MENDELEEV, MEYER, AND ATOMIC VOLUMES: AN INTRODUCTION TO AN ENGLISH TRANSLATION OF MENDELEEV'S 1869 ARTICLE "ON THE ATOMIC VOLUME OF SIMPLE BODIES" (1)

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Supplemental material

Introduction

The German chemist Julius Lothar Meyer (1830-1895) is well known for having pointed out that the atomic volumes of the chemical elements vary in a regular way as a function of increasing atomic weight, in a paper submitted in December 1869 and published in March 1870 (2). In this paper, Meyer summarized this correlation in a graph that quickly became known as Meyer's curve (3). This visual display of the data, which made it easy to see the rise and fall of the atomic volume of the elements with increasing atomic weight (Figure 1), remains today an iconic representation of an important scientific correlation (4).

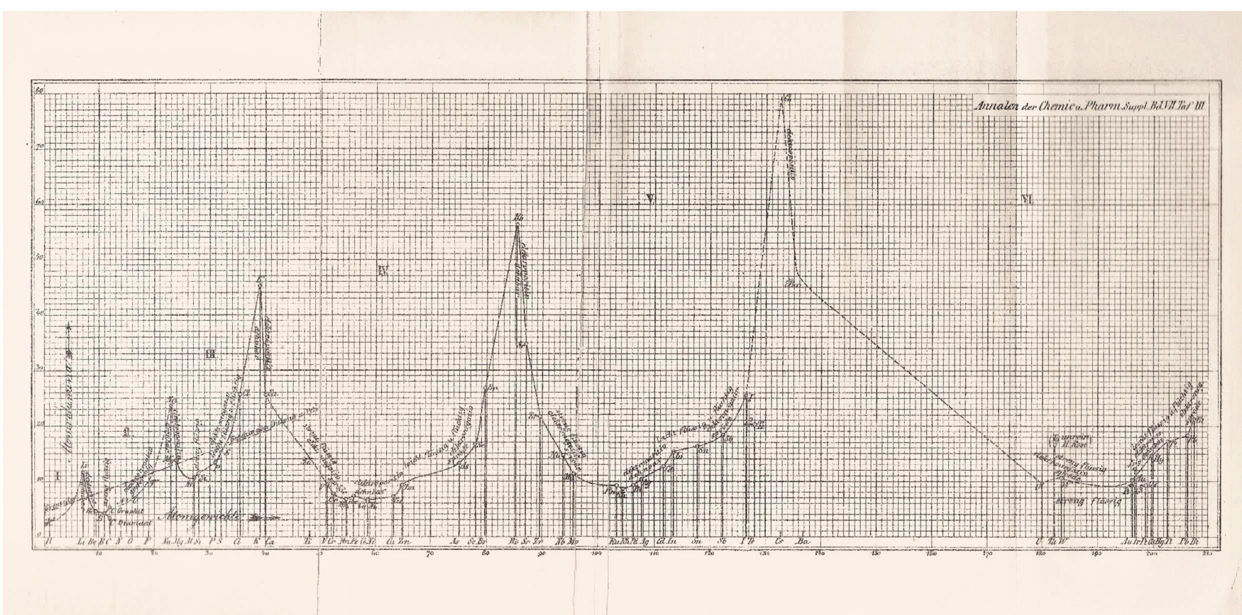


***Figure 1**. Meyer's curve, from Ref. (2). Although this chart has often been reproduced, the resolution is invariably poor. This figure has been constructed from new scans of the original journal publication. A high-resolution digital image is included in the supplemental material.*

Meyer had been prompted to submit his paper in response to a brief abstract in German of the periodic system that Dmitri Ivanovich Mendeleev (1834-1907) had submitted in March 1869 (5) to the *Zhurnal Russkogo Khimicheskogo Obshchestva* (*Journal of the Russian Chemical Society*) (6). Because neither Mendeleev's first journal publication nor his 1869 book *Osnovy Khimii* (7) contained a detailed discussion of the dependence of atomic volumes on atomic weight, it is often assumed that Meyer was the first to reveal this relationship (8).

But on the 23rd of August 1869 (O.S.; 4 Sep 1869 N. S.), a few months after having published his announcement of the periodic system, and several months before Meyer's paper was submitted, Mendeleev presented his second full paper on his periodic system to the chemical section of the Second Congress of Russian Scientists and Physicians, held in Moscow. A short abstract of the paper Mendeleev read was published at the time of the Congress (9); the full paper did not appear until the Congress proceedings was printed in early 1870 (10).

In part because this 1869 Congress paper has never been translated in its entirety from the original Russian into English or German (11, 12), it has often been ignored in discussions of Meyer's curve and the early history of the periodic system. To be sure, a few scholars have discussed it briefly, as we will mention below, but this paper deserves greater attention for at least three reasons: (a) as the second full paper that Mendeleev wrote on his periodic system it gives valuable insights into his early thinking, (b) it contain Mendeleev's first detailed predictions of the properties of undiscovered elements, and (c) it shows that Mendeleev had anticipated Lothar Meyer's 1870 paper on the periodic relationship of atomic volume to atomic weight.

Historical Context of Mendeleev's 1869 Congress article

In order to better understand the historical context of Mendeleev's 1869 Congress paper "On the Atomic Volume of Simple Bodies," we present a short history of the relevant science of the time. Atomic volumes (and the related concept of molar volumes) are easily calculated by dividing the atomic or molecular weight (g/mol) of a substance by the density (g/cm^3), earlier called the specific weight, of a solid sample of the substance. Before the mole was named or formally defined, atomic and molar volumes were reported as unitless quantities; today, they are reported in units of cubic centimeters per mole. Atomic volumes played an important role in the development of chemistry in the 19th century (13).

The concept of atomic volume had been devised in 1821 (14) by the French chemists Auguste Le Royer (1793-1863) and his student Jean Baptiste André Dumas (1800-1884). The main part of Le Royer and Dumas's paper was devoted to descriptions of their studies of the densities of various inorganic substances, such as silica, boric acid, chalk, alumina, gypsum, and the oxides of copper, bismuth, lead, and mercury. They then used these measured densities to compute the molar volumes of these substances, and found that many of them (but not all) were integer multiples of the molar volume of ice. Similarly, turning to a group of twenty solid elements, they found once again that the atomic volumes were in simple whole number ratios to one another. To some extent, the attempt by Le Royer and Dumas to find regularities in the atomic volumes of the chemical elements resembles Prout's similar effort six years previously (15) to find regularities in the atomic weights of the elements.

All of the numerical relationships in Le Royer and Dumas's paper, unfortunately, were the result of over-interpretation of a limited body of data. Many of their atomic volumes do not match modern values, because they depend on the atomic weight assigned to the element. Some of their atomic weights (and thus atomic volumes) were correct, but quite a few were not (as was common in those pre-Cannizzaro days). The importance of Le Royer and Dumas's paper lies not so much in its results and analysis, but rather in its definition of a new physical property—atomic volume—and its role in stimulating other chemists to investigate this property.

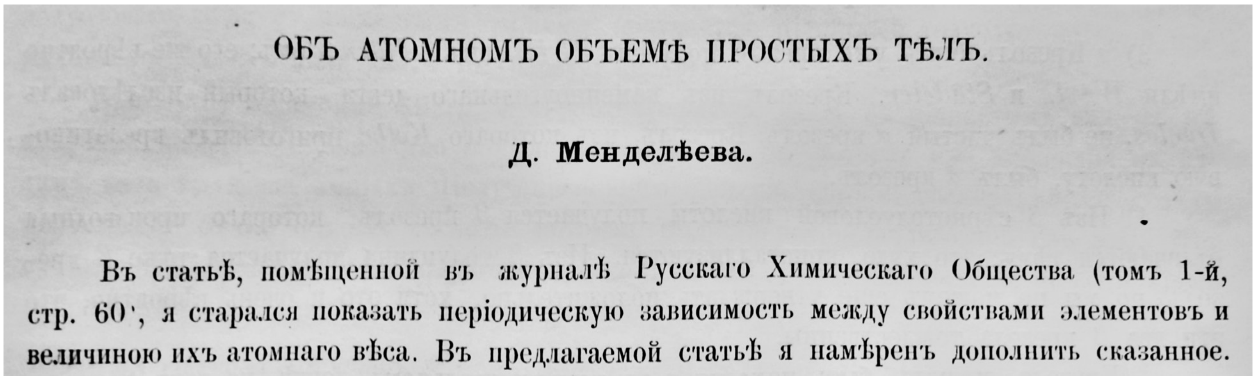
About ten years later, in 1830, the French chemist Polydore Boullay (1806-1835) wrote his doctoral thesis on the subject of atomic volumes (16). In it, Boullay reported that he had been unsuccessful in finding what he had initially sought: a law relating the atomic volume of an element in the uncombined state to that of its volume after combination. But he went on to suggest another kind of relationship: that the atomic volumes of the elements were correlated with their cohesive ability. Boullay noted that the greatest cohesion is found for elements with the smallest atomic volume (such as carbon), and the weakest for elements with the largest volume (such as sodium and potassium). Just as for Le Royer and Dumas, however, Boullay's correlation was based in part on flawed data: for example, his atomic volume for carbon was two times too small because he assigned to this element an atomic weight of six that was commonly used at the time, but which in actuality was half of the correct value.

In 1843, in a lecture to the Turin Academy of Sciences, the Italian chemist Amedeo Avogadro (1776-1856) discussed a topic closely related to his famous hypothesis of 1811. Whereas his earlier paper concerned the molar volumes of gases, in this later paper Avogadro studied the molar volumes of solids and liquids (17). Avogadro summarized his goals as follows: "I sought to establish that the atomic volumes of simple bodies in the solid state . . . depended on their electro-chemical quality, being so much more electro-positive or less electro-negative" (18). In particular, of the elements that are either solids or liquids (or could be rendered such by cooling), Avogadro found that the smallest atoms (such as oxygen and chlorine) were the most electronegative whereas the largest (such as sodium and potassium) were the most electropositive (19).

Atomic and molar volumes formed an important role in Mendeleev's own chemical education: his master's thesis of 1856 (20), which was exclusively devoted to the topic, showed that molar volumes exhibited consistent mathematical regularities. He pointed out, for example, that the molar volume of potassium hydroxide is approximately equal to the average of the molar volumes of potassium oxide and water. Moreover, the tables in his master's thesis often list the elements according to what eventually would be groups in the periodic table: for example, the alkali metals Li, Na, and K are listed in that order, and are immediately followed by the alkaline earths Be, Mg, Ca, Sr, and Ba.

The Translation and Content of Mendeleev's 1869 Congress Paper

Mendeleev's paper "On the Atomic Volume of Simple Bodies" was presented at the Second Congress of Russian Scientists, held in Moscow in the autumn of 1869 (10). The proceedings of the Congress, which were published early in 1870, contain Mendeleev's paper along with contributions from other Russian scientists, including the chemists Friedrich Konrad Beilstein (1838-1906), Alexander Mikhailovich Zaitsev (1841-1910), and Alexander Mikhailovich Butlerov (1828-1886). As far as we can determine, no hard copy of these proceedings exists in any library outside of Russia, and no electronic copy of them is available online as of 2019. The full text of Mendeleev's paper in the original Russian, however, can be found in the set of his collected works


ОБЪ АТОМНОМЪ ОБЪЕМѢ ПРОСТЫХЪ ТѢЛЪ.

Д. Менделѣева.

Въ статьѣ, помѣщенной въ журналѣ Русскаго Химическаго Общества (томъ 1-й, стр. 60), я старался показать періодическую зависимость между свойствами элементовъ и величиною ихъ атомнаго вѣса. Въ предлагаемой статьѣ я намѣренъ дополнить сказанное.

Figure 2. *Mendeleev, D. I., "On the Atomic Volume of Simple Bodies" Proceedings of the 2nd Congress of Russian Scientists, chemistry section (1869), p 62.*

Li = 7	Be = 9,4	B = 11	C = 12	N = 14	O = 16	F = 19
Na = 23	Mg = 24	Al = 27,4	Si = 28	P = 31	S = 32	Cl = 35,5
K = 39	Ca = 40	—	—	—	—	—
Cu = 63,4	Zn = 65,2	—	—	As = 75	Se = 79,4	Br = 80
Rb = 85,4	Sr = 87,6	—	—	—	—	—
Ag = 108	Cd = 112	—	Sn = 118	Sb = 122	Te = 128?	J = 127
Cs = 133	Ba = 137	—	—	—	—	—

Figure 3. *"Attached example" (table) from Mendeleev's Congress paper, (Ref. 10).*

(21). Even so, this paper has largely been unrecognized and undiscussed.

At the end of the present paper, we give a translation of Mendeleev's 1869 Congress article into English; here we wish to make a few remarks about its contents and significance. As has been noted by others (22), there are challenges associated with the translation of pre-Soviet Russian into English. A literal (or close to literal) translation of Mendeleev's text can sound ponderous and stilted. We have tried to be faithful to the original text, but in a few places we have made some stylistic changes and insertions (indicated with square brackets) to make the whole more readable.

The opening text of Mendeleev's 10 page paper (Figure 2) refers to the March article in which he announced his periodic system, and states the purpose of this follow-up paper:

> In an article published in the Journal of the Russian Chemical Society (Volume 1, page 60), I tried to show the periodic relationship between the properties of the elements and the magnitude of their atomic weight. In the present article I intend to supplement what has been previously said.

Mendeleev's paper starts by stating that "similar elements" can be classified into two kinds of groups: those in which the elements exhibit significant differences in atomic weight, and those in which the elements have similar atomic weights. The former groups "can be distributed in terms of the atomic weight into completely symmetrical groups, clearly showing the periodic dependence of the properties on the atomic weight, as can be seen from the attached example." The "attached example" is the short-form (here, a seven column) table in which, for example, the alkali metals and the coinage metals are placed in the same column (Figure 3). Mendeleev comments that, in this arrangement, the column number corresponds to the "atomicity" (= valency) of the elements, so that "the elements of the first column are monatomic, the second, third, and fourth represent di-, tri-, and tetraatomic elements; the elements of the fifth column are triatomic, sixth diatomic, and the seventh monatomic," where Mendeleev is using the term "monatomic" to mean "having a combining power of 1," etc. He further comments that elements with similar properties are placed close together and elements most diverse in chemical properties are farthest apart, so that metals and metalloids are on opposite sides of the table.

Li.	Be.	B.	C.	N.	O.	F.				
Na.	Mg.	Al.	Si.	P.	S.	Cl.				
K.	Ca.	—	Ti.	V.	Cr.	Mn.	Fe.	Co.	Ni. *	
* Cu.	Zn.	—	—	As.	Se.	Br.				
Rb.	Sr.	—	Zr.	Nb.	Mo.	—	Rh.	Ru.	Pl. *	
* Ag.	Cd.	—	Sn.	Sb.	Te.	I.				
Cs.	Ba.	—	—	—	Ta.	W.	—	Pt.	Ir.	Os.

Figure 4*. Table from Mendeleev's Congress paper (Ref. 10, p 65) including similar elements with similar atomic weights. Mendeleev does not comment on the meaning of the asterisks, but a logical guess is that they are to emphasize that Ni and Cu have similar properties and so do Pl (palladium) and Ag.*

Mendeleev then continues by considering the second category of groups of similar elements, those that have similar atomic weights. He identifies four such groups: the cerium metals (cerium, lanthanum and didymium); metals of the iron group (chromium, manganese, iron, cobalt and nickel, and also including titanium and vanadium), metals similar to palladium whose atomic weight is 104-106 (palladium, rhodium, ruthenium), and metals of the platinum group (platinum, iridium and osmium, and gold). He points out that many of these metals can be inserted into the table by taking advantage of chemical similarities (Figure 4).

Before we turn our attention to the main subject of Mendeleev's paper, atomic volumes, we point out that this Congress paper contains a notable advance in the prediction of properties of undiscovered elements (12). In the table Mendeleev included in his long March paper (6) there several gaps, three of which were filled with the entries, ? = 45, ? = 68, and ? = 70. But in reference to these entries, Mendeleev had said only the following: "We should still expect to discover many unknown simple bodies; for example, those similar to Al and Si, elements with atomic weights of 65 to 75." In the Congress paper, Mendeleev goes further (p 67):

> …it is possible to say that the two elements which are not yet in the system should show similarity to aluminum and silicon and have atomic weights of about 70. They will have atomic volumes of about 10 or 15, i.e., they will have specific weights of about 6, and thus will occupy just the middle ground, in all respects, or they will constitute a transition in properties from zinc to arsenic.

Several people had made correct predictions of the atomic weights of unknown elements before 1869 (23), but Mendeleev's 1869 Congress paper was the first to make clear-cut predictions about *other* properties of unknown elements. Meyer's 1864 periodic table can be seen in hindsight to have predicted the valencies of the two then-unknown elements gallium and germanium, but Meyer himself did not make such a prediction (24).

This 1869 Congress paper also contains Mendeleev's first suggestion that indium belongs in the aluminum series (25). Mendeleev had used an atomic weight of 75.6 for indium in his March 1869 paper (6), whereas one of the missing elements in the aluminum series, as he pointed out, should have an atomic weight of about 70. Mendeleev says (p 67),

> It may be that indium occupies a place in the aluminum series if, in determining the weight of an atom, it is possible to admit an error that might occur from incomplete purification from metals heavier than it (maybe cadmium).

In other words, he is proposing that indium's true atomic weight should be about 70. Late the next year (26), Mendeleev came up with the right explanation by recognizing that the atomic weight of 75.6 had been assigned assuming that indium was divalent. By assuming instead that indium is trivalent, its atomic weight of 113 indeed fits in the aluminum group, but one row below that of the element, gallium, that eventually was to fill the place with an atomic weight of 70.

We now turn to Mendeleev's discussion of atomic volumes, which occupies the bulk of the paper. He starts by stating (p 65):

> In order to clearly establish the dependence that exists between atomic weights and the specific volumes of various groups of elements, we shall first compare them in vertical and then in horizontal rows of the table. It has long been known that such homologous elements as potassium, rubidium, cesium, or calcium, strontium, barium, or phosphorus, arsenic, antimony, etc., display a gradual change in specific volumes with a change in atomic weight.

Mendeleev mentions in the latter context the work of Le Royer and Dumas.

Mendeleev goes on to list atomic volumes for all the other elements known at the time (p 65):

> Here are some examples of this: lithium has a specific weight of 0.594, and hence its volume = 11.2; potassium has an atomic volume equal to 44.8; rubidium 56.1; beryllium, corresponding to lithium in the series of alkaline earth metals, has a specific weight of 2.1, and therefore its volume is 4.5; it is less than the volume of lithium, just like the volumes of calcium and strontium are less than the atomic volumes of potassium and rubidium. Indeed, the specific weight of calcium = 1.58, and its volume = 25.5; the volume of strontium = 35.5, and barium about 30.

In tracing the change in atomic volume down a group, Mendeleev is here repeating analyses that had previously been done by others. But then he considers a problem never before discussed: how do the volumes change across a period? Here is how he introduces this issue (p 66):

> The volume of lithium is close to 12, beryllium 5; boron has a volume of about 4, because its specific weight is 2.68. Carbon, which follows boron in the series of elements above, has a specific weight that varies much, depending on the modification [i.e., allotrope]. Only in the form of diamond, whose specific weight = 3.54, is the volume of carbon less than that of boron; in the form of graphite, it is already greater, viz. = 5.7, because the specific weight of graphite is close to 2.1; in the form of coal, the volume of the carbon atom is even greater. Therefore, it is not possible to say with certainty whether the volume will increase or decrease when we pass along the first row of elements from carbon to nitrogen, oxygen and fluorine. By analogy with other rows, however, it is more likely to exhibit an increase, for example, similar to the one that exists in the transition from Si to P, S and Cl, or from Sn to Sb, Te and I.

What follows in the paper is a lengthy and detailed discussion of atomic volumes for elements in the later periods of the periodic table. This discussion includes several generalizing statements of which the following is one (p 66): "in horizontal rows corresponding to Li, K, Rb, Cs as the atomic weight increases, at first the volume decreases rapidly, and then remains almost constant." Here, Mendeleev is referring to rows beginning with Li, beginning with K, etc.; in the short form of the periodic table, these rows end in the "group 8" transition elements. The intervening rows, starting with Cu and Ag in the short-form table, show different behavior (p 67):

> For [the silver] row, therefore, with an increase in the atom weight, the specific volume also increases, despite the difference in chemical character; . . . It is

> obvious that the regularity that is so obvious in the silver series, is less apparent [in the copper row], although there is still a continuous increase in the specific volume with an increase in the weight of the atom.

Mendeleev mentions that the allotropy of carbon, phosphorus, and sulfur makes it more difficult to draw conclusions about the trends in atomic volumes across the relevant periods, because the different allotropes have different densities and thus different (and quite distinct) calculated atomic volumes.

The last part of Mendeleev's paper returns to the changes in atomic volumes within individual vertical groups, paying special attention to the relationships between elements that we now classify as "main group elements" and "transition metals." Thus, Mendeleev compares the atomic volumes (and other chemical properties) of chromium and sulfur, and manganese and chlorine, among others.

Mendeleev concludes his paper with a short discussion of how the molar volumes of compounds cannot be calculated from the atomic or molar volumes of their constituents. Mendeleev does not cite Boullay in this context, but instead credits his earlier master's thesis on specific volumes, published in 1856 (20).

Who Gets the Credit?

In his 1869 paper in the *Proceedings of the Second Congress of Russian Scientists*, Mendeleev discussed in great detail the variation of atomic volumes as a function of increasing atomic weight (i.e., across the rows of the short form of his periodic table). Mendeleev states that the atomic volumes of the elements, when arranged in order of increasing atomic weight, show the following behavior across the periods of the short form of the periodic table: starting with the alkali metals, the volumes initially *decrease* and then stay relatively constant, whereas starting with the coinage metals, they *increase*. Although Mendeleev did not explicitly state that the volumes fall, stay constant, and then rise between one alkali metal and the next (i.e., as viewed in terms of a long-form view of the periodic table) it is clear that Mendeleev's discussion embodies the same trend. In other words, Mendeleev's 1869 Congress article codifies textually what Meyer's chart shows visually.

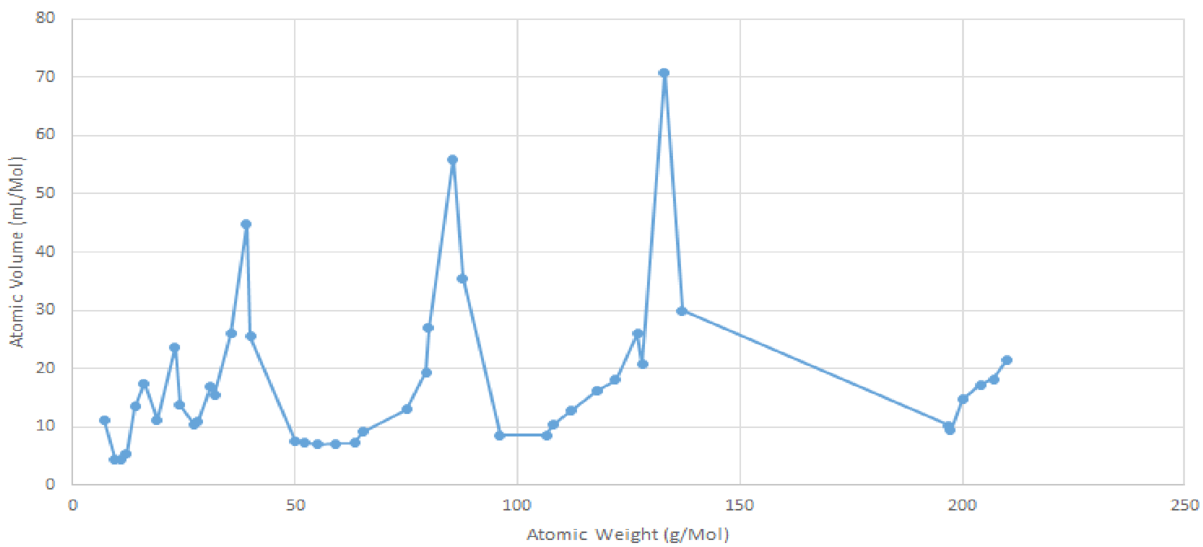


Figure 5*. Plot of atomic volume vs. atomic weight taken from data in Mendeleev's Congress paper (Ref. 10, pp 62-71).*

In the course of his Congress paper, Mendeleev gave values for the atomic volumes of essentially every element known at the time. Mendeleev did not convert these data into a chart, but instead described the trends he saw in words. We can take the data in Mendeleev's paper, however, and do what he did not do: construct a chart of atomic volume vs. atomic weight; the result is shown in Figure 5. It is no surprise that the plot replicates Meyer's almost exactly, because they both had the same raw data in hand. Of course, Mendeleev takes 10 pages of dense text to describe what Meyer's curve shows in a single glance.

Mendeleev's paper is followed by a note added in proof, written after he had seen Meyer's 1870 paper. In this note, Mendeleev gives Meyer credit for devising a way to increase the clarity of the relationship between atomic volume and atomic weight, while making the point that the Congress paper contained all the essential ideas (p 71):

> **Note**. The foregoing was communicated by me at the Congress in August 1869. In 1870, in *Liebig's Annalen* (after this article was sent by me for printing), an article by Lothar Meyer appeared, dealing with the same subject. Mr. Meyer's conclusions are based on the assumption of the system of elements proposed by me and agree with those that I have made with respect to the volumes of atoms. He also pays special attention to the descending and ascending series of elements and to the sequence of volume changes. But the conclusions were increased in clarity by the graphic image attached to the article. By putting this postscript I have no desire to raise the issue of scientific priority, (in my opinion, these questions do not often have any academic interest), and I only want to point to the table attached to Mr. Meyer's article as a means of capturing and explaining those complex relations, which are indicated in the previous text.

Much has been written about the priority conflict between Mendeleev and Meyer (27 -29). Both Mendeleev and Meyer came to be recognized as independent discoverers of the periodic table. For example, they were jointly awarded the Davy Medal from the Royal Society in 1882, "For their discovery of the periodic relations of the atomic weights" (30). The content of Mendeleev's 1869 Congress paper supports and extends the conclusion that the two men independently devised many of the important ideas behind the periodic system. Although credit for the graphic representation of the periodic dependence of atomic volumes on atomic weight is Meyer's alone, it is clear that in August 1869 Mendeleev wrote about this dependence in great detail, analyzing the change in atomic volumes across periods of the periodic table, several months before Meyer—in December of that year—submitted his paper on the same topic.

Supplemental Material

The following can be found in the Supplemental Material for the *Bulletin for the History of Chemistry* at the journal's website, http://acshist.scs.illinois.edu/bulletin/index.php:

1. An image of the original article,

2. A transliteration of the original article (omitting the Russian characters eliminated in 1918) side-by-side with the English translation, and

3. A high resolution image of Meyer's curve (Figure 1) from Ref. (2).

Acknowledgment

We wish to thank Andrei Rykhlevskii for transcribing the Russian text into electronic format, and Dr. Taras Porogolev for his help in improving the translations of idiomatic words and phrases into English. We also gratefully thank Prof. David E. Lewis for his detailed critique of the translation and Prof. Michael Gordin for several helpful suggestions.

References and Notes

1. Presented at the 256th National Meeting of the American Chemical Society, Boston, MA, Aug. 21, 2018, HIST 26 in the HIST Award Symposium Honoring David Lewis.
2. J. L. Meyer, "Die Natur der chemischen Elemente als Function ihrer Atomgewichte [The Nature of the Chemical Elements as a Function of their Atomic Weights]," *Ann. Chem Suppl.*, **1870**, *7*, 354-364.
3. C. T. Blanshard, "The Position and Character of Mercury and Copper, Founded upon their Atomic Weights," *Chem. News*, **1875**, *32*, 151-152.
4. E. Tufte, *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, CT, 1997.
5. For a timeline of Mendeleev's early publications on the periodic system, see M. Kaji, "Mendeleev's Discovery of the Periodic Law: The Origin and the Reception," *Found. Chem.*, **2003**, *5*, 189-214.
6. D. I. Mendeleev, "Sootnoshenie svoistv s atomnyn vesom elementov [The Correlation of Properties with the Atomic Weights of the Elements]," *Zh. Russ. Khim. Obshch.*, **1869**, *1*, 60-77. Most non-Russian chemists (including Meyer) learned of Mendeleev's work through the abstract of this paper, translated into German and printed in D. Mendelejeff, "Über die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente [On the Relation of the Properties to the Atomic Weights of the Elements]," *Z. Chem.*, **1869**, *12*, 405-406. Mendeleev's formulation of the periodic law was also briefly noted in *Ber. Deut. Chem. Ges.,* **1869**, *2*, 553-555 as part of a letter written by Victor von Richter. For a translation of the full article in *Zh. Russ. Kim. Obshch*., see W. B. Jensen, *Mendeleev on The Periodic Law: Selected Writings, 1869-1905,* Dover, Mineola, NY, 2005, pp 18-37.
7. D. I. Mendeleev, *Osnovy Khimii [Principles of Chemistry*], Tovarishchestvo 'Obshchestvennaia Pol'za', St. Petersburg, 1869, Vol. 1.
8. For example, Partington cites Mendeleev's August 1869 Congress paper (i.e., the subject of the present article) but

says only that it contains a periodic table in the modern form. Partington then discusses Meyer's first publication on the periodic properties of the elements, and credits him for "the well-known atomic volume curve showing maxima and minima with increasing atomic weights." J. R. Partington, *A History of Chemistry*, vol. 4, Macmillan and Co. Ltd., London, pp 895-896. Ihde makes no mention of Mendeleev's August 1869 Congress paper at all, but prominently describes Meyer's paper, which "included the curve resulting when Meyer plotted atomic weights against atomic volumes; he observed that similar elements appeared at similar places on the curve; non-metals are on the ascending sides, and metals on the descending sides and in the valleys." A. J. Ihde, *The Development of Modern Chemistry*, Harper & Row, New York, NY, 1964, p 251.

9. Mendeleev's paper is briefly abstracted in an anonymous summary of the chemical papers given at the 1869 Congress in *Zh. Russ. Khim. Obshch.*, **1869**, *1*, 229-230. This short abstract says very little about Mendeleev's ideas about atomic volumes:

   D.I. Mendeleev reported on the periodicity of the atomic weights of the elements and the system of elements proposed on this basis by him in the current year (*Journal of the Russian Chemical Society*, vol. 1. p. 60 and his work *Osnovy Khimii*). The [system] based on the values of the atomic weights not only 1) expresses their chemical similarity, but also 2) conforms to the division of elements into metals and metalloids, 3) distinguishes [elements according to] their atomicity, 4) juxtaposes similar elements of different groups (e.g., B, C, Si, Al, Ti), 5) explains the similar homology of corresponding elements which many chemists have pointed out, 6) distinguishes hydrogen from the typical elements as modern science recognizes, 7) groups together in one place common elements that are mutually accompanying in nature, 8) show the insufficiency of Prout's hypothesis, and 9) even indicates the relation of elements according to their mutual affinity. Moreover, 10) a comparison of the atomic volumes and atomic weights of elements belonging to different rows shows to some extent the naturalness of the system as well. So for example the silver row displays the following weights:

Atomic weights					
Ag-108	Cd-112	Sn-118	Sb-122	Te-128	J-127
Atomic volumes					
10.5	8.6	7.3	6.7	6.2	5.0

   Therefore, the development of further results from the concept of the periodicity of the properties of the elements set in rows in terms of atomic weights is considered by Mendeleev to be able to lead to important consequences in connection with the nature of the elementary bodies of chemistry.

10. D. I. Mendeleev, "Ob atomnom ob'eme prostykh tel [On the Atomic Volume of Simple Bodies]," in *Trudy Vtorogo S'ezda Russkikh Estestvoispytatelei v Moskve 20-30 Avgusta 1869* [*Proceedings of the Second Congress of Russian Scientists in Moscow 20-30 August 1869*], **1870**, Chemistry section, pp 62-71.

11. The footnote Mendeleev added in proof to his 1869 Congress paper, and one other paragraph, was translated into German in D. Mendeleev, "Zur Geschichte des periodischen Gesetzes [On the History of the Periodic Law]," *Ber. Deut. Chem. Ges*., **1880**, *13*, 1796-1804; the footnote was translated from German into English in J. W. van Spronsen, "The Priority Conflict Between Mendeleev and Meyer," *J. Chem. Educ*., **1969**, *46*, 136-139. The footnote, and several other short passages, were translated from the original Russian into English in J. R. Smith, "Persistence and Periodicity: a Study of Mendeleev's Contribution to the Foundations of Chemistry," Ph.D. thesis, Chelsea College (University of London), 1976, p 171 et passim; Smith's thesis can be accessed at https://kclpure.kcl.ac.uk/portal/files/2925773/473179.pdf (accessed Oct. 25, 2019).

12. A translation into English of a brief portion of Mendeleev's 1869 Congress paper, on the prediction of the atomic volumes of ekasilicon and ekaaluminum, appears on p 352 of Smith's 1976 thesis (see Ref. 11 above) and more fully in M. D. Gordin, *A Well-Ordered Thing: Dmitrii Mendeleev and the Shadow of the Periodic Table*; Basic Books, New York, 2004, p 34.

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