 3 is composed of Sc-Y-La-Ac (Fig. 6).

The project raised concerns about a split d-block on the grounds of this being highly uneven (having a 1:9 ratio). Elsewhere, Scerri and Parsons (2018, p. 146) observed that such a split occurs nowhere else in the periodic table. In fact, a more uneven split (1:13 ratio) occurs in the s block due to helium being placed over neon rather than beryllium. Scerri later refers to the split in the s block as representing [only] a 50:50 split of helium from hydrogen (Scerri 2021c, p. 401) seemingly underplaying its significance. Compounding matters, that main group chemistry and transition metal chemistry are two distinct branches of chemistry is a sufficient justification to support the idea of an sp block encompassing all of the representative elements, rather than separate s and p blocks (Jensen 2003, p. 959). In the popular form of periodic table, the unified sp block has a 1:4 split. Apparently, splitting of blocks is not so unprecedented.

Given the arrangement of the modern periodic table is largely informed by a certain regularity in the electron configurations of its elements (Rayner-Canham 2020, pp. 72–73; Jensen 2015, p. 25, Petrucci at al. 2007, p. A-71) it seems incumbent to note that the form of table suggested by the IUPAC project subsequently introduces several irregularities in the arrangement of electron configurations due to not accounting for the delayed appearance of the first f electron. Thus, "In a chemical sense, the internal periodicity is displaced one element to the right." (Imyanitov 2022, p.191)

Historically, so much importance was placed on regularity in electron configurations that the p elements B and Al, which were originally located over the d elements Sc-Y-La,<sup>14</sup> came to be moved over the p elements Ga, In, and Tl, in group 13, even though the periodic trends going down B-Al-Sc-Y-La were smoother than those going down B-Al-Ga-In-Tl (Parkes & Mellor 1943, p. 677; Greenwood & Earnshaw 2002, p. 223). As Parkes and Mellor (1943, p. 677) wrote:

The exact sub-classification to be adopted in...group [III] has in the past occasioned some difficulty, but it is now generally agreed that B and Al are best associated with Ga, In and Tl. This is supported by the conclusions at present accepted for the electronic configurations of these elements.

The move occurred from the 1930's onwards, with the rise of modern electron theory, and appears to have taken until the 1960's to be effectively realized.<sup>15</sup>

It is somewhat ironic that the report of the IUPAC project concludes with an emphasis on presenting a periodic table to the "widest possible audience of chemists, chemical educators and chemistry students" apparently overlooking the fact that their suggested form of group 3 as Sc-Y-Lu-Lr introduces further chemistry-based irregularities (Vernon 2021).

<sup>&</sup>lt;sup>14</sup> The first person to do so may have been Rang (1893, p. 178)

<sup>&</sup>lt;sup>15</sup> It may have taken this long for the teachings of the old chemists to be regarded as passé. Even then there were some holdovers. Pauling (1988, p. 182) has group 3 as B-Al-Sc-Y-La in his periodic table showing electronegativity values. Elsewhere he refers to the congeners of B as being Al-Sc-Y-La (Pauling 1988, p. 635).

H																	
Li	Be																
Na	Mg																
К	Ca	Sc														Ti	
Rb	Sr	Y														Zr	
Cs	Ва	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu	Hf	
Fr	Ra	Ac	Th	Ра	U	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	Rf	

Η																	
Li	Be																
Na	Mg																
К	Ca														Sc	Ti	Γ-
Rb	Sr														Y	Zr	
Cs	Ва	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu	Hf	
Fr	Ra	Ac	Th	Pa	U	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	Rf	<b>—</b> —

**Figure 6.** The two possible locations of group 3 in a 32-column periodic table. If the group is composed of Sc-Y-La-Ac the d-block is split into two portions.

At time of writing, IUPAC has not taken any further action with respect to the provisional report of the Group 3 project, at least until a new element is discovered. Given the report was only provisional and called for "feedback or suggestions from members of IUPAC and other readers" this is understandable. It may also be that IUPAC wish to avoid a Pluto-like-demotion situation in which a favourite form of periodic table is effectively deprecated (Scerri 2022, 54:23–54:41).

More broadly, IUAPC has never taken a position with regard to a recommended form of periodic table and it seems better to leave the question to the applicable context at the time. Of course, and as noted earlier, "students will always be annoyed when the answer is not 'yes' or 'no' but 'on the one hand'...However there is value in learning that is how things are in real life" (Öhrström 2021), or being able to walk and chew gum at the same time: "There is room for both approaches." (Imyanitov 2022, p.191)

# **Historical context**

Jensen, in his 1982 *J. Chem. Educ.* article on the composition of group 3, suggested the ideal electron configuration for the f-block elements in general was  $f^xs^2$  and that lanthanum, as [Xe]4f<sup>0</sup>5d<sup>1</sup>6s<sup>2</sup>, would be considered an f-block element with an irregular configuration derived from its ideal configuration of [Xe]4f<sup>1</sup>6s<sup>2</sup> (Jensen 1982). The last member of the 4f row would then be ytterbium with its configuration of [Xe]4f<sup>14</sup>6s<sup>2</sup>, thereby completing the filling of the 4f row. The actinides would similarly start with actinium [Rn]5f<sup>0</sup>6d<sup>1</sup>7s<sup>2</sup>.

Further analysis of Jensen's suggestion raises concerns to do with the irregularity of the start of the f block and blocks generally; dominant electron configurations; solid state electron configurations; and cation electron configurations.

# The start of the f-block and blocks generally

**1.** Jensen's proposal to start the f block with lanthanum and actinium was objected to by Lavelle (2008) who noted it would represent the only instance where respective rows of a periodic table block started with elements having no relevant differentiating electrons.

**2.** In a Sc-Y-La-Ac table, the 4f row has one irregular start at Ce and the 5f row starts with four irregular elements.

In a Sc-Y-Lu-Lr table, the 4f row has two irregular starts with La and Ce and the 5f row starts with five irregular elements. The first element in the 6d row (Lr) is likewise irregular.

Based on this criterion the Sc-Y-La-Ac periodic table is the more regular form.

**3.** Further, in a periodic table with group 3 as Sc-Y-La-Ac, each periodic table block starts with, and is subtended by, the applicable differentiating electron: s at H; p at B; d at Sc; and f at Ce.

This is not the case in an Sc-Y-Lu-Lr table where the f-block starts with La although the first 4f electron does not appear until Ce, the following element.

# **Dominant electron configurations**<sup>16</sup>

**4.** In a periodic table with group 3 as Sc-Y-La-Ac the dominant or most common configuration in the d block is  $d^{(n)}s^2$  with 21 occurrences; and in the f block is  $f^{(n+1)}$  (where the +1 reflects the delayed start of filling of the 4f subshell) with 19 out of 28 occurrences, for a total of 40 dominant configurations.

If group 3 is instead composed of Sc-Y-Lu-Lr then the dominant or most common configuration in the d-block is  $d^{(n)}s^2$  with 20 occurrences; and in the f block  $f^{(n)}s^2$  with 19 out of 28 occurrences, for a total of 39 dominant configurations.

Based on this criterion the Sc-Y-La-Ac periodic table is the more regular form.

# Solid state electron configurations

**5.** Since the lanthanides and actinides are solids in standard conditions of pressure temperature it is relevant to consider their electron configurations in this state in order to provide some more insight into their properties. For example, while gas phase neodymium is  $[Xe]4f^46s^2$  it is  $[Xe]4f^3d^16s^2$  in the solid phase. In condensing to a solid, one 4f electron is transferred to the 5d subshell, which subsequently becomes a conduction electron, along with two 6s electrons (Johnson 1969, p. 1528).

Tables 1 and 2 compare the position numbers of the f block elements with the actual numbers of f electrons in their solid states, rather than gaseous states; there are  $20\frac{1}{2}$  matches in the first table compared to 6+ in the second, out of 28 elements.

Based on this criterion the Sc-Y-La-Ac periodic table is the more regular form.

<sup>&</sup>lt;sup>16</sup> Electron configurations are those of the isolated gas phase atom in a vacuum unless otherwise stated.

4f row position	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Period 6	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu
Actual number^	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	~7	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	~14	<u>14</u>
Period 7	Th	Ра	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actual number†	~1/2	<u>~2</u>	<u>~3</u>	<u>~4</u>	<u>~5</u>	6	<u>7</u>	<u>8</u>	<u>9</u>	11	12	13	14	<u>14</u>

 Table 1: Sc-Y-La-Ac periodic table f block showing solid state electron configurations (underlined, grey shading = match with position number)

5f row position	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Period 6	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb
Actual number^	>0?	1	2	3	4	5	<u>~7</u>	7	8	9	10	11	12	<u>~14</u>
Period 7	Ac	Th	Ра	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
Actual number†	0	~1⁄2	~2	~3	~4	~5	6	7	8	9	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>

#### Table 2: Sc-Y-Lu-Lr periodic table f block showing solid state electron configurations

<sup>^</sup> Johansson and Rosengren (1975, p. 1367); Greenwood and Earnshaw (2002, pp. 1232, 1234): "...most of the metals are composed of a lattice of Ln<sup>III</sup> ions with a 4f<sup>n</sup> configuration and 3 electrons in the 5d/6s conduction band. Metallic Eu and Yb, however, are composed predominately of the larger Ln<sup>II</sup> ions with a 4f<sup>n+1</sup> configuration and only 2 electrons in the conduction band."

† Haire (2007, p. 65); Moore and van der Laan (2009, pp. 269; 270; 272; 275; 276; 283; 286); Lawson (2016, p. 87)

? The 4f levels in La, "lie just above the Fermi energy and could easily be occupied at least to a small extent" (Gschneidner 1993, p. 2) That said, such involvement would not be representative of the chemistry of La.

~ Some or all *f* electrons in the early actinides are itinerant, and become hybridized with *ds* electrons and orbitals. That, and the radioactivity and relative scarcity of the metals involved, makes it hard to pin down their *f* electron numbers beyond approximations, as denoted by a tilde. In thorium, the number of *f* electrons is shown as a fraction due to a 5f/6d overlap (Johansson et al. 1995, p. 282).

#### **Cation configurations**

**6.** Stewart (2018, p. 117) observed that an argument for lutetium in Group 3 was that the p<sup>th</sup> element in the f-block series, with the exception of [Ce and] Gd, has p (for place) f-electrons.

In contrast, Wulfsberg (2006, p. 3) emphasized the greater importance of the electron configurations of ions of the elements:

...valence electron configurations of atoms and ions are also important in predicting the periodicity of chemical properties. Since ions are more important than isolated gaseous atoms for nearly all atoms, and important ions have no anomalous electron configurations, there is little reason to worry students with anomalous electron configurations of atoms: we prefer to teach 'characteristic' electron configurations without anomalies in the occupancies of d- and s-orbitals in the transition elements or d-, s-, and f- orbitals in the inner transition elements.

Thus, with lanthanum in Group 3, the number of f-electrons in the trivalent cations of the f-block elements correspond perfectly with their position in that block.

A similar observation applies to the divalent cations of the d-block elements. The number of d electrons in these ions corresponds to their position in the block. Trivalent cation configurations cannot be relied on here since there are no such species for the group 12 elements zinc, cadmium and mercury.

Based on this criterion the Sc-Y-La-Ac periodic table is the more regular form.

# **Earlier arguments**

Five other properties related to electron configurations have been previously examined and shown to support the Sc-Y-La-Ac periodic table as the more regular form (Vernon 2021, pp. 159, 170, 176–177). A brief recap of these arguments, and a related newly arising argument, follows.

**7. Incumbency.** Lanthanum has the advantage of incumbency in the d-block, since the 5d<sup>1</sup> electron appears for the first time in its structure whereas it appears for the third time in lutetium, having already made a brief appearance in gadolinium.

**8. Predominant differentiating electrons.**<sup>17</sup> A 32-column table with an intact d-block is quantitatively less homogenous than a split d-block table. By this I mean a periodic table with Sc-Y-Lu-Lr, and helium over neon, has 13 differentiating electron discrepancies whereas a table with Sc-Y-La-Ac, and helium over neon, has 12.

**9. The f-block filling sequence.** Placing lutetium and lawrencium under yttrium obscures the start of the filling of the f-block (it would appear to start at lanthanum) and visually truncates its double periodicity (it would be cut off at ytterbium whereas it would actually end in the d-block). Thus, the 4f subshell filling sequence, which runs from cerium to lutetium, is periodic, with two periods. After the occurrence of a half-full 4f subshell at europium and gadolinium, the filling sequence repeats with the occurrence of a full subshell at ytterbium and lutetium (Rokhlin 2003, pp. 4–5). A similar, but weaker periodicity (Wiberg 2001, pp. 1643–1645) is seen in the actinoids, with a half-full 5f subshell at americium and curium, and a full subshell at nobelium and lawrencium.

**10. The lanthanoid contraction.** In a lanthanum table, the 4f-electron associated contraction naturally spans the f-block as cerium to lutetium (Housecroft & Sharpe 2008, p. 749). Cause and form are harmonized.

In a lutetium table the contraction does not start until the second element of the f-block; and the contraction then finishes after the end of the f-block, in the first period 6 d-block element, namely Lu. Cause and form are disaggregated. A table with lanthanum in Group 3 is thus more regular in this particular context.

**11.** The knock-on impact of the contraction on the 5d metals can shed further light on the Group 3 question. The result is that the 4d and 5d metals, in periods 5 and 6, tend to have similar radii. Figure 7 shows the differences in 12-coordination metallic radii<sup>18</sup> between the period 5 and 6 elements for groups 1 to 14.

For group 3 with La, the trend along groups 1, 2 and 3 looks to be as expected<sup>19</sup> whereas for Lu as a 5d metal in group 3, the difference in radii between it and Y appears anomalous compared to the rest of the 5d metals.

Figure 8 shows the differences in 6-coordination ionic radii<sup>20</sup> between the period 5 and 6 elements for groups 1 to 14.

<sup>&</sup>lt;sup>17</sup> The differentiating electron is the electron that distinguishes an element from its predecessor. They are relevant from a chemistry perspective since they enable the periodic table to be parsed into four major blocks according to the predominant differentiating electron in each block, and each block shows distinctive physical and chemical properties (Stewart 2018a, p. 118).

<sup>&</sup>lt;sup>18</sup> Radii from Smith (1990, p. 117)

<sup>&</sup>lt;sup>19</sup> More broadly, Greenwood and Earnshaw (2002, p. 946) wrote that Sc-Y-La-Ac, "display the gradation of properties that might be expected for elements immediately following the strongly electropositive alkaline-earth metals and preceding the transition metals proper."

<sup>&</sup>lt;sup>20</sup> Radii from Shannon (1976)



**Figure 7.** Differences in metallic radii of period 5 and 6 elements, for groups 1 to 14. The blue jagged line traces the progress of the Ln contraction among the Ln. It shows the difference in radii between Y and each of the metals from Ce to Lu. Thereafter, from group 4 (Zr/Hf) to about group 11 (Au/Ag) the radii are reasonably close.

There are more than 15 columns as the chart includes all the trivalent lanthanide cations and all the comparable differing oxidation states for the 4d and 5d ions.

The blue diagonal tracks the lanthanide contraction. It shows the difference in ionic radii between yttrium and each of the trivalent cations from cerium to lutetium. The knock-on effect of the contraction peters out after the platinum group metals.

The anomalies appear to be Y/Lu (if Lu is a 5d metal); maybe Tc/Re(+7); and certainly Pd/Pt(+2). The latter dyad was included by Shannon & Prewitt (1969, p. 944) in their list of ions exhibiting irregular coordination and which frequently resulted in inconsistent interatomic distances.

Yttrium has virtually the same ionic radius as Ho<sup>+3</sup> and thus very similar chemistry (Leggett 2017, p. 434; Cotton 2018, p. 292) whereas if lutetium was a genuine 5d metal it would be expected to have an ionic radius closer to that of yttrium.

Based on metallic and ionic radii, the La form is more regular. Conversely, while the Lu form looks more regular, it introduces another irregularity elsewhere. Or one could turn things around and say that the La table is more irregular when seen in the rarely occurring 32-column form. But since this form is so rarely seen whereas the similarities between the 4d and 5d metals are an omnipresent phenomenon, effectively no one is particularly concerned about the 32-column form.



Figure 8. Differences in ionic radii of period 5 and 6 elements, for groups 1 to 14

Further support for La under Y on the basis of atomic radii was alluded to by Atkins (2019, p. 6):

The periodic table and the concept of the elements of education inspires all manner of other thoughts. One is the desert-island thought: if you were asked to identify the central elemental concept summarized by the periodic table...with you isolated on a conceptual desert island and asked to set about rationalizing chemistry, what would it be? My choice would be atomic radius. In molecular biology a common precept is that shape determines function, with shape interpreted as including size, I think that the same maxim applies in the less elaborate region of chemistry. Atomic radius correlates with ionization energy and electron affinity, and thus it correlates with much of the energetics of bond formation.

Atomic radius controls, perhaps even more than simple energetics, the numbers and arrangements of bonds that an element can form, and so is central to considerations of bonding and the formation and stereochemistry of compounds. Atomic radius plays a crucial role in the mechanisms of reactions, both in organic and inorganic chemistry, especially in the formation of intermediates and transition complexes. Atomic radius plays a role in the arrangement of electrons around nuclei, as well as that arrangement affecting the radius. When the elements form compounds, the sizes of the constituent atoms affect the size of the molecules and through that size (and the underlying aspects of the energetics of electron excitation, itself size-dependent) the intermolecular forces that determine the physical properties of the compounds. It is hard, in fact, to identify a property that cannot, with sufficiently deep probing, correlate in some way with atomic radius. Function, does indeed follow form and should perhaps be a fundamental element of education.

While the similarity of radii of the 4d and 5d metals is due to the knock-on impact of the Ln contraction the regularity of this trend turns out to depend, in part, on the composition of group 3.

It has been known for over half a century that metallic lutetium resembles closely metallic erbium and holmium (except that it melts at a slightly higher temperature and is essentially nonmagnetic) and that its metallurgy is almost identical to that of holmium (Spedding & Beaudry 1968, p, 378).

As far as the stoichiometry of binary compounds is concerned, yttrium was reported to be more like lanthanum than lutetium, with the latter appearing in a four-element cluster of erbium, holmium, lutetium and gadolinium, as observed by Restrepo (2018, pp. 94–95)

Based on the stability of 2,198 binary compound bonds occurring between 97 elements, lanthanum was found to cluster separately from the cerium to lutetium series (Liu et al. 2019).

Cotton et al. (2022), on the basis of a correlation of overall structural differences with the size of the metal ions, found, "no true chemical basis for arranging Lu rather than La in one triad with Sc and Y." Further, "We would say that Sc, Y, and La, show a progression of structural properties and that Lu does not fit into this progression as well as La does." (Cotton S 2023, pers. comm., Feb 11).

**12. The most important orbital in a chemical sense.** While gas phase electron configurations appear to indicate that lanthanum Xe]5d<sup>1</sup>6s<sup>2</sup> and lutetium Xe]4f<sup>14</sup>5d<sup>1</sup>6s<sup>2</sup> have equal claims to the position under yttrium, lanthanum is not subject to the lanthanoid contraction (as is the case with scandium and yttrium) whereas lutetium is, having incurred a 16.5% reduction in ionic radius.

Lutetium is subsequently the least basic of the lanthanoids.

On this basis, including that the most important sub-orbital is 4d for lanthanum and 4fd for lutetium, and that the progressive filling of the 4f subshell contributes to the uniform and characteristic +3 oxidation state among the metals concerned (Mingos 1998, p. 375; Cotton 2006, p. 12), placing lanthanum under yttrium results in a more congruent chemical periodic table.

# **Electron configuration analogy**

The total (i.e., core plus valence) electronic configurations of lanthanum and actinium are closer to those of scandium and yttrium than they are to the configurations of lutetium and lawrencium (due to their filled 4f subshells.

According to Jensen (1982 p. 635–636) this is a misleading argument since intra-period (Lu–Hg) and intragroup (Sc–Lu) electron configurations favour Lu under Y. That is to say all the period 6 d block elements would have a filled f shell and in going from period 5 to 6 there would be a consistent addition of 32 to the atomic number.

However, not only does the s-block already break this pattern (going from Sr to Ba does not add 4f electrons, but going from Te to Po does), but the symmetry in atomic number is already broken in period 1 for chemistry-based reasons: consider H and Li (Z = 1, 3) versus He and Ne (Z = 2, 10). Consistency in going from period 5 to period 6 (Lu-Hg) further introduces the irregularities that are the subject of this this article.

While the differences between the chemistry of La and Lu are obviously not of the same order, it should at least raise the possibility that Jensen's argument needs to be assessed in light of other considerations such as the anomalous difference in radii between Y and Lu, as 4d and 5d metals, as explored in argument 12 of this paper.

# Coda

The twelve numbered arguments discussed or mentioned in this part of the article, each related to electron configurations, show that Group 3 as Sc-Y-La-Ac provides a more regular periodic table. Thus, while the hood or bonnet of the car may be irregular, given the split d block that occurs in the rarely seen 32-column form, the engine runs smoothly. Conversely, a periodic table with Group 3 as Sc-Y-Lu-Lr, while having an aesthetically more pleasing appearance due to the lack of a split d block in the 32-column form, introduces multiple irregularities in the pattern of electron configurations or associated properties. The hood or bonnet of the car is streamlined but the engine runs irregularly.

\* \* \*

# Conclusion

Conventionally, Group 3 as Sc-Y-La-Lr is the most popular arrangement. There is no objective basis to regard triads as supporting the left step table (which shows Group 3 as Sc-Y-Lu-Lr) nor for viewing such a table as the most fundamental form. A dozen electron configuration arguments support Group 3 as Sc-Y-La-Ac. Any confusion as to the composition of Group 3 of the table can easily enough be addressed via some appropriately worded guidance from IUPAC noting that the selection of any particular form of periodic table will always be contingent on the perspective of interest as the time.

#### References

- Allen, L. C.: Electronegativity is the average one-electron energy of the valence-shell electrons in ground-state free atoms, J. Am. Chem. Soc. 111, 9003–9014 (1989). https://doi.org/10.1021/ja00207a003
- Atkins, P.: Elements of Education, Chem. Int. 41, 4, 4-7 (2019). https://doi.org/10.1515/ci-2019-0404
- Bent. H.: New ideas in chemistry from fresh energy for the periodic law. Author House, Bloomington, IN (2006)
- Brauer, O. L.: Chemistry and its Wonders. American Book Company, New York (1938)
- Cao, C., Hu, H., Li, J., Schwarz, W. H. E.: Physical origin of chemical periodicities in the system of elements. Pure Appl. Chem. 91, 12, 1969–1999 (2019). <a href="https://doi.org/10.1515/pac-2019-0901">https://doi.org/10.1515/pac-2019-0901</a>
- Cao, C., Vernon, R. E., Schwarz, W. H. E., Li, J.: Understanding periodic and non-periodic chemistry in periodic tables. Front. Chem. 8, 813 (2021). <u>https://doi.org/10.3389/fchem.2020.00813</u>
- Cotton, S. A.: Lanthanide and Actinide Chemistry. Wiley, Chichester (2006)
- Cotton. S. A.: The Rare Earths, a challenge to Mendeleev, no less today, in Giunta et al. (eds.), 150 Years of the Periodic Table. Perspectives on the History of Chemistry. Springer, Cham (2018). https://doi.org/10.1007/978-3-030-67910-1\_11
- Cotton et al.: A comparison of the structural chemistry of scandium, yttrium, lanthanum and lutetium: A contribution to the group 3 debate, Coord. Chem. Rev. 455, 214366 (2022). https://doi.org/10.1016/j.ccr.2021.214366
- Deming, H. G.: General Chemistry, John Wiley & Sons, London (1923)
- Fernelius, W. C.: Some reflections on the periodic table and its use. J. Chem. Educ. 63 (1986). https://doi.org/10.1021/ed063p263
- Filippov, G. G., Gorbunov, A.I.: Four regular forms for the periodic table. Russ. J. Phys. Chem. 67, 9, (1993)
- Fluck, E.: New notations in the periodic table, Pure & Appl. Chem., vol. 60, no. 3, pp. 431–436, http://publications.iupac.org/pac/1988/pdf/6003x0431.pdf (1988). Accessed 26 May 2023
- Grandinetti, F.: Neon behind the signs, Nat. Chem. 5, 5, 438 (2013). https://doi.org/10.1038/nchem.1631
- Greenwood, N. N., Earnshaw, A.: Chemistry of the Elements, 2nd edn., Butterworth-Heinemann, Oxford (2002)
- Grochala, W.: A metastable He–O bond inside a ferroelectric molecular cavity: (HeO)(LiF)<sub>2</sub>, Phys. Chem. Chem. Phys., 14, 14860–14868 (2012). <u>https://doi.org/10.1039/C2CP42321A</u>
- Gschneidner, K. A.: Systematics and anomalies, J. Alloys Compd. 192, 1–2, 1–10 (1993). https://doi.org/10.1016/0925-8388(93)90170-R
- Haire R.G.: Insights into the bonding and electronic nature of heavy element materials. J. Alloys Compd. 444–445, 63–71 (2007). <u>https://doi.org/10.1016/j.jallcom.2007.01.103</u>
- Hakala, R. W.: Letters. J. Chem. Educ. 29, 11, 581–582 (1952)

Housecroft, C. E., Sharpe, A. G.: Inorganic Chemistry, 3rd ed., Prentice-Hall, Harlow (2008)

- Imyanitov, N. S.: Periodic tables for cations +1,+2,+3 and anions –1. Quantitative characteristics for manifestations of internal periodicity and kainosymmetry. Found Chem. 24, 189–219 (2022). <u>https://doi.org/10.1007/s10698-022-09421-2</u>
- Imyanitov, N. S.: Spiral as the fundamental graphic representation of the periodic law. Blocks of elements as the autonomic parts of the periodic system. Found. Chem. 18, 153–173 (2016). <u>https://doi.org/10.1007/s10698-015-9246-8</u>
- IUPAC, Division VIII Committee Minutes for the meeting held in Glasgow. <u>https://iupac.org/wp-content/uploads/2019/10/VIII\_09min.pdf</u> (2009). Accessed 26 May 2023
- IUAPC, Division VIII Committee Minutes for the meeting held in Istanbul. <u>https://iupac.org/wp-content/uploads/2016/01/Division-VIII-Meeting-Minutes-Istanbul-August-2013pdf.pdf</u> (2013). Accessed 26 May 2023
- IUPAC, The constitution of group 3 of the periodic table, <u>https://iupac.org/project/2015-039-2-200/</u> (2015). Accessed 26 May 2023
- Janet, C.: La Classification Hélicoïdale des Éléments Chimiques. Imprimerie Départementale de l'Oise, Beauvais (1928)
- Jensen, W. B.: The positions of lanthanum (actinium) and lutetium (lawrencium) in the periodic table. J. Chem. Educ., 59, 8, 634–636 (1982). <u>https://doi.org/10.1021/ed059p634</u>
- Jensen, W. B.: Classification, symmetry and the periodic table. Comput. Math. with Appl. 12B, 12, 487–510 (508) (1986). <u>https://doi.org/10.1016/0898-1221(86)90167-7</u>
- Jensen, W. B.: The place of zinc, cadmium, and mercury in the Periodic Table. J. Chem. Educ. 80 (8), 952, (2003). <u>https://doi.org/10.1021/ed080p952</u>
- Jensen, W. B. (ed.): Mendeleev on the Periodic Law: Selected writings, 1869–1905, Dover Publications, Mineola, New York (2005)
- Jensen, W. B.: The periodic table: Facts or committees? J. Chem. Educ. 85, 11, 1491–1402 (2008). https://doi.org/10.1021/ed085p1491.2
- Jensen, W. B.: The positions of lanthanum (actinium) and lutetium (lawrencium) in the periodic table: An update. Found Chem. 17, 23–31 (2015). <u>https://doi.org/10.1007/s10698-015-9216-1</u>
- Johansson, B., Abuja, R., Eriksson, O., Wills. J.M.: Anomalous fcc crystal structure of thorium metal. Phys. Rev. Lett. 75, 2, 280–283 (1995). <u>https://doi.org/10.1103/PhysRevLett.75.280</u>
- Johansson, B., Rosengren, A.: Interpolation scheme for the cohesive energies for the lanthanides and actinides, Phys. Rev. B, 11, 4, 1367–1373 (1975). <u>https://doi.org/10.1103/PhysRevB.11.1367</u>
- Johnson, D. A.: Third ionization potentials and sublimation energies of the lanthanides. J. Chem. Soc. A. 1525-1528 (1969). <u>https://doi.org/10.1039/J19690001525</u>
- Katz, G.: The periodic table: An eight-period table for the 21st century, Chem. Educ. 6, 324–332 (2001). <u>https://doi.org/10.1007/s00897010515a</u>
- Kauffman, G. B.: Some lesser known aspects of the work and thought of Alfred Werner. Advances in Chemistry. 62, 41–69 (1967). <u>https://pubs.acs.org/doi/10.1021/ba-1967-0062.ch004</u>
- Lavelle, L.: Lanthanum (La) and actinium (Ac) should remain in the d-block. J. Chem. Educ. 85, 11, 1482 (2008). <u>https://doi.org/10.1021/ed085p1482</u>
- Lawson, A. C.: 5f-electron localisation in the actinide metals: Thorides, actinides and the Mott transition. Philos. Mag. Lett. 96, 3, 85–89 (2016). <u>https://doi.org/10.1080/09500839.2016.1157634</u>
- Leach, M. R.: Concerning electronegativity as a basic elemental property and why the periodic table is usually represented in its medium form. Found Chem. 15, 13–29 (2013). https://doi.org/10.1007/s10698-012-9151-3
- Leggett, R.: Biokinetics of yttrium and comparison with its geochemical twin holmium. J. Radiol. Prot. 37, 2, 434–449 (2017). <u>https://doi.org/10.1088/1361-6498/aa6e66</u>
- Leigh, G. J. (ed.): 1990, Nomenclature of Inorganic Chemistry: Recommendations 1990, Blackwell Scientific Publications, Oxford
- Leigh, J.: Periodic tables and IUPAC. Chem. Int. 31, 4–6 (2009). https://doi.org/10.1515/ci.2009.31.1.4
- Lemonick. S.: The periodic table is an icon. But chemists still can't agree on how to arrange it. *Chemical & Engineering News*, 97, 1. <u>https://cen.acs.org/physical-</u>
- <u>chemistry/periodic-table/periodic-table-icon-chemists-still/97/i1</u> (2019). Accessed 26 May 2023 Liu, R., Mao, G., Zhang, N.: Research of chemical elements and chemical bonds from the view of
- complex network. Found. Chem., 21, 193–206 (2019). <a href="https://doi.org/10.1007/s10698-018-9318-7">https://doi.org/10.1007/s10698-018-9318-7</a> Löwdin, P. O.: Some comments on the periodic system of the elements. Int. J. Quantum Chem, III S, 331–334 (1969). <a href="https://doi.org/10.1002/qua.560030737">https://doi.org/10.1002/qua.560030737</a>
- Mendeleev, D.: On the periodic regularity of the chemical elements, Annalen der Chemie und Pharmacie, 6 (Supplmentband) 133–229 (1871) in Jensen (2005)

- Mendeleev, D.: On the question concerning the system of elements, Berichte der Deuthschen Chemishcen Gesellschaft, **4**, 348–352 (1871a) in Jensen (2005)
- Mendeleev, D.: Revue Générale de Chimie Pure et Appliquèe, 1, 211–214, 510–512; 4, 533–546, (1899; 1901) in Jensen (2005)
- Mendeleev, D.: An Attempt Towards a Chemical Conception of the Ether. Longmans, Green & Co. London (1904)
- Mendeléeff, D.: Principles of Chemistry, 3rd English ed., Longmans, Greene, & Co., London (1905)

Mingos, D. M. P.: Essential Trends in Inorganic Chemistry. Oxford University Press (1998)

- Moore, K. T., van der Laan, G.: Nature of the 5f states in actinide metals. Rev. Mod. Phys. 81, 1, 235–298 (2009). <u>https://doi.org/10.1103/RevModPhys.81.235</u>
- Nagle, J. K.: Atomic polarizability and electronegativity, J. Am. Chem. Soc., 112, 4741–4747 (1990). https://doi.org/10.1021/ja00168a019
- Neve, F. Chemistry of superheavy transition metals, J. Coord. Chem. 7, 17–18, 2287-2307 (2022). https://doi.org/10.1080/00958972.2022.2084394
- Öhrström, L.: email to Eric Scerri (2021). In Scerri (2022), 54:23
- Parkes, G. D., Mellor, J. W.: Modern Inorganic Chemistry, impression of 1939 edition, Longmans, Green and Co., London (1943)
- Pauling, L. General Chemistry, Dover Publications, New York (1988)
- Petrucci, R. H. et al.: General Chemistry: Principles and Modern Applications, 9th ed. Pearson/Prentice Hall, Upper Saddle River, NJ (2007)
- Poliakoff, M.: In Bradley, D.: Periodic debate: Complete not finished. ChemViews Magazine, 9 June, (2011). <u>https://doi.org/10.1002/chemv.201000093</u>
- Rahm, M., Zeng, T., Hoffmann, R.: Electronegativity seen as the ground state average valence electron binding energy. J. Am. Chem. Soc. 141, 342–351 (2018). https://doi.org/10.1021/jacs.8b10246
- Rang, P. J. F.: The periodic arrangement of the elements, Chemical News, 67, (1893)
- Rayner-Canham, G. R.: The Periodic Table: Past, Present, and Future, World Scientific, Singapore (2020)
- Reger, D. L., Goode, S. R., Ball, D. W.: Chemistry Principles and Practice, 3rd edn. Brooks/Cole Cengage Leaning, Australia (2010)
- Restrepo, G.: The periodic system: A mathematical approach. In: Scerri, E., Restrepo, G. (eds.): Mendeleev to Oganesson: A Multidisciplinary Perspective on the Periodic Table. Oxford University Press, New York (2018)
- Restrepo, G.: Challenges for the periodic systems of elements: Chemical, historical and mathematical perspectives, <u>https://arxiv.org/pdf/1909.13621.pdf</u> (2019). Accessed 12 March 2023
- Robinson, A. Creating a Symbol of Science: The Development of a Standard Periodic Table of the Elements, Doctoral Dissertations, 1385, <u>https://scholarworks.umass.edu/dissertations 2</u>/1385 (2018). Accessed 26 May 2023
- Rokhlin, L. L.: Magnesium Alloys Containing Rare Earth Metals: Structure and Properties. Taylor & Francis, London (2003)
- Rydberg, J. R.: Untersuchungen über das system der grundstoffe, Lunds Univ. Ärsskrift, 9, 18, (1913). In French: Recherches sur le système des éléments, Journ. de chimie phys. 12, 585 (1914)
- Scerri, É.: Explaining the periodic table, and the role of chemical triads, Found Chem. 12, 69–83 (2010). https://doi.org/10.1007/s10698-010-9082-9
- Scerri, E.: A critique of Weisberg's view on the periodic table and some speculations on the nature of classifications. Found Chem, 14, 3, 275–284 (2012). <u>https://doi.org/10.1007/s10698-012-9164-y</u>
- Scerri, E.: The periodic table: A very short introduction, Oxford University Press, Oxford (2019)
- Scerri, E: Recent attempts to change the periodic table, *Phil. Trans. R. Soc. A.* 378: 20190300, (2020). <u>https://doi.org/10.1098/rsta.2019.0300</u>
- Scerri, E.: Geoff Rayner-Canham: The periodic table: past present, and future. Found Chem. 23, 293–295 (2021). <u>https://doi.org/10.1007/s10698-020-09389-x</u>
- Scerri, E.: Provisional report on discussions on Group 3 of the periodic table, Chem. Int. 43, 1, 31–34 (2021a). <u>https://doi.org/10.1515/ci-2021-0115</u>
- Scerri, E.: The impact of twentieth-Century physics on the periodic table and some remaining questions in the twenty-first Century. In: Giunta, C.J., Mainz, V.V., Girolami, G.S. (eds.): 150 Years of the Periodic Table. Perspectives on the History of Chemistry. Springer, Cham., 409–423 (2021b). <u>https://doi.org/10.1007/978-3-030-67910-1\_16</u>

Scerri, E.: The Periodic Table: its Story and its Significance, Oxford University Press, London (2021c)

Scerri, E.: A brief history of the periodic table. Lecture given to the University of New Hampshire, March 1, <u>https://www.youtube.com/watch?v=srqxDLY\_RAE</u> (2022). Accessed 26 May 2023

- Scerri, E.: In praise of triads, Found Chem, 24, pp. 285–300 (2022a). <u>https://doi.org/10.1007/s10698-022-09434-x</u>
- Scerri, E.: Various forms of the periodic table including the left step table, the regularization of atomic number triads and first-member anomalies. ChemTexts 8, 6 (2022b). https://doi.org/10.1007/s40828-021-00157-8
- Scerri, E., Parsons, W.: What elements belong in Group 3 of the periodic table? In: Scerri, E., Restrepo, G. (eds.) Mendeleev to Oganesson: A Multidisciplinary Perspective on the Periodic Table, pp. 140–151. Oxford University Press, New York (2018)
- Shannon, R. D.: Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides, Acta Cryst. A32, 751–767 (1976). https://doi.org/10.1107/S0567739476001551
- Shannon, R. D., Prewitt, C. T.: Effective ionic radii in oxides and fluorides. Acta. Crystallogr. B. Struct. Sci. Cryst. Eng. Mater. 25, 5, 925–946 (1969).
- https://doi.org/doi:10.1107/s0567740869003220
- Smith, D. W.: Inorganic Substances: A Prelude to the Study of Descriptive Inorganic Chemistry, Cambridge University Press, Cambridge (1990)
- Sommerfeld, A.: Atomic Structure and Spectral Lines, E. P. Dutton & Co., New York (1923)
- Spedding F. H., Beaudry B.J.: Lutetium, in Hampel, C.A.: The Encyclopedia of the Chemical Elements, Reinhold Book Corporation, New York (1968)
- Stewart, P. J.: Amateurs and professionals in chemistry. In: Scerri, E., Restrepo, G. (eds.) Mendeleev to Oganesson: A multidisciplinary perspective on the periodic table, pp. 66–79. Oxford University Press, New York (2018). <u>https://doi.org/10.1093/oso/9780190668532.003.0006</u>
- Stewart, P. J.: Tetrahedral and spherical representations of the periodic system. Found. Chem. 20, 111–120 (2018a). <u>https://doi.org/10.1007/s10698-017-9299-y</u>
- Vernon, R. E.: The location and composition of Group 3 of the periodic table. Found. Chem. 23, 155–197 (2021), https://doi.org/10.1007/s10698-020-09384-2
- Vogt, T.: The value of vague ideas in the development of the periodic system of chemical elements. Synthese 199, 10587–10614 (2021). <u>https://doi.org/10.1007/s11229-021-03260-y</u>
- Werner, A.: Beitrag zum Aufbau des periodischen Systems. Per. Deut. Chem. Ges. 38, 914–921, 2022–2027 (1905)
- Wiberg, N.: Inorganic Chemistry. Academic Press, San Diego (2001)

Wong, J., Scerri, E.R.: Textbook survey of Group 3 depictions, progress tab. Dec. https://iupac.org/project/2015-039-2-200/ (2019). Accessed 26 May 2023

Wulfsberg, G. P.: Periodic table: Trends in the properties of the elements. In: Encyclopedia of Inorganic Chemistry, 2nd ed. John Wiley & Sons, New York (2006)

# Acknowledgements

I thank:

- Bill Jensen for his work in seeking to clarify the composition of Group 3;
- Gavin Jared Bala, John Marks, Eugen Schwarz, Valery Tsimmerman, Mikhail Boldyrev, and Charles Meeker for helpful discussions;
- Simon Cotton and Paul Raithby for helpful discussions and for reviewing a partial draft of this article;
- Eric Scerri for his ongoing interest in the question and pointing out to me, many years ago, apparent shortcomings in Jensen's 1982 article.

# Appendix: Preferences for regularity or symmetry in the arrangement of the periodic table

Several notable authors, to no avail,<sup>21</sup> have shown a preference for regularity or symmetry in the design of the periodic table despite there being no grounds to necessarily regard these attributes as being expected or fundamental.<sup>22</sup> Jensen referred to this phenomenon as an abuse of (Platonic) symmetry, including to the extent of triumphing over the inconvenient facts of chemistry (Jensen 1986, *passim*; 2003, pp. 953).

**Mendeleev (1904):** As well as his achievements, Mendeleev later succumbed to the lure of symmetry. Scerri takes up the story (2021c, pp. 154–155):

The discovery of the noble gases at the turn of the twentieth century...suggested to Mendeleev the possible presence of six new elements between hydrogen and lithium, as he indicated in his periodic table of 1904. In one of these cases, Mendeleev was more specific; namely, he predicted a possible analogue of the halogen fluorine. He claimed that the new element would serve to restore symmetry to the table by making the number of halogens five, to coincide with the five known alkali metals...Mendeleev was mistaken about these predictions, since none of the six elements were subsequently discovered."

#### Werner (1905): According to Jensen (1986, p. 508):

The temptation to read more into the shape of the table than is really there is almost overwhelming. Even someone as great as Werner was tempted (1905). Having postulated a missing element between H and He, he decided to perfect the symmetry of his table by guaranteeing that rows of differing length always occurred in pairs. Consequently, he further postulated a row of three missing elements lying above the H-X-He row.

On the other hand, in the view of Kauffman (1967, p. 65) Werner, "was merely pursuing a legitimate scientific activity—the search for regularity and order in nature."

**Rydberg (1913):** The origin of the paired periods concepts (i.e. 2, 2, 8, 8, 18, 18 etc) was instead attributed by Hakala (1952) to Rydberg (1913, pp. 12–13), of whom Hakala wrote: "Rydberg was a spectroscopist, with a spectroscopist's love of order and symmetry." Hakala goes on: "In order to be able to have 2 periods each of 2, 8, 18, and 32 elements, he [Rydberg] postulated the existence of two elements, 'coronium' and 'nebulium' (for which spectral lines were thought to exist), having positions between hydrogen and helium."

**Janet (1928)**: The left step table was developed by Janet purely on the basis of symmetry and proportion (Stewart 2018, pp. 69). According to Scerri (2022b, p. 4) it shows, "considerably more regularity than the conventional 32-column table." When Janet realized that his table corresponded to the electron structure of the elements but for a few anomalies he concluded that the latter must be due to errors of measurement (Stewart 2018, pp. 69–70). Janet was wrong; the anomalous electron figurations were correct.

**Katz (2001):** He advocated the adoption of the left step table on the basis that it followed, "a mathematical plan of construction based on quantum principles and the electronic configuration system" as well as regularizing the recurrence of periods, and showing a three-dimensional symmetry. (Katz 2001)

**Bent (2006):** The left step table was a personal favourite of Bent. He referred to it as a, "Point of departure for construction of less regular tables" (Bent 2006, p. xiii). Helium over beryllium, in his view, supported a number of overlooked regularities, including triads, and the phenomenon of first-element distinctiveness (p. xvii).

<sup>&</sup>lt;sup>21</sup> Consistent with the phenomenon noted by Brauer (1938, p. 390): "There have been dozens of attempts to work out a perfect periodic table, but they have all failed. Mendeléeff's scheme is about as good as any of them and is better known; hence it is retained with all its imperfections for want of a better system." In the event, Mendeléeff's scheme was superseded by the 18-column form, as popularized via Deming (1923).

<sup>&</sup>lt;sup>22</sup> It is further amusing to note that the periodic table is only *semi-regular* in the first instance given the varying lengths of its periods.