ESSAY

Ordering the elements

Elegant and intuitive, today’s periodic table belies the hard-won discoveries hidden within

By Michael D. Gordin

In 2019, even those with the most cursory of science educations can recognize the standard image of the periodic table. Its contours are broadly familiar: a thin peak on the left separated from a broader plateau on the right by a valley of boxes, all floating on top of two rows of similar squares. With a little more training, the asymmetrical shape reveals itself as natural, the compact visual representation of a series of hard-won discoveries about the atomic structure hidden behind the wondrous diversity of matter that makes up our world.

In 1869, neither the atomism nor the visual representation would have been familiar. During the preceding decade, five chemists (four Western Europeans and one Dane who had settled in the United States) had produced partial two-dimensional arrangements of the elements, but none had seemed to catch on (1, 2). In February of 1869, Dmitri Ivanovich Mendeleev (1834–1907), professor of general chemistry at St. Petersburg University in the capital of the Russian Empire, published his own classification that included all the known elements (Fig. 1), apparently unaware of the previous abortive attempts (3). Mendeleev’s version is now acknowledged as the ancestor of our poly chromatic grid of chemical elements, and the pattern it represents is universally marked with the adjective that Mendeleev borrowed from trigonometric functions to designate the recurrence of properties: “periodic.”

Seeing the relationship between our table and Mendeleev’s is more complicated than might appear at first blush. The history connecting Mendeleev’s 1869 “An Attempt at a System of Elements, Based on Their Atomic Weight and Chemical Affinity” and today’s International Union of Pure and Applied Chemistry (IUPAC)–approved “Periodic Table of the Elements” (Fig. 4) is a story of fundamental transformations in our understanding of matter, not simply changes in design (4). This article identifies some of the central characteristics of Mendeleev’s classification—the “short-form” periodic system—in his own context and examines the changes by the time of the chemist’s death in 1907 that laid the groundwork for our familiar, electron-based table.

READING MENDELEEV’S TABLE

Take a close look at Mendeleev’s 1869 “Attempt.” First, there is the matter of orientation. Mendeleev’s table is not designed to be read like a book, left to right and then top to bottom, but rather the inverse: top to bottom and then left to right. To orient it like the IUPAC table, you need to rotate the picture clockwise by 90° and then reflect it across the vertical axis. The preference for vertical rather than horizontal arrangement is purely contingent, and Mendeleev would soon adopt the right-left orientation we are now familiar with.

Other aspects of Mendeleev’s arrangement are more alien and reveal a good deal about the state of chemical knowledge of his day. The table consists of alphabetic symbols equated with numbers. The symbols are familiar: They are largely those promoted by Swedish chemist Jöns Jacob Berzelius (1779–1848) earlier in the century. A few are slightly different, but easy to translate (“J” instead of “I” for iodine, “Ur” instead of “U” for uranium), whereas another, “Di = 95,” is nowhere to be found on today’s grid.

The abbreviation Di represented didymium, a rare earth discovered by Carl Mosander in 1841 and believed to be an element. Beginning in 1874, a series of chemists suspected that didymium might in fact be a mixture of substances, and in 1885, Carl Auer von Welsbach, through fractional crystallization, isolated two new elements, soon dubbed praseodymium and neodymium. (They can be found as Pr and Nd, elements 59 and 60, in Fig. 4.) The rare earths share very similar properties to each other—a major reason, besides topographical economy, why they are isolated in the

![Fig. 1. Mendeleev’s original February 1869 publication of his short-form periodic system, entitled “An Attempt at a System of Elements, Based on Their Atomic Weight and Chemical Affinity.”](image-url)

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southern island of the contemporary representation—and they caused Mendeleev no end of headaches (5).

Next to those symbols are the numbers. The numbers on the IUPAC table stand for the element’s atomic number (Z), the quantity of protons in the nucleus of each atom. Those positively charged particles determine the number of orbiting electrons whose configuration is largely responsible for the chemical properties.

The layout of the IUPAC table (tower, valley, and plateau) accentuates electron configuration: If you know the place of an element in the table, you can straightforwardly read off this property. Atomic number also tells us that there are no “gaps” in the table: Every number, up to 118 as of 2018, is filled.

VALUING ATOMIC WEIGHTS

Mendeleev knew nothing of atomic number, which was fully elaborated by Henry Moseley in 1913, 6 years after the Russian's death. Indeed, Mendeleev waxed hot and cold about the notion of atoms in general and was especially suspicious of electrons (discovered by Joseph John Thomson in 1897) (3). The numbers in Mendeleev’s classification are atomic weights, the only principle he ever recognized for organizing the elements.

Calculating atomic weights was a difficult business. Most elements come to us in nature as compounds, and tricky purification practices, plus an estimate of the substance's valency, could often generate results off by a factor of two or four.

In September 1860, at a chemical congress in the southern German town of Karlsruhe—Mendeleev, then a postdoctoral student at nearby Heidelberg, happened to be in attendance—Italian chemist Stanislao Cannizzaro advocated using the principles articulated almost half a century earlier by his countryman Amedeo Avogadro to rationalize the determination of atomic weights. Soon, most of the elements (aside from the frustrating rare earths) acquired newly standardized atomic weights. It is no accident that all the attempts to develop periodic systems stemmed from the 1860s; without the revised weights, the patterns would have remained invisible.

Mendeleev used the post-Karlsruhe weights as one of the two axes of his classification: They increase from top to bottom of the image, for the most part. There are still some older weights—uranium (Ur) is listed as 116 (Mendeleev would later double it, making it much closer to today’s value)—and he appended question marks to those weights he felt were still dubious.

This is especially true for the two “inversions” of copper and nickel (both listed as 59) and tellurium and iodine, with the lighter iodine stuck behind the heavier tellurium because of its chemical properties. (Mendeleev always believed there was some mistake in the tellurium weight. There isn’t.)

The elements arrayed around the edges, some with question marks and some without, are not arranged by atomic weight. They are in a holding pattern, a residue of Mendeleev’s draft of the system (Fig. 2), and clear evidence that this 1869 “Attempt” was, as the name suggests, a work in progress.

Most striking, however, are the three elements that are just listed as atomic weights with a question mark: 45, 68, and 70. By 1871, Mendeleev would come to dub these eka-boron, eka-aluminum, and eka-silicon (the prefix being the Sanskrit word for “one”) and offered detailed predictions of their chemical properties. Unexpectedly for all concerned, they were soon discovered as scandium (in 1879), gallium (in 1876), and germanium (in 1886).

The unprecedented success of these predictions solidified Mendeleev’s European reputation and his status as the main discoverer of the periodic system, despite the competition. (Nonetheless, he shared the Royal Society’s Davy Medal with Julius Lothar Meyer in 1882 for their separate efforts.)

The second axis, chemical properties, was a bit harder to define precisely. Mendeleev’s insight about these properties—that they repeat periodically when the elements are arranged by increasing atomic weight—endows the arrangement with its conceptual economy and power.

BUILDING OUTWARD

If you compare Mendeleev’s table and IUPAC’s, you see something else a bit odd about the former: Mendeleev placed the alkali metals (the row beginning with Li = 7) immediately adjacent to the halogens (beginning F = 19). On today’s table, they are at opposite ends—except for the noble gases, which were only discovered in the mid-1890s. Mendeleev only grudgingly accepted those into the system as their own column, but he placed them on the far left of the table, not today’s far right (Fig. 3).

The juxtaposition of alkali earths and halogens provides a tell, a trace of how Mendeleev put his system together. He developed the 1869 arrangement while composing his two-volume introductory textbook of inorganic chemistry, The Principles of Chemistry (first edition, 1869–1871; there were eight editions in Mendeleev’s lifetime).

Volume one addressed only eight elements, ending with the four halogens; Mendeleev needed to cram the remaining 55 into volume two. He began by comparing the alkali earths and the halogens as the most extreme contrasts in properties. He noticed a regularity of the increase of atomic weights and then built the table out of there. By 1871, Mendeleev would separate them as we do today.

What we commemorate this year by declaring it the 150th anniversary of the periodic table was born out of Mendeleev’s struggles to organize information for students. That today’s version—long-form with its island of rare earths—graces every chemistry classroom on the planet is a fitting conclusion. Today’s periodic table is not precisely the same as Mendeleev’s short form, either in layout or in content, but it is still used for the same ends.

REFERENCES

4. E. G. Mazurs, Graphic Representations of the Periodic System During One Hundred Years (Univ. Alabama Press, 1974).
Fig. 3. Mendeleev’s 1904 periodic system, incorporating the noble gases as a left-hand column. Elements x and y at the top of that column are predictions related to the hypothesized luminiferous ether.

Fig. 4. The IUPAC Periodic Table of the Elements.