

The Different Periodic Tables of Dmitrii Mendeleev

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The year 2007 is important as the 100th anniversary of the death of Dmitrii Mendeleev (1834–1907), creator of the periodic table of elements. The date 1907 is even more interesting because it precedes the atomic number concept discovered by Moseley in 1913 (1), and follows Becquerel's discovery of natural radioactivity in 1896 (2), and the isolation of the radioelements, radium and polonium, by the Curies in 1898 (3a).

Examining the changing format of the periodic table offers insights into Mendeleev's thinking and discoveries in chemistry from his first arrangement of 1869 to the final form of 1905. It is instructive to compare these tables with those published in Russian textbooks in 1931, and 1969 (the 100th anniversary of the periodic table). The 1931 book is the 10th revised edition of *Osnovy Khimii* by Mendeleev himself (4). The 1969 book, *Osnovy Obshchei Khimii* (5), is by Nekrasov. The tables in these two books bracket in time the form used for the monument celebrating the centenary of the birth of Mendeleev, erected in 1934 in St. Petersburg (Leningrad), Russia (6).

Initial Conceptions of Periodicity

Figure 1 shows the periodic table as published by Mendeleev in 1869. The elements are in columns and ordered on atomic weight from the top down. The groups as we understand them run from left to right, for example: N, P, As, Sb, Bi. There are question marks for the missing elements of atomic weights 45, 68 and 70 that he is sure must exist, but which have not yet been discovered. Thallium, Tl, and lead, Pb, are placed "below" Cs and Ba respectively, because of their misleading robust oxidation states of 1^+ and 2^+ . Hg and Au are also wrongly placed.

Note the placement of those elements that are positioned according to their atomic weights as accepted at the time: In, 75; Ce, 92; and Ur, 116. It was clear to Mendeleev that these weights were wrong (uranium between tin and cadmium!), so during 1870 he obtained pure samples of these three elements and determined their specific heats. He then used Dulong and Petit's law to determine their correct atomic weights: In, 113; Ce, 138; U, 240 (7). These values were incorporated into his remarkable table of 1871, reproduced here as Figure 2.

This revised table is quite beautifully complete, and the format is recognizable as what became the "short form" that was widely used until the 1950s. The elements are listed horizontally in order of atomic weight with the groups in vertical columns. Each vertical group contains two families linked by a common oxidation state: for example, in group II there are Be, Ca, Sr, Ba and Mg, Zn, Cd, Hg. This is very different from the 1869 arrangement where Be, Mg, Zn, Cd are remote from Ca, Sr, Ba. Thorium is now correctly placed under group IV, with atomic weight 232, compared with the wrong positioning of Th at atomic weight 118 in the 1869 table.

The missing *eka* elements of atomic weights 44, 68, and 72 are clearly indicated, as is the missing element of atomic weight 100 (to become technetium after 1940). The predicted properties of the missing *eka* elements are listed in his textbook,

below the table (3b). The positions of the elements Cu, Ag, Au are duplicated in group VIII transition elements and in group I.

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ,
ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ

| | | | | | |
|----------|-----------|------------|------------|------------|----------|
| | 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 = 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 | U = 116 | Au = 197,2 | |
| 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 | I = 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 | | |
| | | ?Fr = 56 | La = 94 | | |
| | | ?Yt = 60 | Di = 95 | | |
| | | ?In = 75,6 | Th = 118? | | |

Figure 1. The first periodic table of Mendeleev, published in 1869. The places for three missing elements at weights 45, 68, and 70 are clearly marked with question marks ("?"). Several atomic weights are wrong: In = 75, Ce = 92, Ur = 116 (later corrected by Mendeleev) and Th = 118, La = 94. (This figure is reproduced from ref 5.)

216 VI. ПЕРИОДИЧЕСКАЯ СИСТЕМА ЭЛЕМЕНТОВ

в статье 1871 г. данъ развернутое изложение периодического закона и мало отличающаяся от современной форму периодической системы

| | Группа I | Группа II | Группа III | Группа IV | Группа V | Группа VI | Группа VII | Группа VIII переходная группа I |
|------------------------------|------------------|--------------------------------------|-------------------------------|---|-------------------------------|---|-------------------------------|---|
| Типичные элементы | H 1 | | | | | | | |
| Первый период | Li 7 | Be 9,4 | B 11 | C 12 | N 14 | O 16 | F 19 | |
| Второй период | Na 23 | Mg 24 | Al 27,3 | Si 28 | P 31 | S 32 | Cl 35,5 | Fe 56 |
| Третий период | K 39 | Ca 40 | Ti 50? | V 51 | Cr 52 | Mn 55 | Ni 59 | Cu 63 |
| Четвертый период | (Cu) 63 | Zn 65 | (Y) 88? | Zr 90 | Nb 94 | Mo 96 | 100 | Ru 104 |
| Пятый период | Rb 85 | Sr 87 | (Y) 88? | In 90 | Sb 122 | Te 128? | 127 | Rh 104 |
| Шестой период | (Ag) 108 | Cd 112 | Ce 138? | Sn 118 | Pb 207 | 128? | 127 | Pd 104 |
| Седьмой период | Cs 133 | Ba 137 | — | — | — | — | — | Ag 108 |
| Восьмой период | — | — | — | — | — | — | — | Ru 104 |
| Девятый период | (Au) 197 | Hg 200 | Tl 204 | Pb 207 | Bi 208 | — | — | Rh 104 |
| Десятый период | — | — | — | — | — | — | — | Pd 104 |
| Высшая соляная окись | R ₂ O | R ₂ O ₂ или RO | R ₂ O ₂ | R ₂ O ₃ или RO ₂ | R ₂ O ₃ | R ₂ O ₄ или RO ₂ | R ₂ O ₇ | R ₂ O ₃ или RO ₂ |
| Высшее водородное соединение | | | (RH ₃ ?) | RH ₄ | RH ₃ | RH ₂ | RH | |

Figure 2. The amazing 1871 periodic table. The three elements with their newly corrected atomic weights are indicated; Missing elements are clearly shown; The place of thorium is corrected. The periodic table in the 3rd edition of his textbook, dated 1877, is the same, except it includes Ga, discovered in 1875. (This figure is reproduced from ref 5.)

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Hydrogen is again placed separately, but this time at the head of group I. In 1869 it was almost floating free.

Over the following 15 years the three *eka* elements (Ga, Ge, and Sc) were found in nature and correctly occupied their places in the periodic system (3b). Their identities were confirmed by comparing their observed properties at discovery with those predicted by Mendeleev in 1871.

Further Periodic Table Developments

Then in the 1890s the inert gases were isolated (8, 3c). The periodic system now demonstrated its power and flexibility by

allowing these mysterious new gases to be incorporated in the table as elements of a new group 0, after the halogens in group VII and before the alkali metals of group I.

The table presented in Figure 3 is from the 1905 edition of Mendeleev's book: *Osnovy Khimii*, as shown in the 1931 revised edition of the book (4) and is labeled "System". It is clearly recognizable as the table in use up to the 1950s. The inert gases are neatly on the left as group 0. The transition metals are in group VIII on the right. The metals Cu, Ag, Au are still causing a problem: where to place them? They are duplicated in groups I and VIII, but now it is the group VIII positions which are in brackets. (Note the printing error: An for Au.) Radium, discovered in 1898, is present in group II as Rd. But polonium, also discovered in 1898, is absent. Mendeleev was always dubious of the existence of the naturally radioactive elements. The 1902 periodic table of his friend Bohuslav Brauner is almost identical in omitting polonium (8).

Hydrogen is apart, but above group I. There is a gap for an element in group VII, after Mo and below Br, termed *eka-manganese* in the text, atomic weight 99. Well-defined gaps in Row 12 wait for the (rare) radioactive elements to come. There is a series of gaps for elements following La, Ce. Rare earth elements were already reported with atomic weights from 141 (Pr) to 171 (Tu), although their identities were not certain. In a footnote Mendeleev comments on the difficulty that he faces in trying to place these elements, and so he simply chooses to omit them (4). He puts Yb below La, because of the common 3+ oxidation state, and he leaves a gap before Ta, for the element that in 1923 becomes hafnium, and one after W for rhenium-to-be. The symbol for iodine is J.

However, this system is not the only arrangement that Mendeleev presents. Figure 4 reproduces a table originally printed on the page facing the table described above. In this table Mendeleev orders the elements by atomic weight going from top to bottom, with the columns labeled "rows" and the "groups" horizontal. But as in the 1869 table, group II Be, Mg, Zn, Cd, Hg is well separated from group I Ca, Sr, Ba, Rd. The inert gases are duplicated top and bottom as group 0, but He, Ne seem to be in an anomalous position adjacent to Ni and Pd.

Figure 3. The periodic table of 1905, showing the inert gases correctly placed, and the elements Ga, Ge, and Sc whose existence had been predicted by Mendeleev. Note his signature and the date at the foot of the table. (This figure is reproduced from ref 4.)

ПЕРИОДЫ ХИМИЧЕСКИХ ЭЛЕМЕНТОВ И ВЕСА ИХ АТОМОВ.
 СЧИТАЯ АТОМНЫЙ ВЕС КИСЛОРОДА O = 16.

| Высшие солеобраз. Группы окисл. | | Элементы четных рядов | |
|---|-------------------------------|--|------------------------------|
| 0 | 0 | Ar=38 | Kr=81,8 Xe=128 |
| R ₂ O | I | K=39,10 Rb=85,5 | Cs=132,9 |
| RO | II | Ca=40,1 Sr=87,6 Ba=137,4 | Rd=225 |
| R ₂ O ₂ | III | Sc=44,1 Y=89,0 La=138,9 Yb=173 | |
| RO ₂ | IV | Ti=48,1 Zr=90,6 Ce=140,2 ²⁾ | Th=232,5 |
| R ₂ O ₃ | V | V=51,2 Nb=94,0 | Ta=183 |
| RO ₂ | VI | Cr=52,1 Mo=96,0 | W=184 U=238,5 |
| R ₂ O ₃ | VII | Mn=55,0 ?=99 ³⁾ | |
| Газообразные высшие солеобраз. Группы окисл. | Легчайшие типические элементы | VII | |
| 0 | 0 | He=4,0 Ne=19,9 | Os=191 |
| R ₂ O | I | H=1,008 Li=7,03 Na=23,05 | Cu=63,6 Ag=107,9 |
| RO | II | Be=9,1 Mg=24,36 | Zn=65,4 Cd=112,4 |
| R ₂ O ₃ | III | B=11,0 Al=27,1 | Ga=70,0 In=115,0 |
| RH ₄ RO ₂ | IV | C=12,0 Si=28,2 | Ge=72,5 Sn=119,0 |
| RH ₄ R ₂ O ₃ | V | N=14,01 P=31,0 | As=75,0 Sb=120,2 |
| RH ₂ RO ₂ | VI | O=16,00 S=32,06 | Se=79,2 Te=127 |
| RH R ₂ O ₇ | VII | F=19,0 Cl=35,45 | Br=79,95 J=127 ⁴⁾ |
| 0 | 0 | He=4,0 Ne=19,9 Ar=38 ¹⁾ | Kr=81,8 Xe=128 |

Элементы нечетных рядов

Figure 4. The alternative arrangement of the elements. The formulas of the oxides and hydrides are indicated on the lower left. The formulas of oxides only are given on the upper left. These elements of groups I to VII do not form hydrides. This division finally becomes the A/B notation when the elements of the C, N, O, F families are labeled A and the metals are labeled B on periodic tables. (This figure is reproduced from ref 4.)

The columns of elements He to Ne and Ne to Ar are labeled "typical elements". This arrangement of a continuous series in a column makes it obvious that the set Fe, Co to Ge, and As is closely related to the set Ru, Pd to Sn, and Sb, and to the set Os, Ir to Pb, and Bi. The label of the block Fe, Co, and Ni is wrongly printed as VII (it should be VIII).

Here are two tables, quite different in appearance, yet both by the discoverer of the periodic law and periodic system. He was satisfied with both, otherwise he would not have published them on facing pages in his book (4).

Mendeleev's Still-Evolving Legacy

Mendeleev's final table is a memorial to celebrate the centenary of his birth in 1934. An artistic representation of his last periodic table is on the wall of the Main Chamber of Weights and Measures in St. Petersburg, Russia (6), and is simply labeled "System". (See Figure 5.) This version is very similar to the 1905 table (Figure 3), although the radioactive elements Rn, Ra, Ac, Pa, Po have been added, as have the lanthanoids, including JI, illinium, later to be proven spurious. The number of lanthanoid elements between Ba and Hf is now correct, thanks to the work of Moseley (1). Not only does each element have its place in this periodic table, each is now fitted into the system by its characteristic atomic number. There is still a gap after Mo and below Br, although Re is now included in the table. The inert gases, group 0, are well placed to the left of group I. Hydrogen again stands alone at the head of group I. There is still much debate about where to place it in a periodic table (9).

Note that symbols begin with J and not I: J, iodine; Jr, iridium; Jn, indium.¹ Formulas for the ideal oxides and hydrides are given at the bottom of the table, yet the numbers are superscripts (e.g., R₂O⁵ and RH³ from group V), while in both the 1871 and 1905 tables (Figures 2 and 3), they are given in the modern notation² as subscripts, R₂O₅ and RH₃. In addition, this periodic table memorial was color-coded, with the elements

discovered after Mendeleev's death in 1907 shown in dark blue while the rest are in red (10, 6).

One must ask: is there one "correct" form of the periodic table? Mendeleev has in fact already answered this question for us: see Figures 3 and 4.

In the 1969 book by Nekrasov (5) we have his modernized version of the tables of 1905 and 1934 labeled "System of Mendeleev". This 1969 version (see Figure 6) is interesting



Figure 5. Photograph by Valentin Ostrovsky of the memorial in St. Petersburg titled "Periodic System of Elements of D. I. Mendeleev" based on his periodic table of 1905. The groups are subdivided in vertical families, although not specifically labeled, nor are atomic numbers or atomic weights indicated (this is an artwork rather than a scientific document).

Figure 6. Reproduction of the periodic table from Nekrasov's 1969 textbook (5), printed on the inside front cover. This periodic table is a compromise between the classic format of Mendeleev and the form with lanthanoids and actinoids separated. Placing the inert gases as group VIII interrupts the smooth flow: compare Figures 3 and 5 where they are group 0, to the left of the group I metals.

| ПЕРИОДИЧЕСКАЯ СИСТЕМА ЭЛЕМЕНТОВ Д.И.МЕНДЕЛЕЕВА | | | | | | | | | |
|--|----|----|-----|----|----|----|-----|------|--------|
| ГРУППЫ | | | | | | | | | |
| ГРУППЫ | I | II | III | IV | V | VI | VII | VIII | ГРУППЫ |
| 1 | H | | | | | | | | |
| 2 | Li | Be | B | C | N | O | F | Ne | |
| 3 | Na | Mg | Al | Si | P | S | Cl | Ar | |
| 4 | K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co |
| 5 | Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh |
| 6 | Cs | Ba | La | Ce | Pr | Nd | Pm | Sm | Eu |
| 7 | Fr | Ra | Ac | Th | Pa | U | Np | Pu | Am |
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because the inert gases become group VIII, and intervene between the halogens, group VII, and the "triads", Fe, Co, Ni. The lanthanoids and actinoids are withdrawn and separated from the main body of the table, as was first proposed by Seaborg in his actinide hypothesis (11). Of course, many other possible arrangements exist! (12).

More of interest is the existence of two rough, hand-drawn drafts by Mendeleev of his first "System of the Elements" of 1869. (See Figure 7). As in accordance with his system, the elements are ordered on atomic weight, but in one draft the atomic weights increase upwards, while in the other they are ordered on atomic weight increasing downwards (13). This version ultimately became his first periodic table, published in 1869.

It seems apt to remember Dmitrii Mendeleev as his students saw him, and how he looked when he was creating the periodic system and those first periodic tables to be used in his textbook for his students. (See Figure 8.) The USSR honored him and his periodic table by publishing in 1969 two postage stamps featuring him, his first periodic table, and his predictions (14).

Figure 7. Draft of the periodic table of 1869, dated 17 February 1869, with its title in French (English translation: An Attempt at a System of the Elements). Note the element "Q = 8" above "Be = 9.4". This entry is gone in the final printed form, as has "Q = 22". These corrections show the remarkable speed of development over about a week. Also note that he spells his name "Mendeleeff".³ (This figure is reproduced from ref 13.)

Acknowledgment

I thank Valentin Ostrovsky for generously providing photographs of the Periodic Table Memorial in St. Petersburg, Russia.

Notes

1. The use of the symbol J for iodine is not unusual. It is used in German where the element is termed Jod. The German translations of Mendeleev's papers use the symbol J for iodine, although iridium is Ir, and indium is In. In Russian the classical name of the element is Йод; however, in regular textbooks (see refs 4 and 5) it is spelled more simply Иод. The use of Jr for iridium and Jn for indium in Figure 5 is probably the result of using a sans-serif font for the letters with the result that uppercase letter "I" looks like the lowercase letter "l".

2. The use of superscripts rather than subscripts for formulas was common (e.g., the 1872 German version of Mendeleev's table of 1871, and in French publications). Nonetheless, Brauner's table of 1902 uses subscripts (see ref 8).

3. The name of Dmitrii Mendeleev has been spelled in many different ways. This arises from people's attempts to write the name so that it would sound correctly. His first name is seen as both Dmitri and Dmitrii. His surname has been spelled Mendelejeff, Mendeleeff, Mendel'eff, and Mendelejev depending on the person writing and the language and the date of writing (see Figure 7 and ref 13).

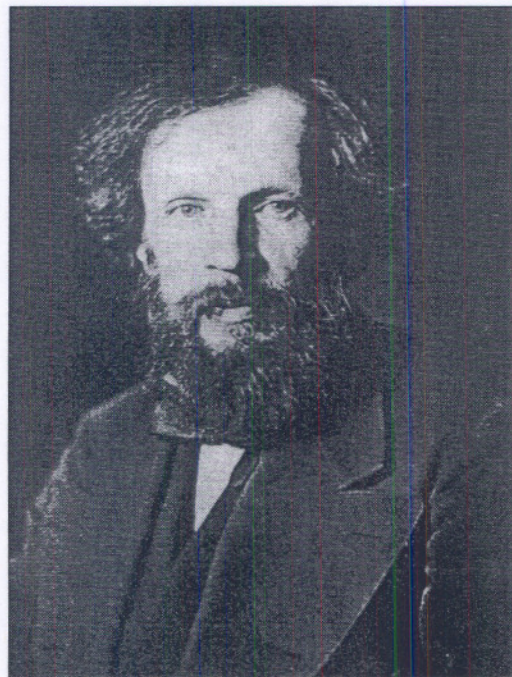


Figure 8. Dmitrii Mendeleev as he was photographed in the 1870s—an excited and exciting teacher of chemistry, who discovered the periodic law, described the periodic system, and developed the periodic table from his draft of February 1869 to the masterwork of 1871 and thereafter. (This image is reproduced from ref 14; no credit for the photographer was given in the original.)

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Looking for theme-based references to JCE articles, complete with suggestions for their use? The resource papers listed were constructed around National Chemistry Week

- ☆ JCE Resources for Chemistry and Careers; 2007, 84, 1595–1597
- ☆ JCE Resources for Chemistry and Recycling; 2007, 84, 212–213
- ☆ JCE Resources for Chemistry and the Home; 2006, 83, 1444–1446
- ☆ JCE Resources for Chemistry and Soils; 2006, 83, 199–200
- ☆ JCE Resources for Chemistry and Toys; 2005, 82, 1443–1446

and Earth Day themes by Erica K. Jacobsen of the JCE staff. These are great references—in print or online at JCE Online.

- ☆ JCE Resources for Chemistry: Health and Wellness; 2004, 81, 1390–1396
- ☆ JCE Resources for Chemistry and the Atmosphere; 2003, 80, 1106–1112
- ☆ JCE Resources for Chemistry and Cleaning; 2002, 79, 1162–1167
- ☆ JCE Resources for Chemistry and Art; 2001, 78, 1316–1321
- ☆ JCE Resources in Food Chemistry; 2000, 77, 1256–1267