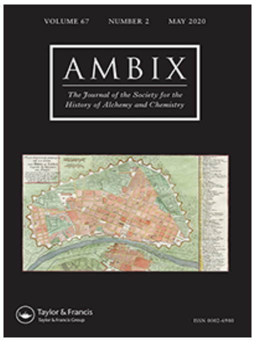

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Values in the Development of Early Periodic Tables

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Julius Lothar Meyer, John Newlands, and Dmitrii Mendeleev were amongst the discoverers of the periodic system of the elements. Although their systems are similar enough to be recognised as the precursors for the modern periodic system, they were also different. Here, I argue that many of their differences can be explained in terms of how the chemists emphasised different values in the process of developing their systems. In particular, Newland highlighted the simplicity of his arrangements; Meyer was more careful about the quality of data that gave rise to his system of elements; and Mendeleev sought to make his system more complete. By shedding light as to how the values of simplicity, completeness and carefulness guided the development of early periodic systems, this paper contributes to a broader understanding of how values influence science.

Introduction

The periodic system was discovered six times in the 1860s.[1] Today, credit for the discovery is often attributed to Dmitrii Ivanovich Mendeleev (1834–1907). In the late nineteenth century, however, apportionment of credit was not so straightforward; also the periodic systems of Julius Lothar Meyer (1830–1895) and John Alexander Reina Newlands (1837–1898) gained recognition.[2]

The periodic table is known for grouping together similar chemical elements and keeping dissimilar ones apart. In a similar vein, its origins offer fruitful grounds for inspecting similarities and differences. The systems of Newlands, Meyer, and Mendeleev were so alike that they all are recognised as competitors for the discovery of

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[1] The number rises to seven if we include Heinrich Baumhauer's classification. The discoverers, in order of publication, are: Alexandre-Émile Béguyer de Chancourtois (1862), Newlands (1864–1866), William Odling (1864), Gustav Hinrichs (1867), Meyer (1864, 1868, 1870), Mendeleev (1869–1871), and Baumhauer (1870).

[2] Both Mendeleev and Meyer received the Davy medal in 1882 from the Royal Society for the discovery of periodic relations of the atomic weights. In 1887 Newlands was awarded one, too.

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the same phenomenon – periodic dependency between various characteristics of chemical elements and their atomic weights. Yet, the systems appear very different.

Here, the aim is to illuminate the contrasts between the periodic systems issued by Meyer, Newlands, and Mendeleev. In particular, I show that many of their differences root from these chemists' emphases on different values during the process of developing their systems, where I follow historians Matthew Stanley and Loren Graham in defining "values" as qualities and attributes that are regarded desirable, praiseworthy, or good.[3] Newlands highlighted having identified a "simple relation" amongst the elements, whereas Mendeleev stressed the importance of having a complete (*polnost'*) system. In contrast to both Mendeleev and Newlands, Meyer had higher standards for the quality of data, and by doing so, I suggest he emphasised carefulness in the curation of data that gave rise to his periodic system. Although no chemist elevated just one value, we have compelling reasons to think that they emphasised the abovementioned qualities over others. Thus, focusing on values of simplicity, completeness, and carefulness gives a nuanced explanation of the differences between these systems.

Such values have not been discussed by historians as the relevant contrasts between the systems of the three chemists (although Mendeleev's system has been described in passing as the most complete one).[4] Instead, authors have stressed that the chemists appeared to disagree about the role of theories in chemistry and how their systems should be used. Mendeleev was not permissive towards theorising, but used his system to make detailed predictions of the properties of unknown elements. In contrast, Meyer offered a nuanced argument in favour of theories, but reserved a more restricted role for predictions. Newlands suggested that his system could be used for making predictions, and his theoretical approach was one of the reasons why his system was initially shunned in England.[5]

Assessing the early periodic systems in terms of values supplements the existing accounts on the distinct approaches of the three chemists. As I will elaborate, there is a link between Mendeleev's valuing of completeness and his predictions; Meyer's valuing of carefulness and his view on theories; and Newlands's brand of simplicity and the theoretical appearance of his systems. Thus, the framework of

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[3] Matthew Stanley, *Practical Mystic: Religion, Science, and A. S. Eddington* (Chicago and London: The University of Chicago Press, 2007), 5; Loren Graham, *Between Science and Values* (New York: Columbia University Press, 1981), 4.

[4] See Nathan Brooks, "Developing the Periodic Law: Mendeleev's Work During 1869–1871," *Foundations of Chemistry* 4 (2002): 129; Eric R. Scerri, *The Periodic Table: Its Story and Its Significance* (New York: Oxford University Press, 2007), 123; Michael D. Gordin, "Paper Tools and Periodic Tables: Newlands and Mendeleev Draw Grids," *Ambix* 65, no.1 (2018): 40.

[5] For differences between Meyer's and Mendeleev's approaches to theories, see Michael D. Gordin, "The Texbook Case of a Priority Dispute: D. I. Mendeleev, Lothar Meyer, and the Periodic System," in *Nature Engaged: Science in Practice from the Renaissance to the Present*, ed. Mario Biagoli and Jessica Riskin (New York: Palgrave Macmillan, 2012), 59–82. For a more detailed account of Meyer's view on predictions, see A. J. Rocke, "Lothar Meyer's Pathway to Periodicity," *Ambix* 66, no. 4 (2019): 265–302. For Mendeleev's predictions, see Scerri, *The Periodic Table*, 123–57. For the theoretical appearance of Newlands's systems, see Gordin, "Paper Tools and Periodic Tables," 30–51.

values helps to explain some other contrasts between the approaches of different chemists.

Examining how values guided the development of the early periodic systems also contributes to broader accounts of how values influence science. In the historical literature, historians such as Matthew Stanley and Kathryn Olesko have especially focussed on mapping the (dis)connections between values that are "internal" to the practice of scientists and their practices in other forums.[6] The approach taken here is different. Instead of exploring the connections between chemists' systematisation practices and other realms of their lives, the focus will be on the contrasts between three families of periodic systems. Thus, using the values framework helps us to gain a deeper understanding of the distinct character of each system.

To roughly reflect the chronological order in which the systems were published, I will first discuss Newlands's systems, for he was the first of the three chemists to provide a more developed versions of his system in 1865 and 1866. I then discuss Meyer and Mendeleev. Although the earliest versions of Newlands and Meyer's systems were published close in time, there is nothing to suggest that the two chemists were aware of each other's works before 1872. In contrast, we have several reasons to think that Meyer and Mendeleev were responding to each other in their publications of 1869–1872. It was only after Newlands grew aware of the works of Meyer that he started asserting his priority to the discovery of the "periodic law," which culminated in his self-published book that brought together his investigations.[7]

Newlands's Law of Octaves and simplicity

In August 1865, readers of *Chemical News* found a brief article calling attention to "the Law of Octaves." According to its author, the law in question concerned a regular numerical relationship between atomic weights of analogous elements. This relationship was illustrated with a table that appeared very neat and regular (see Figure 3). The table – and the law, for that matter – was issued by John Newlands, a London-born chemist who frequently participated in the meetings of the Chemical Society.[8]

It is not a coincidence that Newlands's explorations of the numerical relations of similar elements appeared in the 1860s. In the course of the nineteenth century, chemists identified 48 new elements with the help of electrolytic techniques and spectroscopy.[9] The newly identified elements came with new information about their

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[6] E.g. Kathryn M. Olesko, "The Meaning of Precision: The Exact Sensibility in Early Nineteenth-Century Germany," in *The Values of Precision*, ed. M. Norton Wise (Princeton: Princeton University Press, 1995), 103–34. Stanley, *Practical Mystic*.

[7] J. A. R. Newlands, *On the Discovery of the Periodic Law, and on Relations among the Atomic Weights* (London: Spon, 1884).

[8] J. A. R. Newlands, "On the Law of Octaves," *Chemical News* 12 (18 August 1865): 83.

[9] Joachim Schummer, "Scientometric Studies on Chemistry: The Exponential Growth of Chemical Substances, 1800–1995," *Scientometrics* 39 (1997): 107–23.

properties and a growing awareness of how the newcomers resembled previously identified elements. But how should such information be presented and organised?

One way to answer this challenge was to classify the elements based on such similarities (or analogies). Systems based on a single characteristic were known as artificial, and they effectively drew attention to how elements resembled each other in terms of the chosen analogy. However, as there were many qualities that the elements shared – smell, heaviness, lightness, malleability, melting-point, acidity, basicity – such artificial classifications could also conceal other similarities between the elements. Apart from systems which focussed on one property, some chemists also sought to organise the elements into a natural system, which expressed many of their analogies.[10] It can be said that most of the groupings of Newlands, Meyer, and Mendeleev were natural rather than artificial, since they brought together both quantitative and qualitative data on the elements.

For the emergence of the early periodic systems, especially central was the information concerning atomic weights of elements (which may be understood as chemically indivisible units that can combine with the indivisible units of other elements). Many authors take the systems of Newlands, Meyer, Mendeleev and others as the discoverers of periodicity because they utilised the newly standardised atomic weight data.[11] Indeed, the prompt for the rapid arrival of such systems was Italian chemist Stanislao Cannizzaro's (1826–1910) influence on the question of standardisation of atomic weights at the first international chemistry congress at Karlsruhe. During the congress, Cannizzaro argued for standardising atomic weights on the basis of Amadeo Avogadro's (1776–1856) hypothesis. After the last session in the congress, Angelo Pavesi from the University of Pavia distributed pamphlets containing Cannizzaro's arguments.[12] For Mendeleev and for Meyer, both of whom attended the congress, Cannizzarro's arguments left a lasting impression.[13] Newlands, who did not attend the conference, noted Cannizzarro's influence later when he pointed out that "it was only with the atomic weights of Cannizzarro that such extremely simple relationship could be observed."[14]

Newlands's Law of Octaves of 1865 – together with the slightly updated version of 1866 – was just one of his many systems. Although in his brief explanation of the

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[10] On artificial and natural classifications, see B. Bensaude-Vincent, "Philosophy of Chemistry," in *French Studies in the Philosophy of Science: Contemporary Research in France*, ed. Anastasios Brenner and Jean Gayon (New York: Springer, 2009), 165–86. José Ramon Bertomeu-Sánchez, Antonio Garcia-Belmar, and Bernadette Bensaude-Vincent "Looking for an Order of Things: Textbooks and Chemical Classifications in Nineteenth Century France," *Ambix* 49, no. 3 (2002): 227–50.

[11] Such authors include at least Francis Preston Venable, *The Development of the Periodic Law* (Easton: Chemical Publishing, 1896), 63; Jan van Spronsen, *The Periodic System of Chemical Elements: A History of the First Hundred Years* (Amsterdam: Elsevier, 1969), 97; Scerri, *The Periodic Table*, 66–7. For the difficulty of determining atomic weights, see especially Hasok Chang, *Is Water H_2O?* (Dordrecht: Springer, 2012), 141. Note that especially Rocke and Chang hold that the most pressing issues regarding atomic weight standardisation were solved before the Karlsruhe Congress. See Alan J. Rocke, *Chemical Atomism in the Nineteenth Century: From Dalton to Cannizzaro* (Columbus: Ohio State University Press, 1984), 295–96; Chang, *Is Water H_2O?*, 146.

[12] Clara de Milt, "The Congress at Karlsruhe," *Journal of Chemical Education*, 28, no. 8 (1951): 424.

[13] de Milt, "The Congress at Karlsruhe."

[14] Quoted in Newlands, *On the Discovery of the Periodic Law*, 21.

tables of 1865 and 1866 Newlands did not explicitly evoke simplicity, he emphasised having identified a "simple relation" in the previous versions tending towards the law. Later, Newlands evoked a "simple relation" when defending his priority in the discovery of the periodic law.[15]

Initially, Newlands associated simplicity with a regular numerical relationship among analogous elements. Newlands's first classification – published in 1863 – contained eleven groups of elements with analogous properties. His aim was to examine the numerical relations between "the equivalents of bodies belonging to the same natural family or group [of elements resembling each other]." His chief observation from the groupings concerned a numerical relationship among the equivalent weights: "if we deduct the member of a group having the lowest equivalent from that immediately above it, we frequently observe that the numbers thus obtained bear a simple relation to each other."[16]

Newlands illustrated this simple relation with a small table, where many of the weights differed by a factor of 8, or a number close to 8 (Figure 1). This was the first time Newlands evoked both completeness and simplicity, and he continued to emphasise especially the "simple relation" in the course of developing his system.

Only a year later, Newlands appeared to doubt the significance of his findings. In July 1864, he published a response to "Studiosus," an pseudonymous reader of *Chemical News*, who argued that the atomic weights of the elements were "very nearly multiples of eight."[17] Newlands opposed to Studiosus's claim because the generalisation appeared to depend on whether the atomic weights were determined in relation to hydrogen or oxygen. The opposition is somewhat surprising, since Studiosus's suggestion is highly similar to what Newlands himself had noted in 1863.

After critiquing Studiosus's findings, Newlands declared that there was a numerical relationship much more significant: triads, or groups of three elements where the atomic weight of the middle one was the mean between the two others. He supplied a table to illustrate such triadic relationships, but noted that it was "by no means so perfect as it might be" and that "I have some by me of a more complete character." Although Newlands did not share this more complete table on the grounds that the positions of some of the elements was controversial, his comment indicates that he strived towards completeness, which marks a similarity between his approach and that of Mendeleev.[18]

Although the table attached to the article was incomplete, the results appeared promising:

> So frequently are relations to be met with among the equivalents of allied elements, that we may almost predict that the next equivalent determined, that of indium, for instance,

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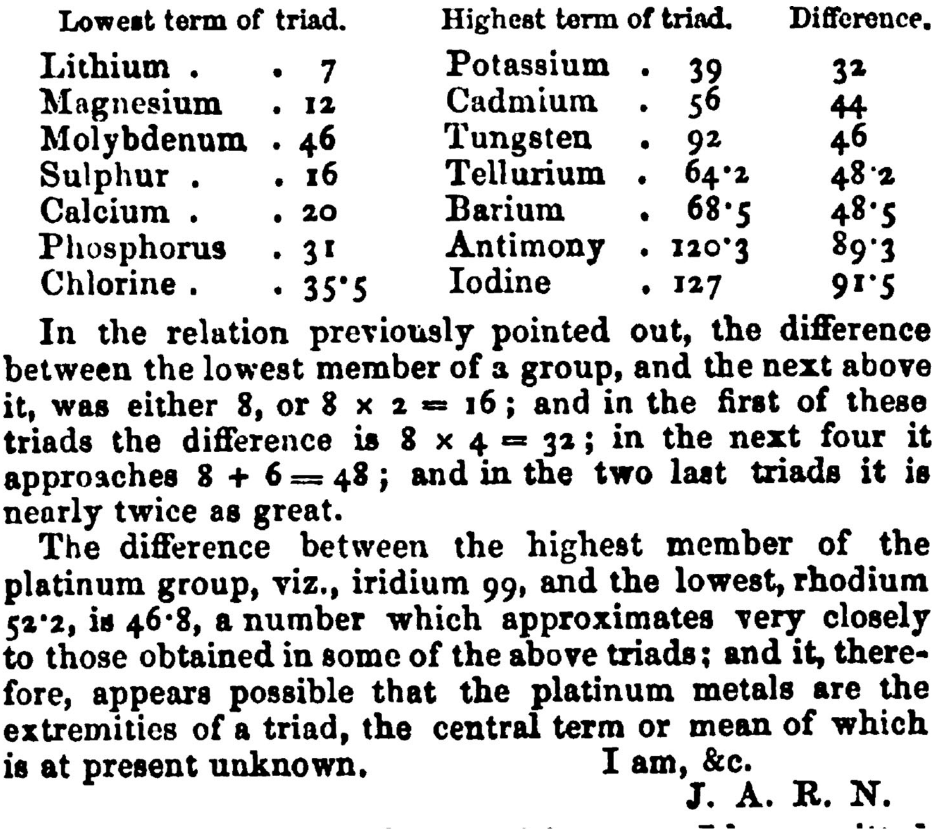
[15] Here, I will not provide an overarching definition of simplicity, because Newlands's papers point towards several contradictory understandings of the term. For a discussion on the theoretical nature of the system, see Gordin, "Paper Tools and Periodic Tables," 30–51.

[16] J. A. R. Newlands, "On Relations among the Equivalents," *Chemical News* 7 (7 February 1863): 70–2. All of the direct quotes are on 71.

[17] J. A. R. Newlands, "Relations between Equivalents," *Chemical News* 10 (30 July 1864): 59.

[18] Newlands, "Relations between Equivalents," 59.



Lowest term of triad.		Highest term of triad.		Difference.
Lithium .	. 7	Potassium .	39	32
Magnesium	. 12	Cadmium .	56	44
Molybdenum	. 46	Tungsten .	92	46
Sulphur .	. 16	Tellurium .	64·2	48·2
Calcium .	. 20	Barium .	68·5	48·5
Phosphorus	. 31	Antimony .	120·3	89·3
Chlorine .	. 35·5	Iodine .	127	91·5

In the relation previously pointed out, the difference between the lowest member of a group, and the next above it, was either 8, or 8 × 2 = 16; and in the first of these triads the difference is 8 × 4 = 32; in the next four it approaches 8 + 6 = 48; and in the two last triads it is nearly twice as great.

The difference between the highest member of the platinum group, viz., iridium 99, and the lowest, rhodium 52·2, is 46·8, a number which approximates very closely to those obtained in some of the above triads; and it, therefore, appears possible that the platinum metals are the extremities of a triad, the central term or mean of which is at present unknown.

I am, &c.

J. A. R. N.

FIGURE 1. Newlands's arrangement of 1863.

> will be found to bear a *simple relation* to those of the group to which it will be assigned.[19]

Thus, the "simple relation" was not an arbitrary numerical relationship, but something that arose among groups of resembling elements.

The close association of simplicity as a numerical relation between qualitatively similar elements is especially visible from Newlands's next system of elements. A month after his response to Studiosus, Newlands published another table which included 24 elements and a space for a new one (Figure 2). Newlands explained that if one lined up the elements from lightest to heaviest and replaced the measured atomic weights with order numbers – numbers that corresponded to their position on the list – one could arrange the elements so that every eighth element showed similarities. Thus, each horizontal line of Newlands's system depicted a group of qualitatively similar elements that he had identified earlier in 1863 (although the system did not include all of his 11 groups). As each horizontal line expressed

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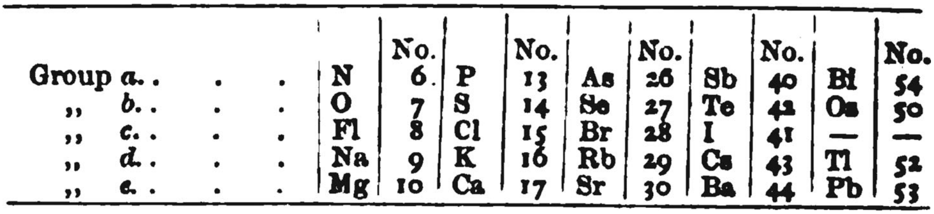
[19] Newlands, "Relations between Equivalents," 60.



		No.		No.		No.		No.		No.
Group *a*. . . .	N	6.	P	13	As	26	Sb	40	Bi	54
,, *b*. . . .	O	7	S	14	Se	27	Te	42	Os	50
,, *c*. . . .	Fl	8	Cl	15	Br	28	I	41	—	—
,, *d*. . . .	Na	9	K	16	Rb	29	Cs	43	Tl	52
,, *e*. . . .	Mg	10	Ca	17	Sr	30	Ba	44	Pb	53

FIGURE 2. Newlands's table of 1864. Note that some of the analogous groups of elements that he had identified in 1863 were represented on the horizontal lines of this system.

similar elements, the simple numerical relation truly arose among a group of "allied" elements.[20]

The arrangement revealed a pattern of repetition in the properties of elements after a regular interval, leading Newlands to introduce his famous musical analogy: "the eighth element starting from a given one is a kind of repetition of the first, like the eighth note of an octave in music." The closing paragraph linked the finding to triads. In particular, Newlands suggested that if one takes some elements as the centre of a triad, this allows for identifying which "extremes" were unknown. This, and the two empty spaces, indicates Newlands's acknowledgement that the table would have to accommodate new elements.[21]

Newlands's next system – published in August 1865 – is striking in its completeness. It contains 62 elements, meaning that Newlands had found a home for 32 elements within a single year (Figure 3).[22] Although this makes it his most complete table in terms of elements accommodated, there are reasons to think that he prioritised simplicity over completeness. For starters, Newlands did not much elaborate on how qualitative characteristics of the elements were represented on the system. Furthermore, no longer was it important to dedicate a single horizontal line to a group of similar elements. Instead, such groups can be *found* from the lines.[23] This suggests that the numerical pattern of octaves itself took the centre stage over representing the many analogies between the elements.

There are also two other indicators of Newlands's prioritisation of simplicity of the numerical pattern. As can be seen, Newlands again utilised order numbers rather than measured atomic weights. For the clearest possible expression of the "octave," one needed them, as they allowed expressing the simple numerical relation more clearly than the atomic weights did.

Second, what also indicates Newlands prioritising simplicity over completeness in accounting for qualitative similarities is that the parts of the columns displaying the order numbers are neat, whereas the columns indicating the names of elements are filled with several elements. Adamant to fit only seven elements per each column,

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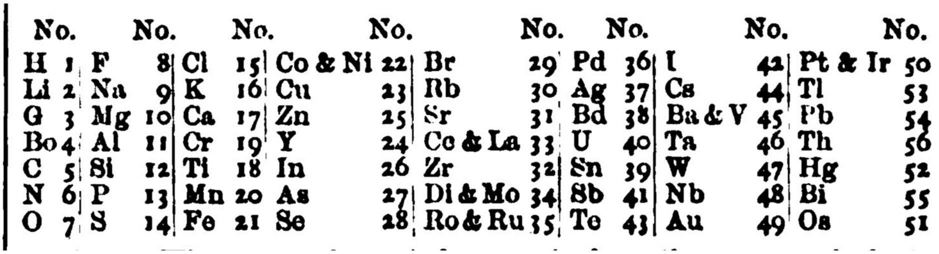
[20] J. A. R. Newlands, "On Relations Among the Equivalents," *Chemical News* 10 (20 August 1864): 94.

[21] Newlands, "On Relations Among the Equivalents," 94.

[22] Newlands, "On the Law of Octaves," 83.

[23] As noted originally by Carmen J. Giunta, "J. A. R. Newlands' Classification of the Elements: Periodicity, But No System," *Bulletin for the History of Chemistry* 24 (1999): 24–31, on 26.



	No.		No.		No.		No.		No.		No.		No.		No.
H	1	F	8	Cl	15	Co & Ni	22	Br	29	Pd	36	I	42	Pt & Ir	50
Li	2	Na	9	K	16	Cu	23	Rb	30	Ag	37	Cs	44	Tl	53
G	3	Mg	10	Ca	17	Zn	25	Sr	31	Bd	38	Ba & V	45	Pb	54
Bo	4	Al	11	Cr	19	Y	24	Ce & La	33	U	40	Ta	46	Th	56
C	5	Si	12	Ti	18	In	26	Zr	32	Sn	39	W	47	Hg	52
N	6	P	13	Mn	20	As	27	Di & Mo	34	Sb	41	Nb	48	Bi	55
O	7	S	14	Fe	21	Se	28	Ro & Ru	35	Te	43	Au	49	Os	51

FIGURE 3. Newlands's table of 1865.

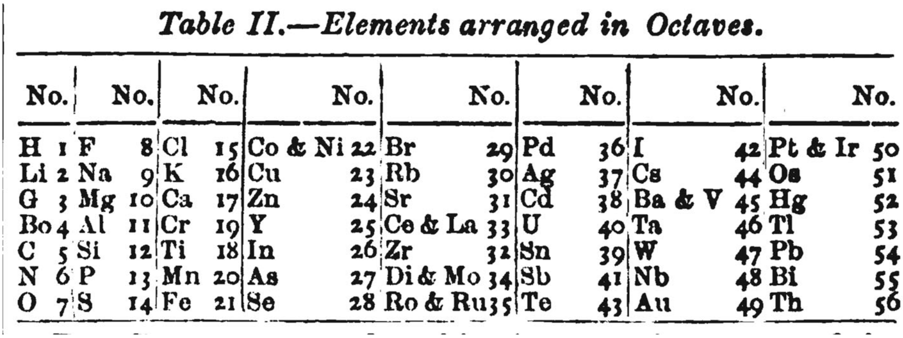


Table II.—Elements arranged in Octaves.

	No.		No.		No.		No.		No.		No.		No.		No.
H	1	F	8	Cl	15	Co & Ni	22	Br	29	Pd	36	I	42	Pt & Ir	50
Li	2	Na	9	K	16	Cu	23	Rb	30	Ag	37	Cs	44	Os	51
G	3	Mg	10	Ca	17	Zn	24	Sr	31	Cd	38	Ba & V	45	Hg	52
Bo	4	Al	11	Cr	19	Y	25	Ce & La	33	U	40	Ta	46	Tl	53
C	5	Si	12	Ti	18	In	26	Zr	32	Sn	39	W	47	Pb	54
N	6	P	13	Mn	20	As	27	Di & Mo	34	Sb	41	Nb	48	Bi	55
O	7	S	14	Fe	21	Se	28	Ro & Ru	35	Te	43	Au	49	Th	56

FIGURE 4. Table of 1866. Note the contrast between the final columns of Figure 3 and 4.

Newlands sometimes had to fit two elements in the same position. Thus, a single number could designate two elements. This shows that the simple, regular numerical pattern became the most central finding expressed on the table – regardless of whether it arose among qualitatively similar elements.

When Newlands presented an updated version of his system to the Chemical Society in March 1866, the audience members perceived especially the double-bookings as problematic (Figure 4). An anonymous author reporting the meeting noted that despite Newlands arranging "the known elements in order of succession," he had placed "nickel and cobalt, platinum and iridium, cerium and lanthaum, &c., in positions of absolute equality or in the same line."[24] Moreover, "Dr. Gladstone" (John Hall Gladstone) worried that Newlands's table suggested that no elements would be discovered.[25]

In his response to the criticism, Newlands evoked the simplicity of his arrangement:

> I have endeavoured to describe relations actually subsisting among the atomic weights of the elements at present known, but am far from thinking that the discovery of the new elements (or the revision of the atomic weights of those already known) will upset, for any length of time, the existence of a *simple relation* among the elements … The fact

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[24] J. A. R. Newlands, "Proceedings of Societies," *Chemical News* 13 (9th of March 1866), 113.

[25] Newlands, "Proceedings of Societies," 113.

> that such *a simple relation* exists now, affords a strong presumptive proof that it will always continue to exist, even should hundreds of new elements be discovered. For, although the [numerical] difference in the numbers of analogous elements might, in that case, be altered … the existence of a *simple relation* among the numbers of analogous elements would be none the less evident.[26]

Although the simplicity of Newlands's system was more tied to the order numbers rather than the empirically identified qualitative features of the elements, Newlands was adamant of its existence among the elements.

Newlands continued to appeal to simplicity in this way in his later writings. In 1872, after the discoveries of Meyer and Mendeleev had received some acknowledgement, Newlands asked the editor of the *Chemical News* to "vindicate his priority" in discovering the "Relations between Atomic Weights of Cannizzaro." After all, "it was only with the atomic weights of Cannizzaro that such *extremely simple relationship* could be observed."[27] In the 1880s, after Mendeleev and Meyer received the Davy medal for their discovery from the Royal Society, Newlands published a book that compiled his publications on the Law of Octaves. In its preface, he argued that already in 1864 he had "announced the existence of a simple relation or law among the elements when arranged in the natural order of their atomic weights." He explained that "[i]n the *Chemical News* … I published a full horizontal arrangement of the elements in order of atomic weights, and proposed to designate the simple relation existing between them by the provisional term 'Law of Octaves.'" In his conclusion to his preface, he again appealed to simplicity: "I claim to have been the first to publish a list of the elements in order of their atomic weight, and also the first to describe the periodic law, showing the existence of a simple relation between them when so arranged."[28]

In summary, Newlands's approach to the systematisation of the elements is distinctive in its emphasis on simplicity. Although it is undeniable that Newlands's systems were quantitatively complete in the sense that they included many elements, his explanations of how their qualitative properties were distributed on the system were thin. Instead of emphasising both qualitative and quantitative completeness, Newlands attached more importance to the expression of the "simple relation" – often at the expense of completeness.

Meyer and carefulness

Of the three chemists examined here, Meyer was the most explicit about the quality of the data that gave rise to his systematisations. Although both Newlands and Mendeleev occasionally noted when some atomic weight data were unreliable, the concern for their quality was a far more integral part of Meyer's approach and he employed many ways of highlighting the quality of data. As a shorthand for all

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[26] Newlands, "Proceedings of Societies," 113, emphasis added.

[27] J. A. R. Newlands, "Relations Between the Atomic Weights of Cannizzaro," *Chemical News* 25 (1872): 252.

[28] Newlands, *On the Discovery of the Periodic Law*, vi–vii.

these strategies of signalling the quality of observation and prioritising well-known chemical elements, I will refer to as valuing carefulness.[29]

The existing accounts on Meyer's periodic systems rarely elaborate on the influence of Meyer's educational background on his approach to systematisation. Meyer, who initially studied medicine, spent four months in 1853 working in Robert Bunsen's (1811–1899) laboratory in Heidelberg, where his interests broadened to physiological chemistry and physical chemistry.[30] In autumn of 1856, Meyer followed his brother Oskar Emil Meyer (1834–1909) to Königsberg (Kaliningrad) to enrol in Franz Ernst Neumann's (1798–1895) seminar on mathematical physics, which Oskar Emil was already attending.[31] Julius Lothar spent around a year and a half in Königsberg, and was listed as a faculty member attending Neumann's seminar even after his appointment as *Privatdozent* of chemistry and physics in the University of Breslau in 1859.[32]

Neumann's seminar strongly influenced Meyer's approach to systematisation. As shown by Kathryn Olesko in her account of the Königsberg seminar, Neumann sought to instil his students with a number of professional habits. As we will see, especially Meyer's use of the system to identify error in atomic weight determinations echoes Neumann's ideas about the appropriate role for theories in investigations. Moreover, Meyer drew his atomic volume curve with the help of techniques employed by his fellow students at the seminar. This suggests that the Königsberg seminar inspired Meyer to distinguish between different kinds of data visually.[33]

Soon after attending Neumann's seminar and the Karlsruhe Congress of 1860, Meyer started writing a textbook on the role of theories in chemistry. The book argued for the usefulness of theories in chemistry while also warning against premature theorising and the overvaluation of hypotheses. It was in this context of hinting of the helpfulness of theories that Meyer introduced his tables on the numerical relations and valences (or the combining power of the elements). The main table (see Figure 5) begins with lithium (Li) and ends with thallium (Tl). Below the atomic

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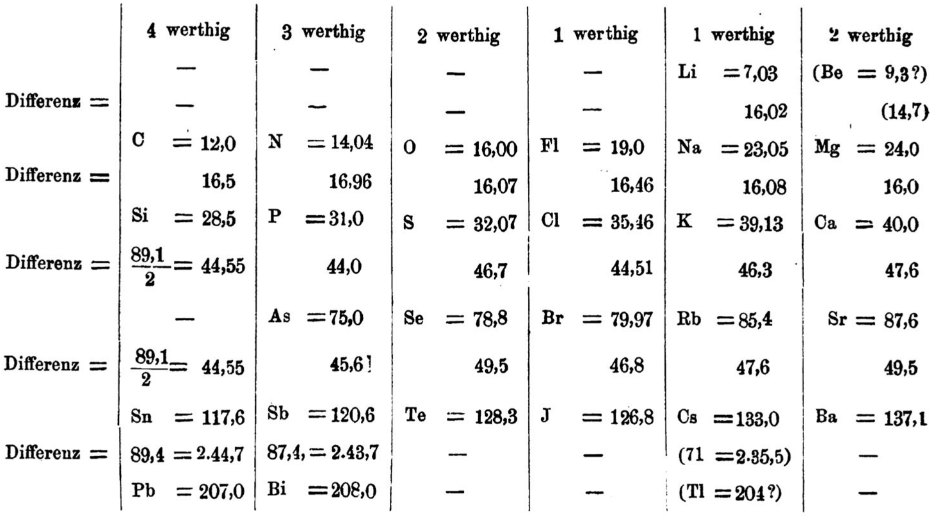
[29] I define valuing of carefulness as *signalling the differences in the quality of observations of the phenomena on the problem area, and prioritizing observations of higher quality over those that are lacking*. In this case, the problem area refers to the task of systematising the elements. Meyer discussed the importance of "careful" generalisation and being careful in Julius Lothar Meyer, *Die modernen Theorien der Chemie und ihre Bedeutung für die chemische Statik* (Breslau: Verlag von Maruschke & Berendt, 1864), 9. However, it should be noted that this sense of carefulness differs from the more colloquial understanding of the term, as it features e.g. in Gordin's discussion of the differences in Mendeleev's and Meyer's approaches to theories and predictions. See Gordin, "The Textbook Case of a Priority Dispute," 75–7.

[30] Karl Seubert, Wilhelm Wislicenus, and Lothar Waldemar Meyer, *Gedächtnisfeier bei der Enthüllung des Marmorbildnisses von Professor Dr. Lothar Meyer* (Tübingen: Laupp, 1911), 6. For a fuller biography, see Rocke, "Lothar Meyer's Pathway to Periodicity," 265–302; Gisele Boeck, "The Periodic System and Its Influence on Research and Education in Germany between 1870 and 1910," in *Early Responses to the Periodic System*, ed. Masanori Kaji, Helge Kragh, and Gabor Palló (New York: Oxford University Press, 2015), 47–71.

[31] Otto Theodor Benfey, "Meyer, Julius Lothar," in *Complete Dictionary of Scientific Biography*, ed. Charles Coulston Gillespie (New York: Charles Scribner's Sons, 1974), vol. 9, 347; Kathryn M. Olesko, *Physics as a Calling: Discipline and Practice in the Königsberg Seminar for Physics* (Ithaca and London: Cornell University Press, 1991), 230.

[32] Kathryn M. Olesko, "The Emergence of Theoretical Physics in Germany: Franz Neumann & the Königsberg School of Physics, 1830–1890" (Ph.D diss., Cornell University, 1980), 392.

[33] Olesko, *Physics as a Calling*.



	4 werthig	3 werthig	2 werthig	1 werthig	1 werthig	2 werthig
	—	—	—	—	Li = 7,03	(Be = 9,3?)
Differenz =	—	—	—	—	16,02	(14,7)
	C = 12,0	N = 14,04	O = 16,00	Fl = 19,0	Na = 23,05	Mg = 24,0
Differenz =	16,5	16,96	16,07	16,46	16,08	16,0
	Si = 28,5	P = 31,0	S = 32,07	Cl = 35,46	K = 39,13	Ca = 40,0
Differenz =	$\frac{89{,}1}{2}$ = 44,55	44,0	46,7	44,51	46,3	47,6
	—	As = 75,0	Se = 78,8	Br = 79,97	Rb = 85,4	Sr = 87,6
Differenz =	$\frac{89{,}1}{2}$ = 44,55	45,6!	49,5	46,8	47,6	49,5
	Sn = 117,6	Sb = 120,6	Te = 128,3	J = 126,8	Cs = 133,0	Ba = 137,1
Differenz =	89,4 = 2.44,7	87,4, = 2.43,7	—	—	(71 = 2.35,5)	—
	Pb = 207,0	Bi = 208,0	—	—	(Tl = 204?)	—

FIGURE 5. The main table given by Meyer in 1864.

weights, Meyer marked the numerical difference between that element and the one situated under it. Apart from the table of 28 elements, Meyer included two smaller tables.

It should be noted that Meyer's goal in this textbook was not to provide a system of *all* of the elements. Instead, he sought to illustrate numerical relations between those that were "well-characterised" (*wohl charakterisirte Gruppen von Elementen*). This provides the first clue of Meyer's careful approach: he included only those he regarded as sufficiently well known.[34]

Apart from focussing on the well-known elements, Meyer also indicated the tentativeness of some placements by using question marks and bringing attention to the uncertainty of some of the atomic weights. For example, he noted that the difference in almost all of the vertical rows amounted to 16 "except between *the still very uncertain* atomic weights of beryllium and magnesium." The numerical relationships on the lower horizontal lines of the main table appeared regular if one disregarded the "not sufficiently secure atomic weight of thallium."[35]

Apart from bringing up the issues with atomic weight determinations, Meyer also highlighted the exceptional quality of data. Especially noteworthy is that Meyer expressed some of the atomic weights with two decimal places (e.g. lithium is 7.03). Use of such precise atomic weights was unusual. From the chemists who are regarded as the discoverers of the periodic system, Meyer was alone in expressing atomic weights to such a high degree of precision. The use of precise atomic weights suggests that Meyer wanted to distinguish them from those which had not been

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[34] Meyer, *Die Modernen Theorien*, 136.

[35] Both quotes are from Meyer, *Die Modernen Theorien*, 138, emphasis added.

determined quite so precisely – an ethos very much emphasised in Neumann's seminars in Königsberg.[36]

After the first tables of 1864, Meyer had drafted another one which was not published until 1895. In this missing table, we may find atomic weights expressed to a high degree precision. However, additional strategies for signalling the quality of data can be found from Meyer's most well-known representation of periodicity: the graph that revealed the periodic relationship between atomic weights and other properties of the elements. The graph was published in 1870, six years after his textbook, in an article for *Annalen der Chemie und Pharmacie*.[37]

Similarly to the introduction of the textbook of 1864, Meyer began his article with a reflection on atomic theory. Meyer saw it as highly likely that atoms were not simple, but complex and molecule-like. However, he also stressed that one should assume them to be made of the same primary matter. The assumption allowed Meyer to state the central finding of the article: that the relationship between weights and chemical properties was *periodic*, which he set to show with a table and a graph.[38]

In the table, Meyer had included those elements that had their atomic weights determined through investigations of their heat capacity or the gas density of their compounds. Apart from hydrogen, Meyer excluded yttrium (Y), erbium (Eb), terbium (marked "Tb?"), cerium (Ce), lanthanum (La), didymium (Di), thorium (Th), uranium (U), and jargonium (Jg). Their exclusion provides us an important indicator of Meyer's prioritisation of well-founded findings: these elements were excluded as neither their equivalent weights nor atomic weights were known with precision or confidence.[39]

Meyer concluded his discussion of the table by stating that "the properties of the elements are, for the most part, *periodic* functions of the atomic weight." However, demonstrating the periodic dependency more clearly required focussing on one specific quality and tracking its relationship with atomic weights. To illustrate their relationship, Meyer introduced a graph examining the relationship between atomic volume and weight (Figure 6).[40]

In this graph, the abscissa displayed the increasing atomic weights and the ordinate atomic volumes. In addition to representing weights and volumes, Meyer drew attention to how other qualitative properties of the elements depended on

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[36] Olesko, *Physics as a Calling*, 229. Although the Königsberg seminar is known for its use of the method of least squares, there is no evidence for Meyer's use of the least squares at this stage. In his later life, Meyer was opposed to using the method to atomic weight determination. See Julius Lothar Meyer, *Outlines of Theoretical Chemistry* (London: Longmans, Green, and Co, 1892), 59. Meyer and his co-author did not use the method in the atomic weight determinations they issued in 1883. See Julius Lothar Meyer and Karl Seubert, *Die Atomgewichte der Elemente aus den Originalzahlen neu berechnet* (Leipzig: Breitkopf & Härtel, 1883).

[37] The missing table of 1868 was reprinted in Karl Seubert, ed., *Das natürliche System der chemischen Elemente: Abhandlungen von Lothar Meyer (1864–1869) und D. Mendelejeff (1869–1871)* (Leipzig: Engelmann, 1895), 6–7.

[38] Julius Lothar Meyer, "Die Natur der chemischen Elemente als Function ihrer Atomgewichte," in *Annalen der Chemie und Pharmacie, VII. Supplementband*, ed. Friedrich Wöhler, Justus Liebig, and Hermann Kopp (Leipzig und Heidelberg, 1870), 354. For Meyer's reflection on the relationship between atomic theory and periodicity, see p. 358.

[39] Meyer, "Die Natur der chemischen Elemente," 357.

[40] Meyer, "Die Natur der chemischen Elemente," 358, emphasis original.

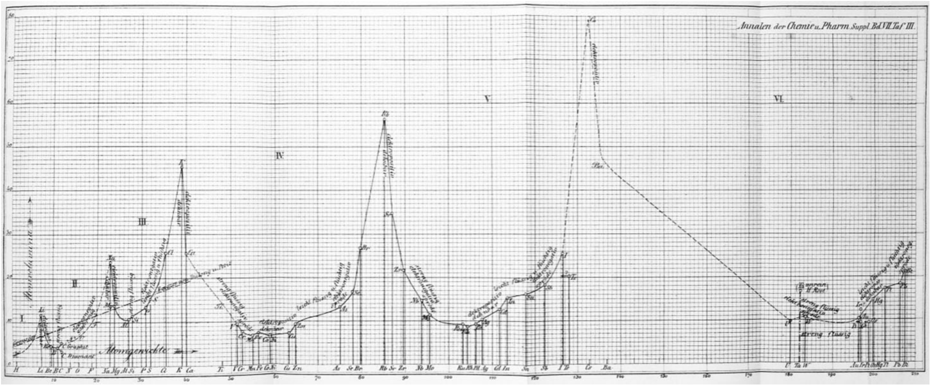

FIGURE 6. Meyer's graph of 1870. Note the dotted line between areas "V" and "VI."

atomic weights by writing on different sections of the curve in cursive. Although Meyer's graph primarily focussed on atomic weights and volumes, the periodic relationship seemed to arise with volatility, electrochemical behaviour, and ductility too.

In addition to Meyer's exclusion of poorly known elements and the signals of precisely expressed atomic weights, his graph gives us a new visual indicator of carefulness. In several sections the graph starts with a broken line, and then changes to a continuous one. The changes in the line are especially visible with iodine and tellurium. In Meyer's words, "[w]here the knowledge of the atomic volume of one or more elements is lacking, the curve is drawn in dotted lines." The continuous line for the well-known atomic weights and volumes, whereas the broken line was for the weights and volumes that were not as well known. Thus, the differing lines drew attention to the differences in the quality of data.[41]

Meyer's use of different kinds of lines was a technique employed by Neumann's other students in the 1850s. The similarities are especially visible when inspecting the graph of Heinrich Wild (1833–1902) who was Meyer's contemporary at the Königsberg seminar. (Later, Wild would become a member of the Russian Academy of Sciences, where he voted against Mendeleev's membership of the academy.) Wild, who participated in the physical division of Neumann's seminar in 1856, conducted his own independent investigation to determine the intensity of brightness after having attended Neumann's lectures on theoretical physics and theory of light. According to Olesko, Wild was exceptional in setting unusually high expectations for the precision of his instrument at detecting brightness levels. For Wild, it was not sufficient to have the levels of an exceptional human eye (i.e. differentiate 1/100 to 1/120 difference in brightness). Instead, his goal was the precision up to three decimal points, which required precision of 1/500 to 1/1000 difference in brightness. In order to distinguish between different levels of precision of his measurements, Wild drew a graph that had both smooth and a dotted area. Thus, similarly to

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[41] Meyer, "Die Natur der chemischen Elemente," 359.

Meyer, Wild's achievement at making highly precise measurement was accompanied with an unwillingness to conflate precise data with the more dubious kind.[42]

It is likely that Meyer picked up graphic methods from Wild and other students at the seminar.[43] Both Wild and Meyer used high decimal places to signify the precision of measurements, and different lines for different kinds of data. After publishing his investigation on brightness, Wild returned to Neumann's seminar at that very semester when Meyer had joined it.

Crucially, for Meyer, the graph was not solely a display of the periodic relationship between atomic weights and volumes, but also a useful guide for further investigations to determining atomic weights. The final section of Meyer's article demonstrated how the curve could be applied to rule out uncertain weights, where indium provided an especially good example. From indium's competing atomic weights, the one that fit on the regular course of the curve was most likely the correct one.[44] However, Meyer argued that such use of the curve did not justify changing atomic weights. For Meyer, "[i]t would be premature, on such uncertain grounds, to make a change in previously adopted atomic weights." The curve – essentially a theoretical construct, a generalisation – did not give as certain outcomes as experiments. At most, it could direct "our attention to dubious and uncertain assumptions and urge to re-examine them."[45] And, indeed, Meyer's valuing of carefulness in curating the data that gave rise to his system rendered it a more useful guide for determining errors in atomic weights.

Two years after the publication of the atomic volume curve, the second edition of Meyer's textbook was published. There, Meyer introduced a new tabular periodic system and an updated version of the atomic volume curve. We may find the familiar indicators of his carefulness: the exclusion of little-known elements; drawing attention to uncertainties in data in writing; the use of different visual strategies to signal certainty and uncertainty; and the use of more precise atomic weights to signify exceptional quality of data. As to the new version of the atomic volume curve, the version of 1872 had a gap between barium (Ba) and tantalum (Ta) because "the density and hence the atomic volume are unknown for a number of elements."[46]

In the 1870 version of the curve, Meyer had indicated the periodicity of other properties of the elements by writing on the slopes of the curve. In the second edition of the textbook, Meyer supplemented his earlier discussion by elaborating on the relationship between atomic weights and ductility, volatility, and malleability, electrochemical behaviour, and how elements refracted light. Meyer explained how

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[42] Olesko, *Physics as a Calling*, 225–9. On Wild's membership in Russian Academy of Sciences, see Michael D. Gordin, *Well-Ordered Thing*. 2nd ed. (Princeton: Princeton University Press, 2018), 112.

[43] Olesko, *Physics as a Calling*, 228–30. Apart from Wild, Julius Lothar Meyer's brother Oskar Emil also utilised different kinds of lines for different kinds of data. See Olesko, *Physics as a Calling*, 257.

[44] For a more detailed description, see Rocke, "Lothar Meyer's Pathway to Periodicity," 294–9.

[45] On Meyer's views on prediction, see Gordin, "The Texbook Case of a Priority Dispute," 72–4. The quote on re-examining assumptions can be found from Meyer, "Die Natur der chemischen Elemente," 364.

[46] Julius Lothar Meyer, *Die modernen Theorien der Chemie*. 2nd ed. (Breslau: Verlag von Maruschke & Berendt, 1872), 306.

all these characteristics of the elements were distributed around the minima and maxima of the curve.[47] Apart from providing the reader a fuller discussion of the qualitative properties that he had initially brought up in 1870, Meyer also considered previously unmentioned characteristics. In particular, he brought up Mendeleev's discussion of how oxidation depended on atomic weights, and how the elements formed compounds with chlorine and hydrogen. This suggests that alongside valuing carefulness, Meyer also valued completeness with respect to discussing the qualitative properties of the elements (albeit his systems cannot be described as complete in terms of the number of elements included).[48]

In conclusion, Meyer's systematisation of 1862–1872 were distinctive due to his carefulness in signalling the quality of observations that gave rise to the periodic system. In particular, we saw that Meyer expressed atomic weights in an exact form; made uncertainties explicit both in writing and through graphic methods; and was unwilling to combine precise data with imprecise ones. But perhaps the most telling feature of Meyer's distinct approach is that he excluded elements from his systems, as Alan Rocke has noted recently.[49] In 1864, Meyer included altogether 50 elements, where he explicitly focused on those that were well-characterised. By 1868, the number of elements rose to 52. In 1870, he excluded nine elements on the grounds that they were not very well known. His tabular system included 55 elements, but the graph included 57. Both the spiral table and graph of 1872 included 56 elements. In isolation, the gradual raise in the number of elements included might not seem that telling, but if we compare these numbers to Newlands's 62 elements in 1865, William Odling's 57 elements in 1864, and Mendeleev's 63 in 1869, it becomes clear that Meyer was curating the elements to the tables with more care than his contemporaries.

When we consider the uses that Meyer had for his systems, it becomes clear that Meyer's more careful approach is backed up by a convincing argument: using only the most reliable data to construct a generalisation about the elements made that generalisation more useful for further research. Meyer's later research interests dovetail with his ideas about the relationship between theory and observation. After publishing the second edition of the textbook, Meyer's chief work consisted in redetermination of atomic weights. From 1878 to 1895, Meyer redetermined atomic weights together with Karl Seubert, co-authoring several papers on the issue and a book on the subject.[50]

Mendeleev and completeness

In February 1869, after writing the first chapters for the second volume of *Principles of Chemistry*, Mendeleev created a system he titled an "attempt" of organising the

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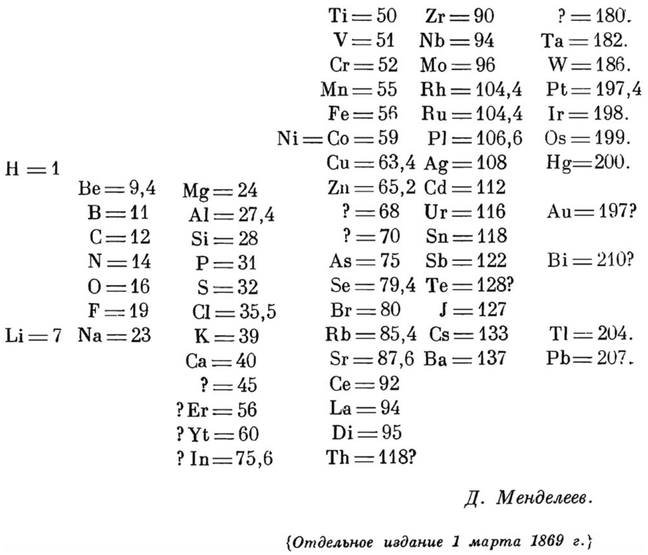
[47] Ductility, volatility, and malleability discussed in Meyer 1872, *Die modernen Theorien*, 309–12. Electrochemical behaviour is discussed on 324–7.

[48] Meyer discussed Mendeleev's findings on Meyer 1872, *Die modernen Theorien*, 328–37.

[49] Rocke, "Lother Meyer's Pathway to Periodicity," 299.

[50] Meyer and Seubert, *Die Atomgewichte der Elemente*.



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

Д. Менделеев.

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FIGURE 7. Mendeleev's system of 1869.

elements according to atomic weights and chemical properties (see Figure 7). While he discovered his periodic system in a pedagogic setting, he developed it in journal articles that were published in 1869–1871.[51]

Mendeleev's system was more complete than those of others. An obvious sign for its completeness is the fact that the first version included 63 elements. Apart from the high number of elements, there are the following additional indicators of its greater completeness: Mendeleev showed how vast array of qualitative properties found their place; emphasised the importance of having a complete systematisation; and incorporated more information (e.g. the row of oxides) to the visual layout of the system. In this sense, Mendeleev's systems were more complete with respect to the quantity of the elements and their qualities considered.[52]

When discussing values guiding Mendeleev's practice, it should be noted that several authors have shown that he attached importance to the idea of the absolute individuality of the elements.[53] Furthermore, in the literature on the value of predictive accuracy, authors often evoke Mendeleev's predictions as an example. For this

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[51] D. I. Mendeleev, "Opyt sistemy elementov," in *Periodicheskii zakon: Klassiki nauki*, ed. B. M. Kedrov ((1958) Moscow: Izdatel'stvo Akademii Nauk SSSR, 1869), 10. On Mendeleev's discovery of the system, see Michael D. Gordin, *A Well-Ordered Thing* (New York: Basic Books, 2004), 26–7; Igor S. Dmitriev, "Scientific Discovery in Statu Nascendi: The Case of Dmitrii Mendeleev's Periodic Law," *Historical Studies in the Physical and Biological Sciences* 34, no. 2 (2004): 233–75.

[52] I define valuing of completeness as *wanting to account for as many phenomena and their observed aspects as possible in a given problem area, giving special attention to phenomena that are deemed most relevant, and acknowledging the accommodation of phenomena that are likely to enter the problem area.* I have argued in favour of this understanding of completeness in Karoliina Pulkkinen, "The Value of Completeness: How Mendeleev Used His Periodic System to Make Predictions," *Philosophy of Science* 86, no. 5 (2019): 1318–29.

[53] See especially Bernadette Bensaude-Vincent, "Mendeleev's Periodic System of Chemical Elements," *The British Journal for the History of Science* 19, no. 1 (1986): 3–17.

reason, it is appropriate to ask why one should take completeness as the main value that characterised his approach to systematisation.

It is undeniable that Mendeleev's belief in the individuality of the elements featured in his discussions on how to represent periodicity, especially in his later years. For example, in the later editions of his textbook, he condemned the graphic representation of Meyer for not showing breaks between the lines to indicate the individuality of the elements, as Bernadette Bensaude-Vincent has demonstrated.[54] Although there is evidence in favour of Mendeleev believing in the individuality of elements in the 1860s, it is not clear to which extent individuality actively guided his process of developing the system in 1869–1871.[55] For example, he did not evoke it when he first discussed Meyer's graph in 1870. Furthermore, in his earliest system, he included two elements in the same vacancy (Ni = Co = 59).[56]

As to predictions, authors have argued that the accuracy of Mendeleev's predictions should be regarded as a value for his systems.[57] Although Mendeleev's predictions of 1871 indeed were accurate, it is difficult to say that predictive accuracy *guided* his process of developing his system. Instead, the accuracy of Mendeleev's predictions could be made only after the discovery of new elements in 1875, when he had stopped developing his system. For this reason, we should not think of predictive accuracy as a value affected his process of organising the elements, although he applied the "periodic law" to make predictions.

In contrast to individuality and predictive accuracy, the completeness of Mendeleev's system has received much less attention despite the fact he explicitly stressed the importance of having a complete system throughout the process of developing his periodic system. As we will see, completeness seems to have been crucial for drawing a contrast between Meyer's approach and for demonstrating that he had created a natural system instead of an artificial one.

Qualitative and quantitative completeness

The importance of completeness becomes clear from Mendeleev's first elaboration of his "attempt," published on March 1869, where he evaluated other available groupings of elements. He considered the groups of Peter Kremers (1827–?), which revealed triadic relationships amongst the atomic weights of dissimilar elements.

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[54] Bernadette Bensaude-Vincent, "Graphic Representations of the Periodic System of Chemical Elements," in *Tools and Modes of Representation in the Laboratory Sciences*, ed. Ursula Klein (Dordrecht: Kluwer Academic Publishers, 2001), 134–5.

[55] For example, Kaji quotes Mendeleev's lectures in arguing that he was suspicious about atomic theory. See Masanori Kaji, "The Origin of Mendeleev's Discovery of the Periodic System," in *Mendeleev to Oganesson: A Multidisciplinary Perspective on the Periodic Table*, ed. Eric Scerri and Guillermo Restrepo (New York: Oxford University Press, 2018), 223, 226–7.

[56] D. I. Mendeleev, "Ob Atomnom Ob'eme Prostyh Tel," in Kedrov, *Periodicheskii zakon*, 48–9.

[57] E.g. Peter Lipton, "Prediction and Prejudice," *International Studies in the Philosophy of Science* 4, no. 1 (1990): 51–65. Predictive accuracy especially features on the debate concerning the value of accommodation vs. prediction. See, for example E. R. Scerri and John Worrall, "Prediction and the Periodic Table," *Studies in History and Philosophy of Science* 32, no. 3 (2001): 407–52. Samuel Schindler, "Novelty, Coherence, and Mendeleev's Periodic Table," *Studies in History and Philosophy of Science Part A* 45 (2014): 62–9.

Although Mendeleev found the relations identified by Kremers interesting, he emphasised that they "have represented and continue to represent in our minds only some fragmented findings that do not lead to a *complete system* of elements." Kremers was not alone in having an incomplete arrangement. Although Ernst Lenssen's (1837–?), Max Pettenkofer's (1818–1901), and Nikolai Nikolayevich Sokolov's (1826–1877) groupings established some numerical relations between the elements, Mendeleev also argued that they failed at "systematic distribution of *all* of the known elements." Thus, completeness with respect to the quantity of elements was important for Mendeleev.[58]

In this setting, Mendeleev did not just call for a complete system, but a system that was based on a rigorous organising principle. After discussing Kremers's groups, Mendeleev noted that bringing elements like rubidium, thallium, and caesium to a system would not be possible until the identification of a "hypothetical basis that is capable of serving as the support for a rigorous system."[59] To attain a rigorous system, Mendeleev argued that it should be organised according to the atomic weights. But his assessment of the other systematisation attempts suggests that even though atomic weights allowed for rigour, both completeness *and* rigour were needed to attain a natural system of elements. In other words, it was insufficient to have a complete list of findings or a rigorous arrangement that lacked in material.[60]

Thankfully, completeness and rigour were mutually inclusive. In Mendeleev's description of his first attempts of systematising the elements, he outlined taking the elements with the smallest atomic weights and organising them according to their weights. He then noticed that there was "almost like a period of properties of simple bodies, and even the atomicity [valency] of the elements follows one another in arithmetic order according to their atomic weights." After organising the light elements in this way, Mendeleev made two rows of similar elements with high atomic weights. It appeared that the row of light elements (Li, Na, K, Ag) was analogous to the rows of heavier ones (C, Si, Ti, Sn, and N, P, V, and Sb). The analogous relationship was so striking that "[i]mmediately a hypothesis was born: are not the properties of the elements expressed by their atomic weights, [and] wouldn't it be possible to form a system based on them?" Mendeleev's initial organisation implied that the ordering according to weight was compatible with the more traditional ordering according to the "natural groups" or qualitative similarities.[61]

The importance of Mendeleev attached to the expression the natural groups shows that completeness was not just about accounting for many elements. Instead, it involved finding a place for their qualitative properties, especially their

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[58] Both quotes from D. I. Mendeleev, "Sootnoshenie Svoistv s Atomnym Vesom Elementov," in Kedrov, *Periodicheskii zakon*, 15, emphases added. For a description on Kremer's triadic systems, see Boeck, "The Periodic System," 47–71.

[59] First quote on Mendeleev, "Sootnoshenie Svoistv," 15.

[60] Mendeleev, "Sootnoshenie Svoistv," 17–18.

[61] Both quotes from Mendeleev, "Sootnoshenie Svoistv," 18.

similarities. When developing his periodic system, Mendeleev discussed how several chemical and physical properties found a suitable place in the system. He especially considered valency (which he called atomicity), steps of oxidisation (how some elements shared the same form of oxide, and the gradual transitioning across the system in how much oxygen the elements could combine with); basicity and acidity; metals and metalloids; compounds with fluorine, nitrogen, ammonia, and hydrogen; isomorphism; homologues; atomic volumes, electrochemical behaviour; organometallic compounds; volatility; reactivity; and how rare or typical the elements were. It was this emphasis on the qualitative properties that makes Mendeleev's systems more complete than those of others.

The importance of qualitative properties becomes especially clear in Mendeleev's later publications of 1871, where he continued providing detailed explanations of their distribution on the periodic system. Especially in his 1871 article "Natural system of elements and its application to the determination of properties of undiscovered elements," he argued that it was important to consider several properties to show that one had established a natural system. For example, in his critique of systems based on valency, Mendeleev argued that they provided artificial systems at best. Writing with a full awareness of the fact that Meyer's table based on valences was published before his "attempt" of 1869, Mendeleev argued that such systems were merely artificial, because they focussed on one property instead of many. In Mendeleev's words, "Just as the division of elements according to the electric and metallic properties … does not constitute natural resemblances … similarly, the division of elements according to the so-called atomicity [valency] is based on completely conventional assumptions … and must be considered as artificial systems of elements, i.e. based on one or a few properties."[62]

In this article, Mendeleev offered an updated version of his system (Figure 8). He proposed calling it a natural system of elements on the grounds that information on the elements and their compounds was expressed with "unexpected simplicity and succession" on its framework. Mendeleev argued that his updated system had the following advantages over his previous "attempt" of a system: firstly, the initial version had placed cerite metals (cerium and uranium) in unsuitable positions, which seemed to threaten the naturalness of his systematisation. The second problem concerned the layout of the original "attempt." Although it had initially appeared a "convenient representation of all relations," it placed alkali metals and haloids together, even though they were different. As can be seen from his updated periodic system, the abovementioned groups are further apart from one another. Thus, in iterating the system, Mendeleev sought to bring the qualitatively similar elements closer to each other and keep dissimilar ones apart.[63]

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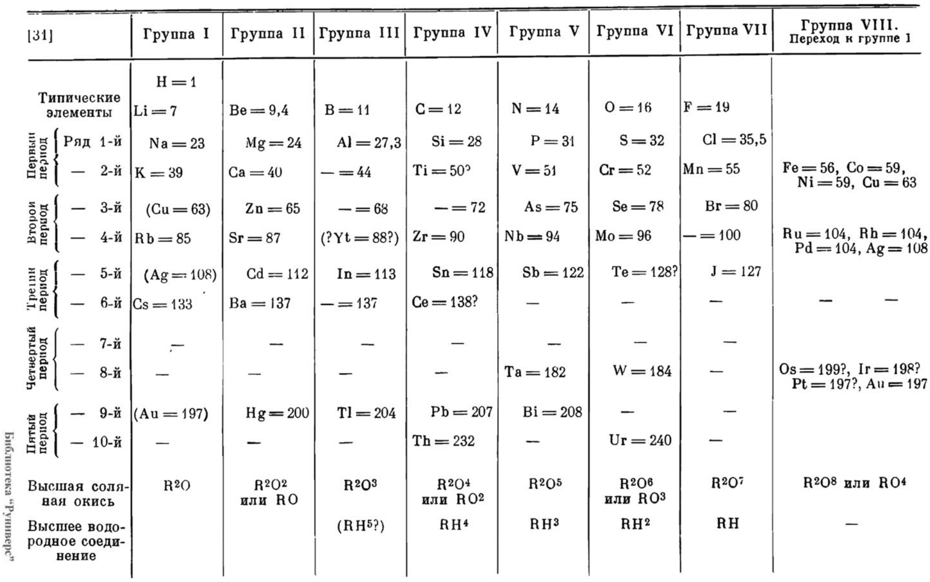
[62] D. I. Mendeleev, "Estestvennaya Sistema Elementov i Primenenie Ee k Ukazaniiu Svoistv Neotkrytyh Elementov," in Kedrov, *Periodicheskii Zakon*, 69.

[63] Mendeleev, "Estestvennaya Sistema," 69–70.



[31]		Группа I	Группа II	Группа III	Группа IV	Группа V	Группа VI	Группа VII	Группа VIII. Переход к группе I
Типические элементы		H = 1 Li = 7	Be = 9,4	B = 11	C = 12	N = 14	O = 16	F = 19	
Первый период	Ряд 1-й	Na = 23	Mg = 24	Al = 27,3	Si = 28	P = 31	S = 32	Cl = 35,5	
	— 2-й	K = 39	Ca = 40	— = 44	Ti = 50?	V = 51	Cr = 52	Mn = 55	Fe = 56, Co = 59, Ni = 59, Cu = 63
Второй период	— 3-й	(Cu = 63)	Zn = 65	— = 68	— = 72	As = 75	Se = 78	Br = 80	
	— 4-й	Rb = 85	Sr = 87	(?Yt = 88?)	Zr = 90	Nb = 94	Mo = 96	— = 100	Ru = 104, Rh = 104, Pd = 104, Ag = 108
Третий период	— 5-й	(Ag = 108)	Cd = 112	In = 113	Sn = 118	Sb = 122	Te = 128?	J = 127	
	— 6-й	Cs = 133	Ba = 137	— = 137	Ce = 138?	—	—	—	— —
Четвертый период	— 7-й	—	—	—	—	—	—	—	
	— 8-й	—	—	—	—	Ta = 182	W = 184	—	Os = 199?, Ir = 198? Pt = 197?, Au = 197
Пятый период	— 9-й	(Au = 197)	Hg = 200	Tl = 204	Pb = 207	Bi = 208	—	—	
	— 10-й	—	—	—	Th = 232	—	Ur = 240	—	
Высшая соляная окись		R^2O	R^2O^2 или RO	R^2O^3	R^2O^4 или RO^2	R^2O^5	R^2O^6 или RO^3	R^2O^7	R^2O^8 или RO^4
Высшее водородное соединение				(RH^5?)	RH^4	RH^3	RH^2	RH	—

FIGURE 8. One of Mendeleev's systems of 1871.

In his elaboration of the new version of his system, Mendeleev again emphasised how the qualitative properties of the elements were distributed on it. When observing, say, the first group of elements (Li-Au), it became clear that every "seventh element" repeated a "sequence of the common chemical characteristics." More specifically, first there were the metals with high valency, which were then followed by metalloids and metals capable of providing acids with lower valency.[64]

Similarities between the elements could also be found in what Mendeleev called the greater periods. A smaller period was expressed on the row of "typical elements" (from lithium/Li to fluorine/F). On the second, fourth, and eight rows we may find the greater periods. They included roughly seventeen members, as the rows transition to a cluster of elements in group VIII. Thus, in the period starting with sodium (Na) there is no eighth after chlorine (Cl), but in the period beginning with potassium (K), we can find that it is followed by group VIII. For Mendeleev, the metals of group VIII shared many similar properties. This was especially visible from how the metals lost hydrogen from their pores; from how they formed ammonium-potassium compounds (which had a character similar to cobalt); provided double-cyanogen compounds and acids; and their atomic volumes were close and rather small (ranging from 7.1 to 9.4).[65]

Apart from discussing the similarities in groups and periods, Mendeleev also drew attention to the distinct character of the periods on even and odd rows. Elements on the even rows tended to be more basic, and its metals did not appear to provide

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[64] Mendeleev, "Estestvennaya Sistema," 75.

[65] First quote on the typical elements is from the table itself. Discussion on greater periods is on Mendeleev, "Estestvennaya Sistema," 77.

organometallic compounds or hydrides. In contrast, many of the elements of the odd rows seemed to provide organometallic compounds.[66]

After having elaborated regarding the distinct character of the even and odd rows, Mendeleev considered the groups on the vertical columns in greater detail. He argued that elements in each group formed higher oxides, hydrides, and chlorides in a principled manner that could be represented with a schematic compound form (see bottom rows of Figure 8). As can be seen from the table, Mendeleev included these schematic rows of oxides and hydrides on the system, which renders them visually more complete, too. Mendeleev then proceeded to give a lengthy explanation of the chemical characteristics of elements in each column and concluded his article by predicting properties of three undiscovered chemical elements he titled ekaboron, eka-aluminium, and eka-silicon.

Completeness and usefulness

So far, we have seen how completeness involved accounting for the high number of elements and many of their qualities. In his seminal article of 1871, "Periodic Law," Mendeleev implied there was a relationship between having a complete system and its usefulness. In particular, completeness seemed to pave the way for applying the system to make predictions. Before implying the connection between having a complete system and its application to predicting, Mendeleev made some remarks about the aims of chemistry, which imply his valuing of completeness. For him, the very goal was the "study of the dependence between the fundamental properties of elements and the composition, reactions, and qualities of those simple and compound substances formed by them." (This sentiment he repeated in the introduction to his textbooks.) The periodic system constituted both an example of such a study and a springboard for further studies made in that vein.[67]

Similarly to his previous papers, Mendeleev started his article with a comparison between different potential organising principles for the system. He deemed physical properties unsuitable, because they were not known "in that level of precision and generality that would allow for creating a *complete* scientific system."[68] As to using chemical properties as an organising principle, Mendeleev noted that "Lack of [exact] measurements of these properties renders them unsuitable for generalizing chemical findings; considerations built only on these properties will always suffer from unsteadiness." Despite this, he stressed that they should not be left "out of sight" as "many sides of chemical findings can be generalized with their help."

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[66] Mendeleev, "Estestvennaya Sistema," 78–9.

[67] D. I. Mendeleev, "Periodicheskaya Zakonnost," in Kedrov, *Periodicheskii Zakon*, 102. Mendeleev also emphasised the importance of completeness in his introduction to the first edition of his textbook, where he stated that "In natural sciences there are no axioms that could help in presentation of those sciences like geometry ... It is this side of the subject that forced me to add ... a more specialised goal: to state together with conclusions a description of the methods of their extraction, enter to one systematic whole as much data as possible without surrendering to extremeness of a scientific encyclopaedia." D. I. Mendeleev, "Osnovy khimii," in *Izbrannye sochineniia*, ed. A. N. Bahu et al. ((1934) Leningrad: Onti: Gos-khimtekhizdat Leningradskoe otdelenie, 1871), 55.

[68] Mendeleev, "Periodicheskaya Zakonnost," 103, emphasis added. As to specific physical properties, Mendeleev listed cohesion, heat capacity, coefficient of refrangibility, and spectral phenomena in this context.

The emphasis on not losing a sight of chemical properties implies that Mendeleev associated completeness with the uses of the system; especially that of making generalisations.[69]

This link between completeness and usefulness reappears soon. After considering physical and chemical properties as potential organising principles, Mendeleev stated that:

> Upon the wish to generalize the properties of elements, to subject them for rigorous investigations that allow for *practical conclusions and chemical predictions*, it is necessary to pay attention both to the shared properties that belong to the particular group of elements … and to its individual properties.[70]

This implies that completeness in accounting for different properties – including shared and individual ones – was no longer just a matter of ensuring that he had a natural systematisation at hand. Doing so helped to render the system useful for making predictions.

Mendeleev concluded this evaluation of potential organising principles with the foreseeable point that only atomic weights offered a firm foundation for systematisation. As atomic weight was a fundamental property of the elements, studying the relationship between atomic weights and other properties of the elements was of importance. But as he was not the first one to engage in such a study, he saw it appropriate to review the existing attempts towards this direction. Perhaps as a response to Meyer, Mendeleev started by considering the relationship between atomic weights and valency. He argued that the studies of valency expressed uncertain results. From the point of view of valuing completeness, Mendeleev's diagnosis of the uncertainty of the studies on valency is telling; he worried that it had been investigated in isolation from other properties of elements. He recommended to study the relationship between *many* properties of elements and their atomic weights, not just one. This emphasis on focussing on "many" over the "few" demonstrates how Mendeleev sought to foreshadow the greater completeness of his system.[71]

Mendeleev then elaborated on some other attempts of mapping the relationship between atomic weight and other properties.[72] He saw three problems in particular in such studies. Firstly, they did not tie together *all* known natural groups into one whole, but left the relationships between the individual members of groups as unexpected and inexplicable phenomena. Secondly, investigators had given attention mostly to similar elements with close atomic weights. This problem was related to the third issue; the investigations to the "simple and exact" relations in the atomic weights of dissimilar elements were scarce. Mendeleev stressed that the investigation of relations between dissimilar elements enabled identifying the "right"

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[69] Mendeleev, "Periodicheskaya Zakonnost," 104. In this context, he noted that they included at least basicity, acidity, the capability to combine (or not combine) with hydrogen and chlorine, and the capability to provide salts.

[70] Mendeleev, "Periodicheskaya Zakonnost," 104, emphasis added.

[71] Mendeleev, "Periodicheskaya Zakonnost," 105.

[72] Here, Mendeleev referred to the studies of J. H. Gladstone, J. P. Cooke, M. Pettenkofer, P. Kremer, J. B. Dumas, E. Lenssen, W. Odling in particular.

(*pravil'noye*) relationships between the changes in the atomic weights and the other properties. Again, this discussion illustrates Mendeleev's call for completeness in considering many elements and similarities between all kinds of elements – not just those that had similar atomic weights.[73]

After deeming the existing studies on the relationship between atomic weights and other properties of the elements lacking, he proposed the "law of periodicity" that was "applicable to study the relations between the properties and the atomic weights of all of the elements." The rest of the article elaborated on the periodic systems and applied it to determine the properties of little-known and unknown elements. Retrospectively, especially his predictions regarding unknown elements have been deemed highly accurate.

In summary, Mendeleev's articles give us several instances of such valuing of completeness: (1) he included a large number of elements in the system, (2) discussed how at least seventeen properties found a suitable place in the system, (3) emphasised the importance of completeness for a systematisation, (4) suggested places for undiscovered elements, and (5) incorporated more information (e.g. the row of oxides) to the visual layout of the system.

Conclusion

Looking at the values that guided the development of periodic systems helps excavate unified themes underlying many of the seemingly distinct design-choices. Meyer's use of precise atomic weights was not divorced from the dotted lines of his graph – both signalled the quality of atomic weight data. Similarly, the round order numbers and double-bookings on Newlands's system were connected in virtue of clearly expressing the "simple relation." And Mendeleev's call for including many elements was in line with his system's two extra rows depicting schematic compounds.

Apart from revealing such underlying connections amongst chemists' design choices, applying the framework of values to this episode in history of chemistry also help to explain how the systems differed. Newlands argued that his systems identified a simple relation, and sought to present his Law of Octaves so as to express that simplicity. Meyer warned against thinking that the periodic system expressed a "simple law."[74] Instead, he emphasised carefulness in distinguishing between different kinds of data. Mendeleev aimed to make his system more complete through considering both a large quantity of elements and many of their qualities.

However, none of the chemists elevated just one value. The Law of Octaves was complete in terms of how many elements it included, although it offered only minimal elaboration of how qualitatively similar elements were represented on its grid. As to Meyer, his systems included fewer elements than those of Mendeleev and Newlands, but Meyer also offered a more thorough elaboration of

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[73] Mendeleev, "Periodicheskaya Zakonnost," 106–7.

[74] Gordin, "The Texbook Case of a Priority Dispute," 73.

how qualitatively similar elements were distributed on the system. With Mendeleev, we saw that he emphasised the importance of rigour, but there are also occasional instances of valuing carefulness. For example, he noted that he had expressed atomic weights in round numbers because he saw little certainty in the accuracy of the atomic weights expressed with several decimal numbers.[75] (This is most likely a response to Meyer's use of more precise atomic weights.) Despite such qualifications, the systems of Newlands, Meyer, and Mendeleev are distinct in how *much* emphasis was placed respectively on simplicity, completeness, and carefulness.

Some other contrasts in the chemists' approaches have been previously identified, though: their views on theories and predictions differed. As to theorising, Meyer had the most developed argument in defence of the usefulness of theories in chemistry. In contrast, Mendeleev was far less bold in his theoretical views, and resisted various theories throughout his career. (He was especially suspicious of atomic theory, as it was in tension with his belief in the absolute individuality of the elements.) Newlands, whose system was accused of being overly theoretical, did not dwell on the relationship between empirical data and theories.

As to making predictions, all of the three chemists made brief interpolations on atomic weights of the missing elements. However, upon a closer inspection, especially Meyer and Mendeleev had different ideas about the function of predictions. Mendeleev argued that the periodic law could be used to predict properties of both little-known and undiscovered chemical elements. In contrast, Meyer saw a threat of over-valuation of hypotheses in making predictions in this way.[76] For Meyer, predictions were more instrumental; they could guide experimental work. For example, in his textbook, Meyer permitted predictions of the characteristics of unknown elements in order to compare them with future observations. In his own work, however, Meyer favoured brief atomic weight interpolations and predicting the atomic weights of *little-known* elements in order to detect errors in accepted atomic weights.[77]

The framework of values offers some explanation to chemists' differing views on theories and predictions. With Meyer, carefulness in the selection of data paved the way for more reliable theories that could be then used in further empirical investigations. As to his predictions, Meyer's idea of their usefulness gives us the link between carefulness and predicting: had such atomic weight predictions been done on the basis of data deemed shaky, they would have been more risky and unreliable guides for experimental work. And, as we saw, Meyer's suggestions on indium's atomic weight were on the smooth-line areas of his curve – where atomic weight and volume data were well-established – rather than the dotted-line, less certain areas of the curve.

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[75] Mendeleev, "Periodicheskaya Zakonnost," 115.

[76] Gordin, "The Texbook Case of a Priority Dispute," 73–4.

[77] Gordin, "The Texbook Case of a Priority Dispute," 75–6; Rocke, "Lother Meyer's Pathway to Periodicity," 299–300.

With Mendeleev, there is an especially clear link between his valuing of completeness and his views on prediction; his consideration of many of the qualitative properties informed his predictions of the characteristics of undiscovered elements that belonged to the group of resembling elements.[78] However, Mendeleev's reluctance to embrace theories is not explained by his valuing of completeness (although his commitment to the individuality of the elements explains his resistance of atomic theory).

As Gordin has shown, Newlands's systems were viewed as rather theoretical. In particular, the order numbers which allowed Newlands to express the simple relation more clearly also gave it a more theoretical appearance, which contributed to the difficulty of getting it published.[79] As to making predictions, the regularity of the numerical relation seemed to help him in interpolating the atomic weights of undiscovered elements.

Thus, the framework of values does not solely clarify the differences between the periodic systems of Meyer, Mendeleev, and Newlands, but also explains some of the already identified contrasts between the approaches of the chemists. Although this article lays out the evidence in favour of values guiding the development of the early periodic systems, it remains to be seen whether they played as strong a role in their reception.

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[78] Pulkkinen, "The Value of Completeness."

[79] Gordin, "Paper Tools," 40, 51.