The Past and Future of the Periodic Table

This stalwart symbol of the field of chemistry always faces scrutiny and debate

Eric R. Scerri

It graces the walls of lecture halls and laboratories of all types, from universities to industry. It is one of the most powerful icons of science. It captures the essence of chemistry in one elegant pattern. The periodic table provides a concise way of understanding how all known chemical elements react with one another and enter into chemical bonding, and it helps to explain the properties of each element that make it react in such a fashion.

But the periodic system is so fundamental, pervasive and familiar in the study of chemistry that it is often taken for granted. A century after the death of the leading discoverer of the periodic system, the Russian chemist Dimitri Mendeleev, it seems time to revisit the origins and modern status of this now-standard chemical classification. There were a number of historic precursors to Mendeleev's periodic system. But there are also current ongoing debates regarding the best way to display the periodic system, and whether there is really a "best way" of doing so.

The periodic system of elements gets its moniker because it graphs how certain properties of chemicals repeat after regular intervals. In the modern table of 117 elements, each is placed across rows in order of increasing atomic number—the number of protons in the nucleus of one atom of each element. There are seven rows, each making up one period. The lengths of periods vary: The first has two elements, the next two eight each, then 18 and 32, respectively, for the next pairs of periods. Vertical columns make up groups, of which there are 18, based on similar chemical properties, related to the number of electrons in the outer shell of the atoms, also called the valence shell. For instance, group 17, the halogens, all lack one electron to fill their valence shells, all tend to acquire electrons during reactions, and all form acids with hydrogen.

The Classics

There have been many changes to the table since Mendeleev's first, which showed eight groups, 12 rows and 66 elements, was published in 1869. But neither did Mendeleev's table spring from a vacuum. Historians of chemistry have long recognized two ideas that contributed to the evolution of the periodic system: the notion of triads of elements and Prout's hypothesis, whereby the atomic weights of the elements are integral multiples of the atomic weight of hydrogen, the lightest of all the elements.

In 1817 the German chemist Johann Döbereiner noticed that several groups of three elements formed triads with two interesting features. Not only was the middle element of a triad of intermediate chemical reactivity, but it also had an intermediate atomic weight. Differing from atomic number, a value that had not yet been ascertained, atomic weight had been measured since the start of the 1800s. The idea was to determine the weight of each indivisible unit of matter relative to hydrogen, whose weight was taken as 1.00. Because formulas for many compounds were unknown, atomic weights remained imprecisely measured for some time. But in triads of elements, Döbereiner found that the weight of the middle element—such as selenium in the triad formed by sulfur, selenium and tellurium—had an atomic weight that was the approximate average of the weights of the other two elements. Sulfur's atomic weight, in Döbereiner's time, was 32.239, whereas tellurium's was 129.243, the average of which is 80.741, or close to the then-measured value for selenium, 79.264.

The importance of this discovery lay in the marrying of qualitative chemical properties, such as degree of reactivity, with numerical data on the elements. It suggested that there might be some underlying numerical order that could serve to relate the elements to one another in a systematic way.

Döbereiner also discovered other triads, such as calcium, strontium and barium, and lithium, sodium and potassium. Other chemists discovered yet more triads and began to make tables that also attempted to relate triads among one another. But some of these contributions degenerated into mere numerology, especially when they neglected chemical relations between the elements. For example, in his 1857 article, German chemist Ernst Lenssen suggested the existence of a triad consisting of silicon, boron and fluorine, even though there was no conceivable chemical connection between these elements. Nevertheless, the lure of the search for triads encouraged chemists to determine atomic weights more accurately, a pursuit that served chemistry in many other ways.

A little earlier, in 1815, the London based physician, William Prout, proposed another general principle. In a few papers, which he published anonymously, Prout wrote that the fact that the atomic weights of many elements seemed to be integral multiples of the weight of hydrogen suggested that all

Eric R. Scerri is a lecturer in chemistry and the history and philosophy of science at University of California, Los Angeles. He is the founder and editor-in-chief of the journal Foundations of Chemistry *and the author of* The Periodic Table: Its Story and Its Significance *(Oxford University Press, 2007). He received his Ph.D. in the history and philosophy of science from King's College London. Address: Department of Chemistry & Biochemistry, UCLA, Los Angeles, CA 90095-1569. Internet: scerri@chem.ucla.edu*

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Figure 1. With its compact form displaying a wealth of information about the elements, the periodic table has long been a standard-issue reference in the field of chemistry. Theodore Gray created this museum display to improve on the appeal of the table by adding samples of each element behind its entry. (This close-up shows, at left, the triad sulfur, selenium and tellurium, studies of which were a precursor to the periodic system.) The story of the periodic table is one of gradual improvements, from early measurements of atomic weight to current-day proposals for new layouts of the elements that look nothing like a two-dimensional chart.

the elements were composite multiples of hydrogen. He also went on to claim that this would imply the essential unity of all matter. But some elements such as nitrogen, which then had a value of 12.6 relative to hydrogen, seemed to point against Prout's hypothesis. Prout's supporters regarded such facts as anomalies that would eventually disappear with the more accurate determination of atomic weights.

As in the case of triads, attempts to confirm or refute Prout's hypothesis contributed to renewed efforts on the part of chemists to measure atomic weights. However, although these ideas were fruitful in some ways, they were also found wanting as more accurate atomic-weight data began to accumulate. The notion of triads was found to be too approximate and even then only applied to carefully selected groups of three elements. Meanwhile, Prout's hypothesis showed too many nonintegral exceptions. In the language of philosopher of science Karl Popper, both ideas had been refuted by the second half of the 19th century.

At the start of the 20th century, it was found that atomic number, rather than atomic weight, serves as the more correct criterion for ordering the elements in a linear sequence. Researchers such as the British physicist Henry Moseley found that they could use x-ray diffraction to relate atomic number to positive charge, or the number of protons in the nucleus of any atom. On re-examining the notions of triads and Prout's hypothesis in the light of atomic number, one finds a remarkable sense in which both notions have made what another famous philosopher of science, Imre Lakatos, has termed a theoretical comeback. In terms of atomic number, the elements have exact multiples of the number of protons in the hydrogen atom—as hydrogen has only one proton, everything is a multiple of it. And perhaps in a deeper sense, modern astrophysics has shown that almost all of the elements are literally formed from hydrogen and helium atoms, which combined together during the Big Bang at the start of the universe, as well as in the interiors of stars and supernovae.

Moreover, if we consider atomic numbers instead of atomic weights for the triads discovered in the 19th century, it turns out that the atomic number of the middle element is *exactly* the average of the other two elements. Indeed, about half of all the possible triads in the modern periodic table are exact in this sense. However, many other potential triads are not even approximately correct in that the atomic number of the middle element is nowhere near the average of the other two elements.

The reason for this behavior is that the periodic table shows a repetition in the length of all periods (with the exception of the first very short period which consists of just the elements hydrogen and helium). The second period consists of eight elements (lithium to neon) followed by another period of eight elements (sodium to argon), followed by two periods of 18 elements, presumably followed by two periods of 32 elements and so on. As a result of these repetitions, atomic number triads are exact in half of all possible cases. Take the element chlorine as an example. In order to encounter another element with similar chemical properties we need to advance 18 places to get to the element bromine. To reach yet another element sharing these same chemical properties it is necessary to advance a further 18 places to the element iodine. Bromine lies exactly between chlorine and iodine in terms of atomic number, precisely because the length of the two periods between these elements is exactly the same—18 elements. But in other cases of potential triads, the second and third elements are not in periods of the same length, so the triads don't work.

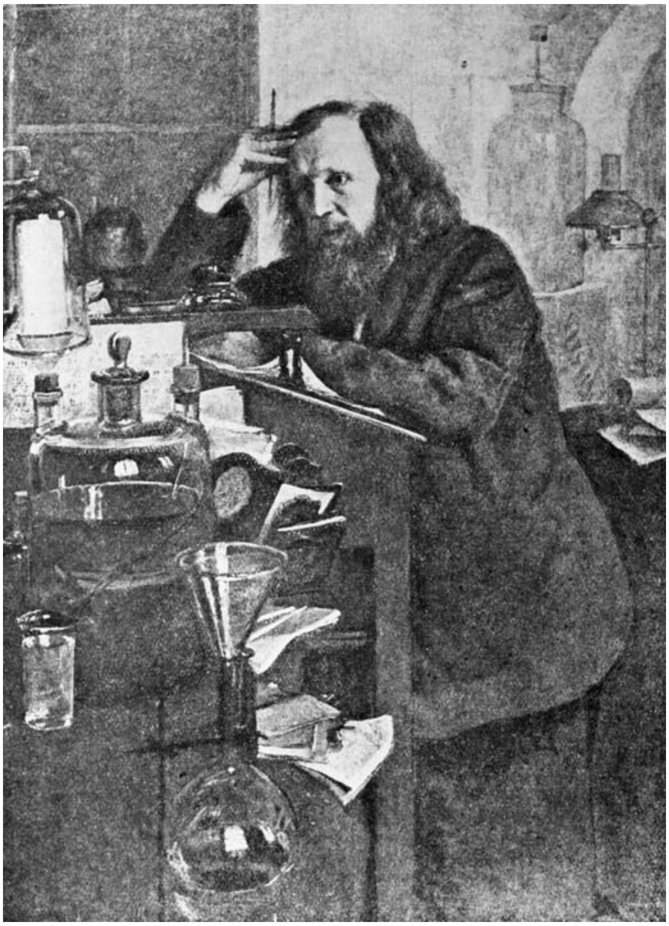

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Figure 2. Dimitri Ivanovich Mendeleev was born in 1834 in Tobolsk, Siberia, the youngest of 14 children. He studied in St. Petersburg, Russia, where he became a professor of chemistry at the university in 1863. He published his initial periodic table in 1869. Although his table was not the first, his version is the one that had the biggest impact on the scientific community. He also championed the system, defending its validity and devoting time to its elaboration. Mendeleev died just over 100 years ago, in 1907. A statue of him with his table stands in St. Petersburg.

Bridging the Gaps

Despite this modern reprieve and explanation, in the mid-1800s, Mendeleev—the undisputed champion of the periodic table—was a critic of the use of triads and especially of Prout's hypothesis concerning the existence of primary matter. Mendeleev was firmly convinced of the individuality and distinct existence of the elements. He is rightly famous for having left gaps in his periodic tables for elements that had not been isolated and for successfully predicting many of their properties, especially in the case of gallium, germanium and scandium.

There are aspects of Mendeleev's system that are not very well known but that nevertheless were quite fundamental to his approach. Mendeleev repeatedly emphasized that there is a dual sense of the concept of element. In the first case, elements are the final stage of chemical analysis, or something that can be isolated and that cannot be further simplified. This is the notion of elements as first emphasized by Antoine Lavoisier in the 1700s, when he called them "simple substances."

But there is a second notion, which Mendeleev sometimes called "real elements," in order to indicate their more fundamental status. In this sense, the elements represent abstract substances that lack what we normally regard as properties and that represent the form that elements take when they occur in compounds. For example, sodium and chlorine as simple substances—a grey metal and a greenish gas respectively—are not literally present in the compound sodium chloride (table salt). Mendeleev would have said that sodium and chlorine are present in the compound as the abstract or "real elements."

Let me emphasize that these abstract elements are still real, and indeed should be regarded as somehow being more fundamental than the elements as simple substances that can actually be isolated. Mendeleev gave just one attribute to the abstract element, namely atomic weight. It is the atomic weight of sodium, for example, that preserves its identity when sodium enters into chemical combination. Just as Mendeleev implied that the abstract version of the concept of element was more real, so he emphasized that his periodic classification was primarily concerned with the abstract elements.

As some authors have argued, this more philosophical view of the elements may have been the crucial sense in which Mendeleev went further than his competitors, who restricted their attention to the elements as simple substances. It also seems to provide a means of understanding how Mendeleev was able to challenge the values of the atomic weights of many elements and the manner in which several elements had been accommodated into the periodic system. This was achieved

element	atomic weight	chemical reactivity toward water
lithium Li	6.94	little reactivity, no flame, no explosion
sodium Na	22.99	intermediate reactivity, produces yellow flame and mild explosion
potassium K	39.10	greatest reactivity, produces lilac flame and considerable explosion

Martyn F. Chillmaid/Photo Researchers, Inc.

Figure 3. The elements lithium, sodium and potassium form a triad of the kind studied by chemist Johann Döbereiner in 1817. Elements formed a triad when the average of the then-known atomic weights of the first and third ones closely approximated that of the center member. The reactivity of the middle element was also known to be intermediate to that of the first and last. In the modern periodic table, this particular triad is part of the group of alkali metals. Actual samples of these elements *(right)* are stored in oil because they are highly reactive with water and air.

by ignoring, to some extent, the more obvious, more superficial properties of the elements as simple substances.

Mendeleev is often given most credit for his fame as the "father of the periodic table" because he predicted elements that were undiscovered at the time. But just how impressive were those predictions? As far as the elements gallium, germanium and scandium are concerned, they were quite outstanding—so much so that Mendeleev was even able to correct some of the initial experimental findings on these new elements.

On the other hand, if one considers all of Mendeleev's many predictions of new elements, his powers of prophecy appear somewhat less impressive, even to the point of being a little worrying. In all Mendeleev predicted a total of 18 elements, of which only nine were subsequently isolated. As one historian of chemistry has wondered, how is it that we are prepared to forgive Mendeleev so many failures?

In addition, it is by no means clear that successful predictions were in fact so decisive in the acceptance of the periodic table by the scientific community in Mendeleev's era. For example, the Davy medal, which predates the Nobel Prize as the highest accolade in chemistry, was jointly awarded to Mendeleev and Julius Lothar Meyer, his leading competitor, who did not make any predictions. Indeed, there is not even a mention of Mendeleev's predictions in the published speech that accompanied the joint award of the Davy prize. It therefore seems that this prize was awarded for the manner in which the two chemists has successfully accommodated the then-known elements into their respective periodic systems rather than for any foretelling.

Theoretical physics has provided a partial explanation for the form and existence of Mendeleev's table and its modern descendents. From the viewpoint of physics, the electrons orbiting the nucleus of an atom are responsible for its chemical properties. Atoms of elements that lie in the same group or vertical column of the table do so because they share the same number of outer-shell electrons. The very idea of electrons in shells is a quantum-mechanical concept. The energy of electrons is said to be quantized in the sense that electrons occupy a set of energy levels or orbitals, each level having a specific and discrete energy value.

In addition, solutions to Austrian physicist Erwin Schrödinger's famous equation for the electron can be characterized by a set of quantum numbers. When this set is supplemented with an additional quantum number for spin, it is possible to predict that subsequent main shells of the atom can contain a maximum of 2, 8, 18 or 32 electrons. This is in perfect agreement with the lengths of periods in the chemist's periodic table. The simple quantum mechanical theory does not, however, account for the repetition of all period lengths except for the first one. Indeed, this problem has continued to elude theoretical

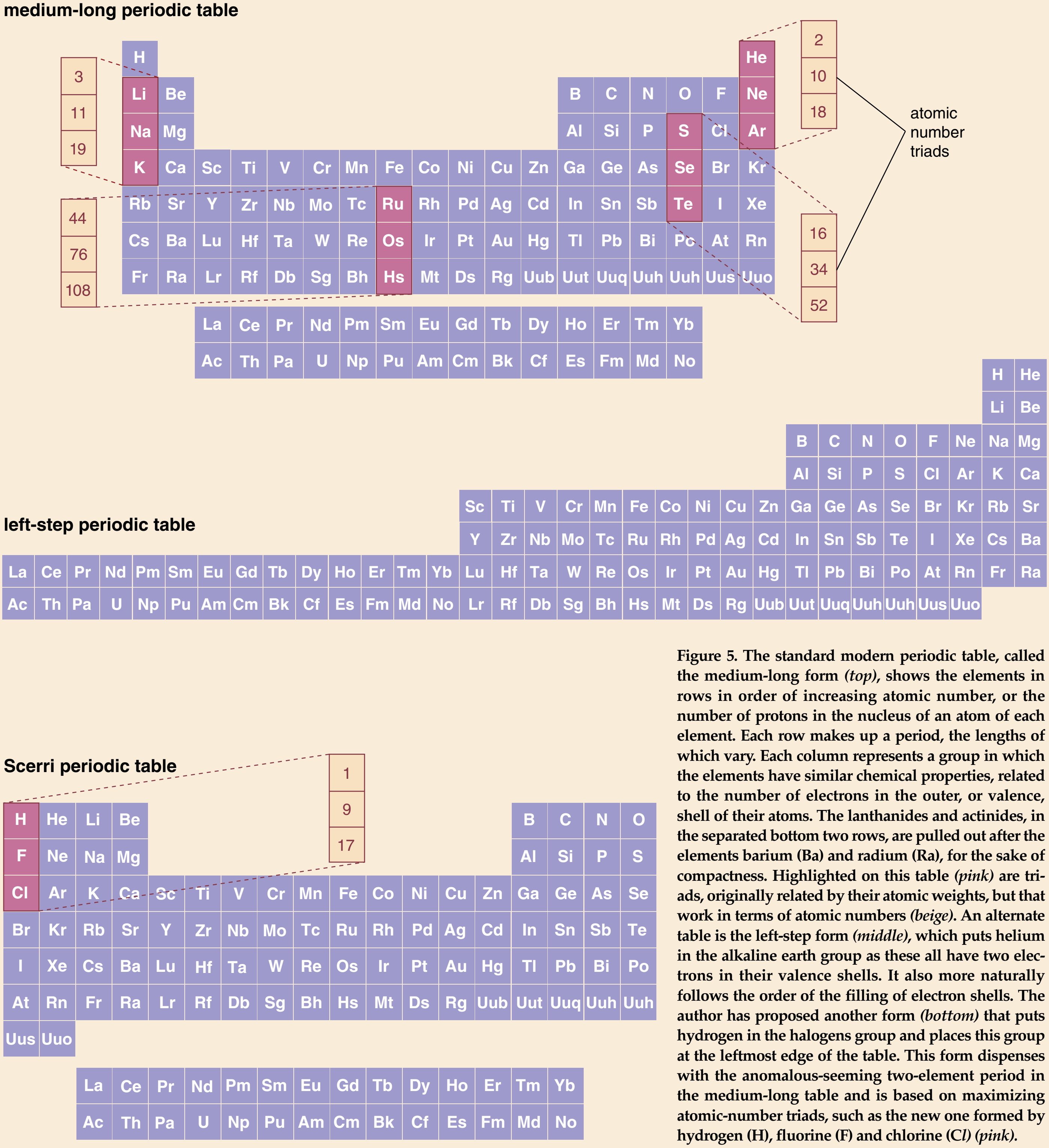
element	atomic weight
hydrogen (H)	1.0
beryllium (Be)	10.9
boron (B)	11.7
carbon (C)	12.0
nitrogen (N)	12.6
oxygen (O)	16.0
fluorine (F)	9.6
sodium (Na)	93.3
magnesium (Mg)	50.0
aluminium (Al)	55.0
silicon (Si)	49.0
phosphorus (P)	27.0
sulfur (S)	32.0
chlorine (Cl)	70.0
potassium (K)	156.0
calcium (Ca)	82.0
titanium (Ti)	28.8
chromium (Cr)	113.0
manganese (Mn)	113.0
iron (Fe)	111.0
cobalt (Co)	117.0
nickel (Ni)	117.0
copper (Cu)	128.0
zinc (Zn)	128.0
arsenic (As)	134.0
strontium (Sr)	178.0

Figure 4. One early attempt at a classification system for the elements related their atomic weights to that of hydrogen, whose weight was taken to be 1.0. Around 1815 London physician William Prout hypothesized that, because the atomic weights of many elements seemed to be integral multiples of that of hydrogen, perhaps all elements were, in fact, composite multiples of hydrogen. The atomic weights shown in this table were typical values that were available in Prout's time, but they are not accurate by modern standards.

physicists until quite recently. Appropriately enough, it was a Russian physicist, the late Valentin Ostrovsky, who recently published a theory to explain this feature, although it is not yet generally accepted. Although the theory is too mathematically complicated to explain here, Ostrovsky's work and some other competing accounts demonstrate that the periodic table continues to be an area of active research by physicists as well as chemists even though it has existed for nearly 140 years.

Fertile Ground

Chemists, physicists and philosophers of science continue to debate the relative virtues of different forms to display the periodic table itself. Some even question whether a two-dimensional table is the best way to arrange the elements. Chemists frequently express the view that there is no one best representation and that the question of representation is a matter of convenience and convention. More recently this view has been questioned by philosophers of science,



medium-long periodic table

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uuh	Uuh	Uus	Uuo
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No		

left-step periodic table

																														H	He
																														Li	Be
																								B	C	N	O	F	Ne	Na	Mg
																								Al	Si	P	S	Cl	Ar	K	Ca
														Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Rb	Sr
														Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	Cs	Ba
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	Fr	Ra
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uuh	Uuh	Uus	Uuo		

Scerri periodic table

H	He	Li	Be											B	C	N	O
F	Ne	Na	Mg											Al	Si	P	S
Cl	Ar	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se
Br	Kr	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te
I	Xe	Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po
At	Rn	Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uuh	Uuh
Uus	Uuo																
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No		

Figure 5. The standard modern periodic table, called the medium-long form *(top)*, shows the elements in rows in order of increasing atomic number, or the number of protons in the nucleus of an atom of each element. Each row makes up a period, the lengths of which vary. Each column represents a group in which the elements have similar chemical properties, related to the number of electrons in the outer, or valence, shell of their atoms. The lanthanides and actinides, in the separated bottom two rows, are pulled out after the elements barium (Ba) and radium (Ra), for the sake of compactness. Highlighted on this table *(pink)* are triads, originally related by their atomic weights, but that work in terms of atomic numbers *(beige)*. An alternate table is the left-step form *(middle)*, which puts helium in the alkaline earth group as these all have two electrons in their valence shells. It also more naturally follows the order of the filling of electron shells. The author has proposed another form *(bottom)* that puts hydrogen in the halogens group and places this group at the leftmost edge of the table. This form dispenses with the anomalous-seeming two-element period in the medium-long table and is based on maximizing atomic-number triads, such as the new one formed by hydrogen (H), fluorine (F) and chlorine (Cl) *(pink)*.

some of whom believe that there may be one best way to arrange the elements in groups of columns. They argue that disputes concerning the placement of certain troublesome elements, such as hydrogen and helium, in the periodic system have one correct solution, even if this is not yet apparent to current-day science.

Consequently, they maintain that some displays of the periodic system may, in truth, be superior to others. Whereas the conventionally displayed table, called the medium-long form, has many virtues, it places helium among the noble-gas elements. Some have argued that in spite of appearances, helium should in fact be placed at the head of group 2, the alkaline earth group, which includes beryllium, magnesium and calcium. Helium has two outer-shell electrons as do the elements in the alkaline earth group.

In addition, the filling of electron shells follows a particular ordering, which is more naturally displayed with this grouping, called the left-step periodic table. This form of the periodic system was first proposed by the Frenchman Charles Janet in the 1920s and has recently been revived by U.S. chemical educator Gary Katz, among others. Further support for this representation also lies in the fact that it renders the periodic system more orderly than the conventional layout. In the left-step table there are two very short periods of two elements, instead of one, with the result that *all* period lengths, without fail, are repeated.

In a recently-accepted paper, I have proposed another periodic table in which hydrogen is placed at the head of the halogen group. Moreover, this table has been rearranged so that the group that is now headed by hydrogen appears at the left-hand edge of the table. The main outcome of this arrangement is to introduce greater regularity into the display of the periodic system, which may reflect the regularity of the periodic law more faithfully. This modified periodic table displays two periods of eight elements at the start of the periodic system and dispenses altogether with the anomalous-seeming very short period of two elements.

The main motivation for this layout is that it leads to the formation of a new perfect triad involving hydrogen. In addition, the perfect triad involving helium is retained, unlike in the left-step table, where it is lost. But why should one even seek to create any new perfect triad? This feature is rather important because it is based solely on atomic number, the only criterion of the elements regarded as basic substances rather than simple substances. As mentioned earlier, Mendeleev went to great lengths to emphasize that the periodic system was primarily a classification of the elements as basic substances (“real elements”).

This more-philosophical view of the elements has come to the rescue of chemistry as its own field, rather than simply a part of physics, on more than one occasion. It suggests that chemistry possesses an essential philosophical foundation even though it is popularly presumed to reduce to quantum physics and thus to be devoid of a philosophical character. In the early years of the 20th century, when isotopes of many elements were discovered, it suddenly seemed as if the number of “elements,” in the sense of simplest substances, that can be isolated had multiplied. Some chemists believed that this proliferation would signal the demise of the periodic table, which would give way to a table of the isotopes.

However, some chemists such as Austrian Friedrich Paneth reconceptualized the notion of elements in such a way as to avoid the abandonment of the chemist’s periodic table. Paneth appealed to Mendeleev’s distinction between “real elements” and elements as simple substances. By concentrating on the “real elements” as Mendeleev had done, but now characterizing them by their atomic numbers, the chemist could ignore the fact that the “elements” occur as many hundreds of isotopes. The isotopes could be regarded as mere simple substances. Moreover, isotopes of the same element, with a few exceptions such as those of hydrogen, tend to show identical chemical properties, thus justifying this approach.

Perhaps the most radical development to take place in contemporary research on the periodic table has been a willingness to challenge tradition by questioning whether the periodic system should be displayed in a two-dimensional form and whether it should even be displayed as a table. At least three distinct three-dimensional periodic systems have been developed and successfully marketed as educational tools. In some cases, such as Canadian chemist Fernando Dufour’s “ElemenTree,” they also serve to emphasize chemical similarities that are not embodied in the conventional two-dimensional table.

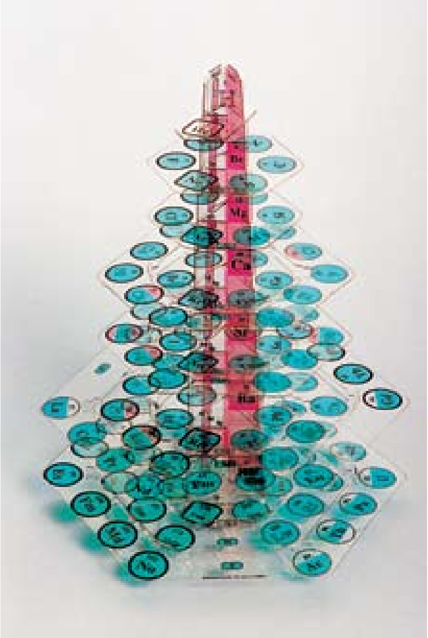


Figure 6. Canadian chemist Fernando Dufour has taken the periodic system from two to three dimensions, dispensing with the idea of a table altogether. His system, produced in 1990 and called the ElemenTree, emphasizes chemical similarities that span different groups on the standard table. (Photo courtesy of the author.)

For example, the elements in group 13 of the conventional-format table, such as boron, aluminum and gallium, all display a combining power, or valence, of three. However, there are a number of other elements that also show this property, such as the elements in group 3 of the conventional table, including scandium, yttrium and lutetium. In Dufour’s system all these elements fall onto the same two-dimensional plane which may be pictured as a slice through the three-dimensional classification system.

Another design that Philip Stewart of the University of Oxford has revived and argued for is the spiral-form periodic system, and it has received a good deal of recent attention. As Stewart contends, the conventional table fails to emphasize the continuity in the sequence of the elements. Spiral systems stress continuity rather than implying breaks between the noble gases at the right-hand edge and the alkali metals at the left edge.

Hindsight

Could it be that our reliance on the

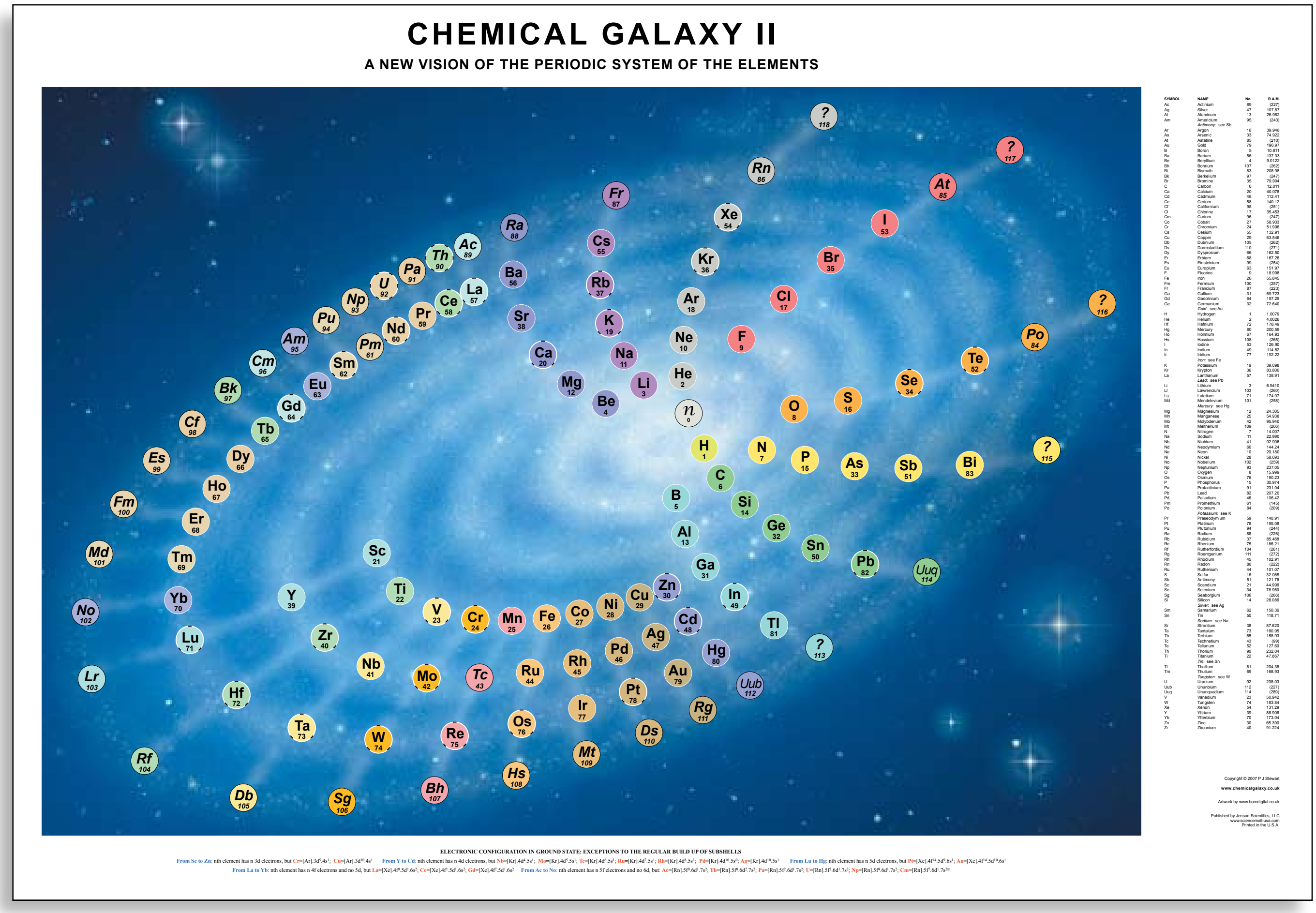


Figure 7. Philip Stewart of Oxford University has championed a spiral format for the periodic system. Such continuous forms get rid of the implied breaks between periods in the conventional table. Spiral forms have been considered for more than 100 years, but this poster shows Stewart's adaptation, which he calls a "chemical galaxy," as the increasing length of the periods can be accommodated by a format similar to the radiating arms of a spiral galaxy. (Image courtesy of Philip Stewart and Carl Wenczek of Born Digital Ltd.)

two-dimensional forms of the periodic table are due to the predominance, until recently, of the two-dimensional textbook page surface and the two-dimensional nature of the walls of lecture theaters? After all, a three-dimensional system is not so easily displayed in a book or indeed on the wall of a lecture hall. But could it also be that with the rise of new technologies in the 21st century, Mendeleev's famous icon might be transformed into something that even he might not recognize if he were still here to see it?

In fact, as far as spiral forms are concerned, Mendeleev did consider such arrangements but did not devise a successful version. As Stewart has written, if Mendeleev had paid more attention to spiral forms, he might have added the prediction of the whole family of noble gases to his other famous predictions of isolated elements. If one uses a spiral display of the elements, the possible existence of the noble gases becomes rather obvious, as was noted by the English chemist William Crookes more than 100 years ago.

The periodic table began with the recognition of triads of elements and arose at the time of Prout's hypothesis of the unity of all matter. From these numerical and philosophical origins it has evolved into an enormously practical tool used not just by chemists, but by all scientists and engineers. But its philosophical aspects have not been completely eclipsed, and, as I argue here, they continue to underwrite the periodic system and sometimes surface to assist in the solution of practical issues concerning its identity and graphical representation.

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