Zamecki, Stefan

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MUZEUM HISTORII POLSKI

UNIVERSITAS VARSOVIENSIS

Stefan Zamecki (Poland)

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Introductory note

Most historians of chemistry agree that the periodic table and the periodic law were discovered by Dmitri Ivanovich Mendeleev (1834–1907), which is said to have happened in Sainkt Petersburg on 17 February 1869. Some historians go as far as to regard the eminent Russian chemist as the sole discoverer, while the others, notably A. E. Beguyer de Chancourtois, J. A. R. Newlands, W. Odling, G. D. Hinrichs and J. L. Meyer, were merely precursors of the periodic table and the periodic law. The former position is taken mainly by Western historians, notably by J. W. van Spronsen, the author of several interesting studies on the history of classification of elements.[1] The other more radical view is voiced mainly by Soviet historians among whom we should mention R. B. Dobrotin, B. M. Kedrov, A. A. Makarenia, D. N. Trifonov.[2] At any rate, even those who say the discovery of the periodic law was the job of several men name Mendeleev as one of the discoverers. I know of no one who would question Mendeleev the title of "discoverer," in 19th or 20th-century historical studies.

The fact that no historian challenges Mendeleev's title to "discovery" is proof of the wide acclaim the Russian chemist got for his work, but it certainly does not decide the question of whether Mendeleev was at all *the discoverer of the periodic table and the periodic law in chemistry*. The answer of course depends on how you interpret the terms "discoverer," "periodic table" and periodic law." But as there is no exact definition of the term "discoverer" or related terms (such as "scientific discovery," say), it is difficult to draw any positive knowledge from propositions such as "*A* is the discoverer," where *A* stands for some person. While the value of such propositions is debatable, the word itself does have a positive ring in colloquial language, and that tends to boost the prestige of a researcher referred to as "discoverer."

But let us not dwell on the semantic implications of the term "discoverer" or related ones and let us go back to the title question without saying for the time being whether or not Mendeleev was the discoverer of the periodic table and the periodic law in chemistry. Needless to say, the replies may differ depending on the meaning of the terms.

In this article, I take for granted a number of established facts from the history of chemistry, such as the one that Mendeleev and other 19th-century chemists did publish studies speaking of the classification of chemical elements.

"Chemical element" in their works stood for natural products with the same general features, specifically products which could no longer be decomposed by chemical methods yet were capable of entering what were called "chemical" reactions (synthesis, analysis, replacement). But some 19th-century chemists did not rule out the possibility that the natural products described as "chemical elements" were mixtures or even some kinds of compounds of other chemical elements and so liable to decomposition using chemical or physical methods. Such views were not at all unusual in the 19th century. At any rate there is good reason to say that many chemists then agreed that certain natural elements products were called "chemical elements," implying that those products were no longer decomposable via chemical methods. Many attempts were made to classify those products in various classifications, "natural" and "artificial" alike. The former included classifications involving periodicity, to mention those put forward by Beguyer de Chancourtois, Newlands, Odling, Hinrichs, Meyer, Mendeleev and their many continuators.

19th-century considerations about chemical elements were generally linked to chemical atomic theories espoused by John Dalton and his successors. But not all 19th-century systematists believed chemical atomic theory was really necessary for the scientific study of chemistry. What Wilhelm Ostwald, the outstanding physical chemist, thought about that is well known, what the outstanding systematist Mendeleev did is less widely known. According to Mendeleev, chemists could excellently do without atomic terminology in research. Mendeleev considered himself to be a continuator of Dalton's work and used those terms himself, especially the term "atomic weight," yet that is a very debatable claim for calling him justifiably an "atomist" in chemical research. Descriptions of him as a "materialist," or an "instinctive dialectical materialist," as Soviet historians, especially B. M. Kedrov, used to do until a short time ago, is likewise a debatable idea. Viewed from the angle of modern chemistry, Mendeleev can be described as a representative of *disciplined eclecticism*, an attitude which is perhaps best described as a medley of realistic views (implying that an objective reality does exist) with minimalistic views (that reality can only be known by its appearance, and only quantifiable scientific laws can be formulated).[4] Mendeleev's faith in minimalistic concepts shows in his estrangement from any theories which involved atomistic theories in such or other versions, whether in Dalton's or W. Prout's versions or those of J. J. Berzelius,[5], S. Arrhenius, N. Morozov,[6] and partly in Marie Skłodowska-Curie's theory. At the same time, though, Mendeleev was remarkably opposed to certain extremely positivistic ideas, notably the theory advocated by Ostwald. A close look at the entire body of Mendeleev's philosophical ideas could perhaps reveal some interesting facts, for considering his great prestige in the scientific community he must have had quite great influence on the philosophical views of his readers.[7] I am sure there is a great deal to be found there.

Mendeleev's first studies

In 1855 Mendeleev graduated from the Physics and Mathematics Faculty of the Main Pedagogical Institute (of Sainkt Petersburg) where he had studied under he chemist A. A. Voskresenski. On completing his curriculum at the college Mendeleev submitted a thesis called *Izomorphism v sviazi s drugimi otnosheniami kristalicheskoi formy k sostavu*.[8] That was a very penetrating study showing that Mendeleev was very much at home with the Western literature of the subject.

In September 1856 Mendeleev submitted a thesis for his first scientific title, Master of Chemistry, called *Udelnyie obiomy*, some extracts from which were published in the same year,[9] while the remaining passages appeared in print only one century later, in 1960.[10] Reading that thesis you will find yourself wondering how it was possible that as excellent a study was produced at the Main Pedagogical Institute, a college not renowned for its excellence in chemical research. No doubt one of the reasons for that was the young scientist's enormous talent and diligence, but Voskresenski's shrewd scientific guidance must have been a great help too.

In 1859 to 1861 Mendeleev stayed at Heidelberg University as a visiting researcher. Mendeleev came home almost fully ripe for his future work as scientist, which he owed mainly to his contacts to leading European chemists and his part in the First Congress of Chemists in Karlsruhe (1860). But then, he also wrote a rather unimpressive study, called *Chastischnoie stseplenie nekotorykh zhidkikh organicheskikh soiedinenii*,[11] a result of his Heidelberg research activities.[12]

From Karlsruhe Mendeleev wrote his tutor, Voskresenski, a lengthy letter, which was actually a report on the congress debates. The letter was published already in the same year in Sainkt Petersburg.[13] The most important point in the letter is Mendeleev's interest in the atomic weight values put forward by Stanislao Cannizzaro. But Mendeleev's does not seem to have been impressed by Cannizzaro's findings. There is some evidence (which I am going to point to later on in this article) that Mendeleev kept to C. Gerhardt's old system of atomic weights (1843). That had a great (adverse) effect on Mendeleev's further work on the classification of elements.

In fact, Mendeleev came home from Heidelberg holding all the theoretical premises which he needed for his job, and so the stage was actually set for his attempt to build the periodic system already at that stage. Some difficulties persisted, of course, the fact, for instance, that indium, In, had not been discovered by then. Indium, incidentally, gave Mendeleev quite a hard time later on. Nor did Mendeleev know a lot about cesium, Cs, an element discovered only in 1860. Rubidium, Ru, and thallium, Tl, were both discovered only in 1861, so he could not have known anything about them either. Still, all the scientific data which were needed were at hand then, and yet for two reasons – both of them of academic nature, if I am not mistaken – Mendeleev did not try to classify the elements in 1861.

For one, Mendeleev took a job with Sainkt Petersburg University as reader in organic chemistry in that year. That was a new line in chemistry for him. He must have spent a lot of time preparing his lectures, especially that he was also working on a book on organic chemistry at the same time. The book appeared in print in 1861 as *Organicheskaia khimia.*[14] That was the first original organic chemistry textbook to be published in the Russian Empire. The important fact about it is that it was written from the angle of the Avogadro-Gerhardt theories. Mendeleev also devoted much space in the book to physical properties of chemical organic compounds. The book contains the following list of equivalents (and atomic weights) of chemical elements in relation to hydrogen,[15]

H = 1	As = 75	Fe = 28
Cl = 35.5	C = 12	Zn = 32.7
Br = 80	B = 11	Sn = 58.8
J = 127	Si = 14	Pb = 103.5
O = 16	K = 39	Cu = 31.7
S = 32	Na = 23	Hg = 100
N = 14	Ca = 20	Ag = 108
P = 31.2	Ba = 68.5	Pt = 98.8

These figures demonstrate that, first, Mendeleev confused the notion of atomic weight with that of equivalent, because he attributed equivalents to some elements and atomic weights to other ones, and, secondly, that he had not adopted Cannizzaro's position by then but remained – with a few minor modifications – faithful to Gerhardt's figures.

The other reason for his failure to start work on classifying chemical elements already in 1861 was that Mendeleev then still clung to Gerhardt's theory. Beguyer de Chancourtois was the first important systematist, albeit not chemist, to take up Cannizzaro's values, and so that is led him to one part of the periodic system in 1862.

In December 1865, Mendeleev was appointed professor at Sainkt Petersburg University's technical chemistry chair, but in October of the same year he also took over the general chemistry chair there, which had been vacated by Voskresenski. Also in that year, Mendeleev started his lectures in general and inorganic chemistry, which he continued in the following years.[16]

In one of his published lectures of 1867/68 Mendeleev sets forth a table of elements along with their atomic weights.[17] Those figures shown that Mendeleev had in the meantime inched closer to Cannizzaro's position. The table is arranged in the alphabetical order of names in Latin. It consists of 63 elements, including a fictious one called didymium, Di (not to be confused with dysprosium, Dy). All those – and only those – elements were included by Mendeleev in his first table of 1869, along with the same mistakes as before.

Mendeleev's work as reader in general and inorganic chemistry resulted in the production of his textbook *Osnovy khimii*, the first part of which (published in March 1869) sets forth the following atomic weights:[18]

H = 1	Mg = 25
O = 16	Zn = 65.3
N = 14	Cu = 63.5
C = 6	Hg = 200
Cl = 35.5	Pb = 207
J = 127	P = 31
Na = 23	Al = 27.4
K = 39	Cr = 52
Ag = 108	Mn = 55
S = 32	Fe = 56
Ca = 40	Si = 28

Compared with those in his *Organicheskaia khimia* the above atomic weights show Mendeleev had dropped Gerhardt's atomic weights system in favour of Cannizzaro's, with one remarkable exception though. He attributed carbon, C, the value 6, which was as much as that attributed by Gmelin (1827) and Dumas (1828). That was a big mistake, which Mendeleev corrected on 17 February 1869 in his table of elements.

Embracement of Cannizzaro's atomic weights was a precondition for the proposed classification of elements to make sense from the point of view of chemical theory. Other systematists, about whom I wrote elsewhere,[19] had adopted the Cannizzaro system before Mendeleev did and so they could arrive at their own periodic tables earlier.

It is hard to say now exactly why it was only in 1869 that Mendeleev embraced Cannizzaro's theory.[20] I can only surmise that on his return from Heidelberg in 1861 he found no one in Sainkt Petersburg to discuss his doubts seriously with. Russian and Soviet commentators quite simply ignore this point. So, unless you make a thorough study of Mendeleev saw the truth in a sudden fit of illumination on 17 February 1869. Not so. Mendeleev was led up towards his periodic table by his earlier studies, lectures and writing the *Osnovy khimii*. It is also likely that his perusal of Western studies had induced him strongly both to drop Gerhardt's old system and indeed to take up the job of classifying chemical elements. This calls for a few words of comments.

Classification as such, not only of chemical elements but also of objects studied by mineralogists and biologists, was a fascinating job to Mendeleev as early as during his college studies at the Main Pedagogical Institute. Soviet commentators, among them L. S. Kerova, believe that Mendeleev was strongly influenced in his views by three professors of the college, Voskresenski, S. S. Kutorg and F. F. Brandt. Kerova says that his interest in biology induced Mendeleev to employ, *by analogy*, the comparative method introduced in biology by G. Cuvier and fruitfully developed by Gerhardt and A. Laurent in chemistry. She also thinks Mendeleev got impulses from biology to look for a natural classification of elements, which he opposed to different artificial classifications, and that he planned to write several books on topics which he found of interest as an amateur encyclopaedist. If Kerova's findings are reliable, then the atmosphere at the Main Pedagogical Institute must have indeed induced Mendeleev to adopt an open-minded attitude towards problems which haunted scientists both in the Russian Empire and in Western European countries. That open-mindedness of his found best expression in Mendeleev's chemical views, especially in his tenuous embracement of Gerhardt's and Laurent's positions on the one hand, and his half-hearted adoption of Berzelius's theories with the rejection of his dualistic (electrochemical) theory of composition of chemical compounds.[21]

Many students of chemical history have noticed that Mendeleev was out for general laws in natural science. That desire found expression in the 1850s when he embarked on a study on specific volumes of gaseous substances, which grew out of his fascination with Newtonian mechanics and on which Mendeleev believed all chemistry would rest in future. Mendeleev, it will be recalled, studied possible applications of the Boyle-Marriotte law showing (as did others) that some gases did not behave strictly in keeping with that law. Mendeleev's search for general laws is widely held to be evidence of his allegedly materialistic outlook. Some commentators, B. M. Kedrov among them, regard Mendeleev as a champion of what they called spontaneous dialectical materialism. While it is undeniable that Mendeleev did show certain features of dialectical thinking, that is really a far-fetched qualification on Kedrov's part.

I am recalling all these facts to put in context Mendeleev's accomplishments in the classification of elements, and to point out that his statements must be interpreted very carefully. As far as his classificatory work is concerned, this means no more than this: he sought to put his natural classification of elements on an objective foundation. But taking that as evidence of his being a materialist would be a tall order indeed. Mendeleev fits well into that class of scientists who can be described as disciplined eclectics, a class which embraced 19th-century materials and positivists, among others.

Mendeleev's first periodic table

So, only after he had embraced Cannizzaro's system of atomic weights could Mendeleev proceed to the question of classification of elements, which took him eventually to his periodic table. From 17 February 1869 through to his death in 1907 Mendeleev worked on that matter, continuing research done by his European and American predecessors.[22] The years of 1869 to 1871 were his most successful period, which historians sometimes refer to as "the period of discovery," during which he produced an impressive 31 original studies on that matter.

In January 1869, Mendeleev began to write the first two chapters of the second part of his *Osnovy khimii*. In keeping with his initial philosophy of studying elements by virtue of their valencies, Mendeleev began that work with a study of the potassium group of monovalent elements. When he was done with the first two chapters Mendeleev faced the question of which group of elements to take up next. The question was compounded by the occurrence – between the typically monovalent potassium group and the typically bivalent group of alkali earth metals – of the copper group of metals which behave like monovalent elements towards some compounds and like bivalent (and even trivalent) towards other ones. At first Mendeleev sought to discuss the copper group right after the potassium group, but he changed his mind to look for some other principle which would enable him to arrange elements in their natural groups. He thought of the chemical affinity of elements in the broad sense (not only their valencies) and their atomic weights.

In February 1869, Mendeleev made his first attempt to classify all elements. On the 17th of that month Mendeleev had his first periodic table at hand. It was called *Opyt sistemy elementov osnovannoi na ikh atomnom vese i khimicheskom skhodstve*. Here it is:

			Ti = 50	Zr = 59	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104.4	Pt = 197.4
			Fe = 56	Ru = 104.4	Ir = 198
			Ni=Co = 59	Pd = 106.6	Os = 199
H = 1			Cu = 63.4	Ag = 108	Hg = 200
	Be = 9.4	Mg = 24	Zn = 65.2	Cd = 112	
	B = 11	Al = 27.4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	Se = 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?		

The elements arranged in this table look very much like a game of patience, which makes this table similar to the one published by the English chemist William Odling in 1864. In April 1869, F. N. Savchenko told Mendeleev at a session of the Russian Chemical Society in Sainkt Petersburg that Odling published in the Russian translation of his book (1867)[24] a table which looked very much like Mendeleev's. Mendeleev had this to say in reply (on 5 April that year), "But Odling says nothing about the meaning of his table, and as far as I can see he mentions it nowhere. I have had no idea of it, and I suppose most chemists have not either. If Odling believed his table was of any significance for theory, he would probably have written about that matter, which I think is of fundamental significance for chemistry. Yet in the book the table is called simply «Atomic weights and symbols of elements»."[25]

There is no evidence to maintain that Mendeleev knew Odling's table as he was developing his own. Let me therefore put it this way: the two tables are similar to each other. But of course it is very unlikely that Mendeleev should not have known Odling's table which was published in Russian translation two years before.

Soon after he published his first table Mendeleev wrote an article called *Sootnoshenie svoistv s atomnym vesom elementov*, which appeared in the official journal of the Russian Chemical Society (1869). From what Mendeleev says it follows the article must have been written not later than on 5 April 1869.[26] A summary of the contribution in German appeared in the same year in *Zeitschrift für Chemie*[27]

Mendeleev's article not only included the table of elements of 17 February 1869 but also supplied an analysis and elucidation of the way in which the table was developed. As he makes a close account of his reasoning, that article can be taken to be a reconstruction of the process that took Mendeleev to his result several weeks before, namely on 17 February.[28]

Mendeleev began with a discussion of previous classifications of chemical elements, those into (1) metals and nonmetals, (2) by their respective relations towards hydrogen and oxygen, (3) by their electrochemical order, and (4) by their valencies. He dismissed all of them as unsatisfactory saying that "at present there is no general principle that could survive a rigorous critical analysis, one that could be relied upon as a foundation for judgments on relative properties of elements, and which would justify their allocation in a more or less exact system."[29] But he mentioned none of the studies by chemists in circulation then.

Mendeleev criticised particularly sharply those classifications which were based on valencies (he used the word *atomnost*). He justly pointed out that some elements have different valencies; lead, Pb, for example, which was bivalent or tetravalent in relation to oxygen. If some elements are known to have different valencies, he concluded, then why not admit right away that other elements, such as hydrogen, may also have different valencies? Such an approach would sweep away all difficulties in the explanation of the existence or structure of any compound, even though there can be no absolute certainty of judgment either.[30]

Yet he conceded he had no doubt whatever that some elements made up "a natural sequence of similar forms of appearance of matter." That point, it will be recalled, was debated by systematists between 1817 and 1860. Mendeleev mentioned only P. Kremers, J. B. A. Dumas, M. von Pettenkofer, N. N. Sokolov and E. Lenssen in that connection. It looks he had not read other studies by Western systematists. Mendeleev in passing touched on the question of allotropy rejecting attempts to classify elements on the basis of such or other allotropic varieties. In his opinion, it made no sense to classify allotropic varieties of elements, but only elements themselves. The only property of elements that could be expressed in quantitative terms, and the only one to remain invariable for each element, was *atomic weight*. Gerhardt and Cannizzaro, Mendeleev argued, had supplied accurate enough values of that property, and so scientists no longer confused the notion of equivalent with that of atomic weight.[31] It will be observed, of course, that Mendeleev ought to have named Gerhardt in that connection, but only Cannizzaro.

That way Mendeleev justified his choice of atomic weight as the fundamental property of classification of elements. He wanted to base his classification on a property which could be compared inside the classified collection of elements.

Referring to his first tentative classifications, Mendeleev wrote, “In my first attempt I did this: I picked bodies of the smallest atomic weights and put them in the order of their respective atomic weights. It turned out that there was something like a *period* [italic mine] of properties of simple bodies, and even when taken by their valencies elements follow one another according to the arithmetic sequence of their values:

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; – ; Ti = 50; V = 51; – ; – .

In the class of elements of weights over 100 you will notice an analogous uninterrupted sequences, this one:

Ag = 108; Cd = 112; Ur = 116; Sn = 118; Sb = 122; Te = 128; J = 127.

It turns out that Li, Na, K, and Ag are in the same mutual relationship to each other as C, Si, Ti, Sn or as N, P, V, Sb are towards one another. At that point the question presented itself, was it not in atomic weights that properties of elements were best expressed? Wouldn’t it make sense to classify elements by virtue of their atomic weights?”[32]

His use of the term *period* perhaps indicates that Mendeleev thought of a periodic classification as he was writing the article or even before. The order of elements in Mendeleev’s table is the same as that given by de Chancourtois in his *Vis tellurique* (1862) except for hydrogen, H, but with vanadium, V. Other systematists in 1862 to 1869 put the elements in the same order.

Mendeleev went on in the article, “In the proposed order, each element is placed in keeping with its own atomic weight. This arrangement of the known simple bodies in the order of their respective atomic weights leads to the conclusion that the order of atomic weights is not at odds with natural similarities between the particular elements, indeed that such an arrangement directly indicates such similarities. It suffices to arrange them in the following six groups:

	Ca = 40	Sr = 87.6	Ba = 137
Na = 23	K = 19	Rb = 85.4	Cs = 133
F = 19	Cl = 35.5	Br = 80	J = 127
O = 16	S = 32	Se = 79.4	Te = 128
N = 14	P = 31	As = 75	SB = 122
C = 12	Si = 28	Sn = 118	

These six groups strongly point to a certain strict relationship between natural properties of elements and their atomic weights. But that relationship need not be one of homology, because no homologous differences are known to exist for elements whose values have been precisely determined. Although the respective weights of sodium and potassium, fluoride and chloride, oxygen and sulphur, carbon and silicon, each differ by 16, those of nitrogen and phosphorus differ by 17, but even more importantly, the differences between calcium and strontium, potassium and rubidium, chloride and bromide etc. are not the same, and the variation in them, first, betrays a certain regularity, and, secondly, it is much greater than the difference which can be attributed to the inaccuracy of test results. In the above figures you will notice a strict sequence in atomic weights horizontally in the rows and vertically in the columns. Tellurium's weight is the only value which seems to stand out from the regular sequence, but it may well be that its value has been wrongly determined, so if we take an atomic weight of between 126 and 124 for it instead of 128, tellurium's value will fit in very neatly".

All these observations of Mendeleev's had been made by his predecessors – systematists of the 1860s and, in some points, even way back in the 1850s.

Mendeleev went on, "All arrangements I have tried to make have led me to conclude that *atomic weight determines the nature of an element* to the extent to which the weight of a particle determines the properties and many reactions of a compound body. If that reasoning finds confirmation in the application of this principle to the study of elements, we shall have made a step towards the day on which the differences and similarities of elemental bodies are fully understood. I suppose the *law* [italics mine] I am putting forward is not at odds with the overall drift of natural science and that up to now no final proof has been provided, even though some sketches of it are available."[34]

What "sketches" he was referring to is difficult to say. Since Mendeleev used the term *law*, it may be useful to remark perhaps that Newlands had used the same term before when putting forward his *law of octaves* in relation to chemical elements.

Then Mendeleev proceeded to a tentative table of elements, giving the following one (in a note to the article)[35]:

Li	Na	K	Cu	Rb	Ag	Cs	-	Tl
7	23	39	63.4	85.8	108	133		204
Be	Mg	Ca	Zn	Sr	Cd	Ba	-	Pb
B	Al	-	-	-	Ur	-	-	Bi?
C	Si	Ti	-	Zr	Sn	-	-	-
N	P	V	As	Nb	Sb	-	Ta	-
O	S	-	Se	-	Te	-	W	-
F	Cl	-	Br	-	J	-	-	-
19	35.5	58	80	106	127	160	190	220

This table, as Mendeleev himself pointed out, was a planar projection of a cubic arrangement, and so, if turned by 90°, it was essentially a spiral system. Spiral systems had been proposed by de Chancourtois (1862) and Hinrichs (1867).

Mendeleev seems not to have been happy with this table, for alkali metals and halogens, both groups being monovalent (towards hydrogen), were too far from each other in it. So he tried a different arrangement, the one he built on 17 February 1869. Yet even that table did not make Mendeleev entirely happy. If he had it published nonetheless, then only because the latest table seemed the best of all considering the figures then at hand and the things he knew about the similarity of elements. His remarks show that he was aware of the debatable nature of his findings, especially those on elements on the fringes.

Mendeleev commented, "Many points are still unclear, say the position of elements which have not been explored well enough and which are in positions close to the margins of the table. Vanadium, for one – if Roscoe's findings are reliable – should be positioned in the nitrogen series, while its atomic weight (51) forces it between phosphorus and arsenic. Its physical properties seem to speak for the same placement of vanadium: thus, vanadium oxychloride, $VOCl^3$ [I am using Mendeleev's own symbols] is a liquid of specific gravity 1.841 at 14° and boiling point at 127°, which also brings it closer, for that puts vanadium oxychloride above the corresponding phosphoric compound. If we put vanadium between phosphorus and arsenic, we should then open a separate column for vanadium, the way we did before. In that column, a position then opens for titanium in the carbon series. Titanium is related to silicon and tin in the same manner, in this arrangement, as vanadium is to phosphorus and antimony. Under it in the series where there are oxygen and sulphur, perhaps chromium should be placed, in which case chromium will be related to sulphur and tellurium in the same manner as titanium is to carbon and tin. Accordingly, manganese should then be placed between chloride and bromide. The following part table would then emerge:

Si = 28	Ti = 50	? = 70
P = 31	V = 51	As = 75
S = 32	Cr = 52	Se = 79
Cl = 35.5	Mn = 55	Br = 80.

But of course that would break up the natural affinity of members of one horizontal series, even though manganese does display some affinity to chloride, just as chloride does to sulphur.

Moreover it would be necessary to open up a new column between arsenic and antimony, with niobium Nb = 94, which is analogous to vanadium and antimony, being put in that group of bodies. In the group together with magnesium, zink and cadmium, perhaps indium (In = 75.6?) should be placed in that column, if it belongs to the same series (if it is less volatile than Zn and Cd). Zirkonium, which has a smaller atomic weight than tin yet a greater one than titanium, would then have to be placed in the carbon and tin series, next to this last-named elements. In that way, a free position would open up in that horizontal series for an element between titanium and zirkonium."[36]

These observations are best proof of Mendeleev's intellectual acuity, so it is all the more disappointing that he did not try to arrange the table in the system he envisaged; he did that only two years later. But he was of course wrong in his suggestion about the possible placement of indium, and it was only Meyer who placed that element in the correct place (in 1870).

Mendeleev went on, "Still, despite all that I finally resolved not to create the extra two columns, for then some analogues which undoubtedly belong to different series would be left hanging. It suffices to indicate that Mg, Zn and Cd are analogous in many ways to Ca, Sr and Ba, and then I am sure it will be clear that a transfer of those bodies into one group Mg = 24, Ca = 40, Zn = 65, Sr = 87.6, Cd = 112, Ba = 137 would violate the natural affinity of elements."[37]

This shows that Mendeleev was in two minds. He could have done either of the following two things: (1) he could have introduced the new columns in his table whereby he would have slightly "simplified" the "patience-like" pattern of the table to make it more like the modern form, yet at the price of slightly obscuring the similarities between particular elements, or (2) he could have kept to the table of 17 February 1869. He eventually chose the latter of the two possibilities, apparently in an effort to keep to the natural similarity of elements. Later (in 1871) he returned to the former possibility slightly modifying his suggestions.

Mendeleev further observed that all elements which are common in nature have atomic weights between 1 and 60 (H, C, N, O, Na, Al, Fe, Ca, K, Cl, S, P, Si, Mg), whereas greater weights were found in elements which are not common in nature and are relatively unexplored. Newlands noticed the same fact (in 1872). But neither of the two drew the right conclusions – that came only half a century later.

Mendeleev was cautious about the positions he attributed to some elements, which showed in the question marks he put at some elements (yttrium, thorium, indium) which were little known in the 1860s. But Mendeleev very shrewdly observed that "The upper members of the fourth column (Mn, Fe, Co, Ni, Zn) step down to lower members of the same column where you will find Ca, K, Cl etc. So, cobalt and nickel, chromium, manganese and iron are those elements which, by virtue of their properties and atomic weights, mark the passage from copper and zink to calcium and potassium.

Perhaps on account of that their respective positions should be changed and instead of being placed in the upper rows they would find themselves at the bottom; then we would have got three columns of elements which display many similarities, namely a column containing cobalt, nickel, chromium, manganese and iron; a second column with cerium, lanthanum, didymium, palladium, rhodium, ruthenium; lastly, a third column including platinum, iridium and osmium."[38]

If you take him by his word, Mendeleev erred in all these observations. yet it was precisely there that Mendeleev later (in 1871) took up his idea of triads of iron-group metals and platinum-group metals (light and heavy metals) which was his original contribution.

Mendeleev also studied the position of hydrogen in the table. He found that hydrogen "had not found any definite position, due to its small atomic weight; it seems most natural to me to put it in the series of copper, silver and mercury, even though it belongs to some unknown series, below the copper series."[39] Again, if you take this literally, Mendeleev is wrong.

In connection with hydrogen's unclear position in the table Mendeleev thought it would be a very good idea to fill to gap caused by what he thought were missing elements between hydrogen and borium and carbon. A modern reader may be baffled by that idea, for except for helium Mendeleev put in his table all those elements which were indispensable between the just-mentioned ones (that is, lithium and beryllium). Perhaps he had by that time embraced the (wrong) hypothesis that beryllium, borium, carbon, nitrogen, oxygen and fluoride should all have lighter analogues, and that hydrogen should have a heavier analogue (above beryllium). As for helium, Mendeleev did not include it in his tables for decades. He developed the hypothesis about the analogues shortly before his death (in 1905).

There is one more point of significance. Mendeleev left in his table four positions with no symbols but only question marks with numbers attributed to them: ? = 45, ? = 68, ? = 70, ? = 80. Those figures correspond to the following elements discovered in the 19th or 20th centuries: scandium, Sc (1879), gallium, Ga (1875), germanium, Ge (1886), and hafnium, Hf (1922). The inclusion of those figures in the table was a first signal that Mendeleev would forecast the existence of some other elements in future. Mendeleev was not always the first to make such forecasts, and people like J. W. Döbereiner, M. Carey Lea, Newlands, "Studiosus", Hinrichs or Meyer predicted the existence of different elements before him.

Mendeleev summed up his article in the following eight points, which he included in the above-mentioned abridged German version of the article.[40]

"1. Properties of elements included [in the table] by virtue of their atomic weights evidently display a *periodic* nature.

2. Elements which appear similar to one another in very general chemical terms have either similar atomic weights (like Pt, Ir, Os) or consecutive

constantly increasing atomic weights (like K, Rb, Cs). The constancy of that increase has not been noticed by previous observers because in their calculations they did not use the conclusions of Gerhardt, Regnault, Cannizzaro and others who have determined the true atomic weights of elements.

3. Arrangement of elements or their groups in the order of their atomic weights corresponds to what is called *valency* (*atomnost*) and, to some extent, to the difference in chemical nature, which is clearly seen in the series, Li, Be, B, C, N, O, F and which exists in the other series.

4. Those simple bodies which are most common in nature have *small* atomic weights, and all elements of small atomic weights have well-pronounced properties. That is why they are typical [a word Mendeleev attached great importance to] elements. Hydrogen, as the lightest of all, is justly shown separately as the most typical element.

5. The *value* of atomic weight determines an element's properties, just as the value of a particle [more precisely, Mendeleev should say "molecular weight"] determines the properties of a compound body, and so compounds should be studied not only for properties or quantities of elements, not only for their reactions with one another, but also for their respective atomic weights. Thus, for example, S and Te, Cl and J etc. display not only similarities but also very clearly certain differences between one another.

6. Many *unknown* simple bodies [more precisely Mendeleev should have said "elements"] are likely to be discovered, say elements similar to Al or Si of values between 65 and 75.

7. The atomic weight value can sometimes be corrected when its analogues are known. The value of Te should not be 128 but 123–126? [this question mark is of significance at this point].

8. Some *analogues* of elements are visible by their atomic weights. Uranium, for one, turns out to be an analogue of borium and aluminium, as a listing of their compounds will confirm."[41]

The above points call for a word of comment. Points 1–6 were known to Western European chemists, especially systematists, between 1860 and 1869. Point 7 is Mendeleev's original idea, although he errs in his suggestion about tellurium, and again in that about uranium in point 8.

Let us go back to Mendeleev's table of 17 February 1869. That table holds 63 elements, including a nonexistent one, didymium, Di (dysprosium, Dy, was discovered only in 1886). Helium, discovered in the corona of the sun in 1868, was the only known element not to have been included in the table. Mendeleev's table can therefore be recognised as basically a complete and disjunctive classification of elements into their natural groups. The elements were placed horizontally in their natural groups, as far as Mendeleev could know them at the time. Altogether there were 19 such groups in the table. Odling's table (of 1864) consisted of 18 such groups, Newlands's (1864) of 10, Meyer's (1868) of 16 (including an empty one). From the standpoint of chemical properties, Mendeleev's table correctly classified a little over a majority of elements except manganese, Mn; mercury, Hg; hydrogen, H (which ought to have been put in the group of alkali metals and/or carbon C and/or fluoride F); zink, Zn, and cadmium, Cd, in one group along with beryllium, Be, and magnesium, Mg (these ought to have been split from each other, they way they were in subsequent years, but Mendeleev still knew nothing about even or odd series at that time); uranium, Ur (now U); gold, Au; thallium, Tl; lead, Pb; indium, In; thorium, Th; and their future triads: the iron-group and platinum-groups metals – all these elements ought to have been put in a different order.

Altogether, then, Mendeleev made twenty-two major mistakes about positions of elements in their natural groups. Cerium was only placed in the table, yet without being classed together with any other element. Erbium, Er, was debatably placed together with lanthanum, La, while yttrium, Y, with the nonexistent element didymium, Di, a totally wrong idea. So, Mendeleev attributed wrong or debatable positions altogether to as many as 27 elements – nearly one half of those he took into account.

Then there is the question of atomic weights adopted by Mendeleev. They were mostly the same as the values Cannizzaro presented to chemists at the Karlsruhe of 1860. Some of them are very different from those held as true today; the weights now attributed to thorium, Th, and uranium, U, are twice as big as those quoted by Mendeleev. Also remarkable is the position attributed (wrongly) to indium, In, which also has a wrong atomic weight.

With all those mistakes, Mendeleev's periodic table cannot be regarded as a very successful idea, which perhaps accounts for the lukewarm reception initially among world chemists. Things changed only in subsequent years.

For a conclusion

The above remarks about Mendeleev's first article concerning the classification of chemical elements lead us up to several important questions. The first one – which may seem preposterous considering what most leading world chemists have written – is, did Mendeleev develop his periodic table in 1869? This question may embarrass those who refuse to acknowledge the feature of "periodicity" in the tables proposed by de Chancourtois, Newlands, Odling, Hinrichs or Meyer. The critics put forward different arguments against those other tables, such as (1) that they were not complete; (2) that periodicity did not show in them well enough; (3) that the scientists who advanced them did not use the term "periodic" to describe them; (4) that they confused the notions of equivalent with that of atomic weight; (5) that they erroneously classified elements in the particular natural groups; (6) that they failed to foresee the existence and/or the properties of undiscovered elements; (7) that they failed to develop their preliminary findings; (8) that they wasted time trying to persuade the community of professional chemists each to their own priority in the discovery of the periodic table; (9) that they ignored Mendeleev's table for several years; and (10) that they drew no philosophical conclusions from Mendeleev's table.

All these charges, however justified they may be to some extent, make the answer to the question only more difficult. Still, the question is important enough, because Mendeleev is regarded as the man who discovered the periodic table in 1869, notwithstanding the many mistakes just mentioned. Why, then, is his table regarded as a periodic table? I think there are two reasons for that: first, Mendeleev's initial hypothesis was advanced in the conclusion to his 1869 article; and, secondly, Mendeleev's table was retrospectively viewed via later obviously periodic tables – to this day – as the one which was all the time so. Neither of these reasons is unimportant, but I still think they do not invalidate the view that other scientists had developed periodic tables even before Mendeleev. Mendeleev's 1869 table is as much a periodic table as those put forward by de Chancourtois, Newlands, Odling, Hinrichs and Meyer.

My next question touches on a delicate point: did Mendeleev just put together a periodic table, or did he also discover it? Scientific discovery as I see it[42] implies, as an indispensable component, the quality of *independence* of the scientist's progress. Did Mendeleev build his table independently? Nobody in their right mind will demand that a scientist performs everything entirely on his own. No scientist works in an empty world, and everyone necessarily has to use other scientists' findings, however far away those others may be. Independence in that sense means no more than that nobody must steal somebody else's findings in order to present them as their own. I have no reason at all to suspect that Mendeleev in 1869 knew earlier studies by five other systematists – de Chancourtois, Newlands, Odling, Hinrichs, and Meyer. Indeed, Mendeleev himself said on several occasions he had not known the studies written by the first three.[43] It is likely that he also did not know some studies by Hinrichs, which appeared in print in the United States, and anyway Hinrichs used to follow a different path than did Mendeleev. Meyer, then, remains as the likeliest rival of Mendeleev's for the title of discoverer of the periodic table. Here is what Mendeleev himself had to say about that.

Writing "On the History of the Periodic Law" (1881), Mendeleev said, "It is fair to use the term author of a scientific idea to describe a man who notices not only the its philosophical significance of the discovery but also its practical implications, and who is able to present the issue in such a manner that everyone can convince themselves of its truth. Subsequently the idea, as well as the substance, become indestructible. It may well be that

Newlands published something like a periodic table before me, but about J. L. Meyer not even that can be said. The present state of affairs about the periodicity of elements is a merit neither of Mr Newlands nor of J. L. Meyer" [retranslated].[44]

Mendeleev apparently evaded the question of whether or not he had drawn any ideas from Meyer's studies. He may have known Meyer's article of 1864 though. Yet even if that was the case, Mendeleev's 1869 table resembles by its "patience-shaped" appearance Odling's table of 1864 rather than Meyer's of the same year.

Mendeleev, then, can be justifiably said to have developed his periodic table independently; or, to put it differently, he can be regarded as the discoverer of the table.

The next question I would like to pose is this: did Mendeleev actually state the periodic law in 1869? In the 1869 article, he used the word "law" only once, never using the term "periodic law" or anything close to that,[45] and there is nothing in the context to show he was using the word in reference to the idea of periodicity. Mendeleev merely wrote, if I may say so, that "the value of atomic weight determines the nature of each element." But that observation is so general that even John Dalton and all his 19th-century followers could easily subscribe to it. In so general a formulation, that remark cannot possibly be recognised as the formulation of the periodic law, and it is at best just a springboard for the formulation proper which came later, in his extensive study called *Die periodische Gesetzmässigkeit der chemischen Elemente* (1871).[46]

So, a perusal of Mendeleev's studies indicates that in his 1869 article Mendeleev independently formulated and partly justified the periodic table, which means that tantamount to a discovery. In subsequent years, he modified and justified the table using the chemical and physical knowledge available to him at the time.

For many years historians of chemistry used to hold wrongly that Mendeleev discovered not only the periodic table but also the periodic law in 1869. That mistake was due, first, to their failure to see the difference between the table and the law. But they also seem not to have read closely enough Mendeleev's studies of 1869 to 1871.

For want of space I cannot discuss Mendeleev's other studies on the periodic table and the periodic law here. Interested readers may consult the relevant sections of my book.[47]

[1] Cf. J. W. van Spronsen, *The Periodic System of Chemical Elements. A History of the First Hundred Years*, Amsterdam 1969.

[2] See my reviews published from 1970 in different journals including *Kwartalnik Historii Nauki i Techniki* or *Człowiek i Światopogląd*.

[3] Cf. S. Zamecki, *The concept of scientific discovery and the history of the field of science* (in Polish), Wrocław 1988.

[4] Cf. S. Zamecki, "On the book *Evolutsia idei D. I. Mendeleeva v sovremennoi khimii* (ed. by B. P. Nikolski and L. S. Lilich)" (in Polish), *Kwartalnik Historii Nauki i Techniki* 1987 No. 2.

[5] Cf. S. Zamecki, "Methodological issues of 19th-century chemistry: Jöns Jacob Berzelius" (in Polish), *Człowiek i Światopogląd* 1984 No. 2; same author, "On Y. I. Solovev's and V. I. Kurinnoi's book *Jöns Jacob Berzelius. Zhizn i deiatelnost*" (in Polish), *Kwartalnik Historii Nauki i Techniki* 1983 No. 1.

[6] Cf. S. Zamecki, *Classification of chemical elements in the 19th century. A historical methodological study* (in Polish) Warszawa 1992, in which I refer to N. Morozov's views as a case of wild speculation in chemical research.

[7] I think we should be careful not to underrate the influence leading scientists have on views of broad circles of society. In fact, that influence may often have been stronger than that of professional philosophers.

[8] D. I. Mendeleev, "Izomorfizm v sviazi s drugimi otnosheniami kristalicheskoi formy k sostavu," in: *Periodicheski zakon*, edited, introduced and annotated by B. M. Kedrow, Moscow 1958 p. 616–635.

[9] D. I. Mendeleev, "Polozhenia izbrannyie dla zashchishchenia na stepen magistra khimii," in: *Periodicheski zakon. Dopolnitelnyie materialy*, edited with commentaries by B. M. Kedrow, Moscow 1960 p. 9–42.

[10] Ibid., p. 42–94.

[11] Part of this study was published in the Sainkt Petersburg journal *Gornyi Zhurnal* in 1860 pp. 380–381, 557–582.

[12] Sainkt Petersburg chemists did not think much of Mendeleev's Heidelberg endeavours.

[13] D. I. Mendeleev, "Khimicheski kongres v Karlsruhe," *Sankt-Persburskie Vedomosti* 1860 No. 238.

[14] Cf. D. I. Mendeleev, *Organicheskaia khimia* 2nd ed., Sainkt Petersburg 1863.

[15] Ibid., p. iv.

[16] Cf. D. I. Mendeleev, Izbrannyie lektsii po khimii, ed. by A. A. Makarenia, Moscow 1968,.

[17] Cf. D. I. Mendeleev, *Periodicheski zakon. Dopolonitelnyie materialy*, p. 210–201.

[18] D. I. Mendeleev, *Osnovy khimii* 1st ed. part i, Sainkt Petersburg 1869 p. 356f.

[19] S. Zamecki, "Classification of chemical elements in the 19th century" (in Polish), *Człowiek i Światopogląd* 1977 No. 9.

[20] Cf. A. A. Makarenia, D. *I. Mendeleev i fizikokhimicheskie nauki*, Moscow 1972 p. 39–42.

[21] Cf. L. S. Kerova, "Niekotoryie osobennosti tvorchestva D. I. Mendeleeva," in: *Evolutsia idei D. I. Mendeleeva v sovremennoi khimii*, Leningrad 1984.

[22] Especially J. P. Cooke and G. D. Hinrichs. Cf. J. W. van Spronsen, *op.cit.*

[23] I quote this table from Mendeleev's *Periodicheski zakon, op.cit.*, p. 9.

[24] Cf. W. Odling, *Kurs prakticheskoi khimii*, Sainkt Petersburg 1867, p. 224.

[25] D. I. Mendeleev, "Sootnoshenie svoistv s atomnym vesom elementov," *Zhurnal Russkogo Khimicheskogo Obshchestva* 1869 vol. 1 fasc. 3, p. 77.

[26] Ibid., p. 77.

[27] D. Mendeleeff, "Über die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente," in: *Zeitschrift für Chemie* Neue Folge 1869, vol. 5., p. 405f.

[28] Cf. B. M. Kedrow, *Filosofski analiz pervykh trudov D. I. Mendeleeva o periodicheskom zakone*, Moscow 1959, p. 38–57.

[29] D. I. Mendeleev, *Sootnoshenie..., op.cit.*, p. 64.

[30] Ibid.

[31] Ibid., p. 66f.

[32] Ibid., p. 67.

[33] Ibid., p. 68.

[34] Ibid., p. 69.

[35] Ibid., p. 70.

[36] Ibid., p. 71f.

[37] Ibid., p. 72.

[38] Ibid., p. 73.

[39] Ibid., p. 75.

[40] Cf. note 27.

[41] D. I. Mendeleev, *Sootnoshenie..., op.cit.*, p. 76f.

[42] Cf. note 3.

[43] Cf. D. I. Mendeleev, *Sootnoshenie..., op.cit.* and also his article "Periodicheskaia zakonnost khimicheskikh elementov," in: *Entsiklopedicheski slovar Brokgauza i Yefrona* vol. 23 part. 45, Sainkt Petersburg 1898, p. 318.

[44] D. Mendeleeff, "On the History of the Periodic Law," *Chemical News* 1881 vol. 43 No. 1103, p. 15.

[45] Cf. note 34.

[46] D. Mendeleeff, "Die periodische Gesetzmässigkeit der chemischen Elemente," *Annalen der Chemie und Pharmacie* Supplementband 8 Heft 2, 1871, p. 133–229.

[47] Cf. note 6.