PERIODIC TABLE

The periodic table is an icon. But chemists still can’t agree on how to arrange it

New data about the elements and their relationships have led to debate over the 150-year-old table’s optimum ordering

by ***Sam Lemonick***

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Credit: Yang H. Ku/C&EN

One hundred fifty years after Russian chemist Dmitri Mendeleev published his system for neatly arranging the elements, the periodic table it gave birth to hangs in every chemistry classroom in the world and is one of the field’s most recognizable symbols. But the solid squares and familiar patterns of today’s table mask one of its fundamental characteristics: “the” periodic table does not exist.

It’s been mutable from the beginning. Not only has it grown as new elements have been discovered; it has also added columns and changed shape as we’ve gained new understanding of the elements’ properties and their relationships to one another. And scientists are still debating its optimum configuration.

Some believe chemical properties should dictate how the elements line up on the periodic table. Others think a more fundamental principle is needed, like electronic configuration or simply atomic number. Partisans are clashing over which elements belong in group 3, where helium should go, and how many columns the periodic table should have. They follow a long line of chemists and physicists who have worked and reworked the elements into a semblance of order.

“What I find interesting about the current debate is there are people who insist on there being one right table,” says Michael D. Gordin, a Princeton University historian who has written about Mendeleev, Julius Lothar Meyer, and other creators of early periodic tables. “It would have struck people like Mendeleev and Lothar Meyer as weird.” Gordin says the periodic table pioneers understood their tables to be a reflection of natural laws but recognized that different tables could represent those laws in different ways. That might be hard to imagine for those of us used to seeing the familiar shape of the table on our coffee mug or shower curtain.

Setting the table

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Mendeleev wasn't the first to recognize patterns in the elements, nor was he the first to try to depict those patterns in a diagram. Chemist Johann Wolfgang Döbereiner, for instance, identified triads of elements with shared properties in 1829. Today we'd recognize these as members of the same group or column of the periodic table, like chlorine, bromine, and iodine.

Geologist Alexandre-Émile Béguyer de Chancourtois published a kind of periodic table in 1862 in which the elements spiraled up a cylinder according to atomic weight. Each column of elements shared properties.

Mendeleev published his table, which he called a "periodic system," in 1869. It included all 56 elements then known, and if you squint, it has a somewhat similar shape to the periodic table we see today, only tipped 90° on its side. Mendeleev arranged the elements in order of increasing weight and broke them into rows such that elements in each column shared valence, the number of other atoms they combined with, as well as other properties.

What made Mendeleev's table special was his recognition that the periodic system was strong enough to predict undiscovered elements, which he left holes for, and even their properties. Lothar Meyer was independently working on an almost identical table, but Mendeleev beat him to publication by a few months and secured his place in history.

One can trace today's controversies over how the periodic table should look to the discovery of quantum mechanics and atomic numbers. Mendeleev ostensibly organized his table by increasing atomic weight, but he gave chemical properties a deciding vote. For example, tellurium is slightly heavier than iodine, but Mendeleev put tellurium first because it has the same valence as oxygen, sulfur, and other elements in its group. Tables have retained that ordering. Mendeleev didn't know that tellurium has one fewer proton—and thus is one atomic number less—than iodine, which explains why they each belong where they do. "When you get atomic number, it provides logic" to the periodic table, Gordin says.

Along with protons came the discovery of electrons and the quantum-mechanical idea of atomic orbitals. These findings provided a whole new kind of logic for the periodic system. Although the organization of Mendeleev's system didn't change, scientists could now see that it was electronic structure that largely dictated elements' properties and explained why members of the same group were similar. The Madelung rule, or aufbau principle, that dictates that electrons fill the 1s orbital first and then the 2s and the 2p and so on, further explained how the elements were ordered.

Related: Adventures with the periodic table

That brings us to the tables we see today, which don't look that different from the versions famed chemist Glenn T. Seaborg drew in the 1940s. Seaborg moved the f-block elements—also called the lanthanide and actinide series—out of the main table to leave them floating below. This decision is generally understood as a concession to convenience; if those elements were in line with the others, the table would be too wide to fit on a standard sheet of paper or the type would be too small to read.

Seaborg included 15 elements in his f-block. That doesn't make a lot of sense from an electronic configuration point of view, since the f orbitals hold only 14 electrons. But many tables—including the table on the website of the International Union of Pure and Applied Chemistry (IUPAC), which has the last word on naming elements and molecules—share this feature. It's a way of avoiding one of the most controversial questions about the periodic table: What elements belong in group 3? No one disputes scandium and yttrium. But which elements come below those two? Lanthanum and actinium? Or lutetium and lawrencium?

Group decision

Today there's no standardization in the periodic tables found in classrooms, labs, and textbooks. Some avoid the group 3 question and use a 15-element f-block. Others put La and Ac in group 3, and still others have Lu and Lr, with the remainder of the f-block floating below.

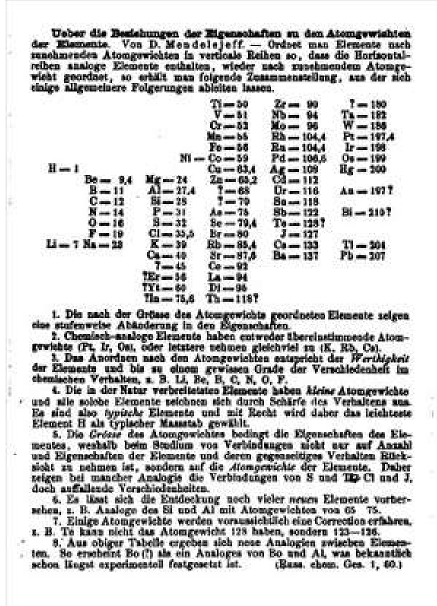
IUPAC has convened a working group to make a definitive recommendation one way or the other. One motivation for forming the task group, according to IUPAC's website, is to clear up confusion among students and teachers about which table is correct.

Philip Ball, a science writer and member of the working group, says the debate comes down to a fundamental question of whether physics or chemistry shapes the table. Put another way, he says the group is debating whether to side with the quantum physics that determines elements' electronic configurations or with the way elements behave chemically.

On the side of chemical behavior is Guillermo Restrepo, a mathematical chemist at the Max Planck Institute for Mathematics in the Sciences. Restrepo takes a historical view of how the table should be organized. He points to Mendeleev and his contemporaries, who found their periodic systems by studying elements' properties, often through their binding behavior. "At the core of the periodic system, what you have is chemistry," Restrepo says, "and you need chemical reactions."

Restrepo and colleagues analyzed some 4,700 binary compounds containing 94 elements to determine how chemical reactions inform the periodic system (*MATCH Commun. Math. Comput. Chem.* **2012**, *68*, **417**). The molecules could consist of more than one atom but only two elements. The researchers created a map that groups elements near those that form similar compounds. For example, fluorine, chlorine, and the other halogens sit next to each other because they all bind to similar elements.

Restrepo says this similarity landscape shows that lanthanum is more similar to scandium and yttrium than lutetium is, so it should be in group 3. But the analysis doesn’t provide a good answer about Lr versus Ac. Restrepo says the problem is there isn’t much data on how Lr and Ac bind to other entities. While there are tens of thousands of compounds one can use to study the similarities of Sc, Y, La, and Lu, Ac provides only about 70 data points, and Lr, fewer than 40, according to Restrepo.



Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente. Von D. Mendelejeff. — Ordnet man Elemente nach zunehmenden Atomgewichten in verticale Reihen so, dass die Horizontalreihen analoge Elemente enthalten, wieder nach zunehmendem Atomgewicht geordnet, so erhält man folgende Zusammenstellung, aus der sich einige allgemeinere Folgerungen ableiten lassen.

			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 — 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	S — 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?		

1. Die nach der Grösse des Atomgewichts geordneten Elemente zeigen eine stufenweise Abänderung in den Eigenschaften.
2. Chemisch-analoge Elemente haben entweder übereinstimmende Atomgewichte (Pt, Ir, Os), oder letztere nehmen gleichviel zu (K, Rb, Cs).
3. Das Anordnen nach den Atomgewichten entspricht der *Werthigkeit* der Elemente und bis zu einem gewissen Grade der Verschiedenheit im chemischen Verhalten, z. B. Li, Be, B, C, N, O, F.
4. Die in der Natur verbreitetsten Elemente haben *kleine* Atomgewichte und alle solche Elemente zeichnen sich durch Schärfe des Verhaltens aus. Es sind also *typische* Elemente und mit Recht wird daher das leichteste Element H als typischer Maasstab gewählt.
5. Die *Grösse* des Atomgewichtes bedingt die Eigenschaften des Elementes, weshalb beim Studium von Verbindungen nicht nur auf Anzahl und Eigenschaften der Elemente und deren gegenseitiges Verhalten Rücksicht zu nehmen ist, sondern auf die *Atomgewichte* der Elemente. Daher zeigen bei mancher Analogie die Verbindungen von S und Te, Cl und J, doch auffallende Verschiedenheiten.
6. Es lässt sich die Entdeckung noch vieler *neuen* Elemente vorhersehen, z. B. Analoge des Si und Al mit Atomgewichten von 65–75.
7. Einige Atomgewichte werden voraussichtlich eine Correction erfahren, z. B. Te kann nicht das Atomgewicht 128 haben, sondern 123—126.
8. Aus obiger Tabelle ergeben sich neue Analogien zwischen Elementen. So erscheint Bo (?) als ein Analoges von Bo und Al, was bekanntlich schon längst experimentell festgesetzt ist. (Russ. chem. Ges. 1, 60.)

Credit: Dmitri Mendeleev

Dmitri Mendeleev's first published table included all the known elements and left space for the elements his periodic system predicted were still undiscovered.

Eric Scerri, a philosopher of science at the University of California, Los Angeles, and the chair of the IUPAC task group, disagrees. He believes Sc, Y, Lu, and Lr should be the group 3 elements. Scerri thinks a focus on chemical or physical properties is misguided. He compares it to early botanists’ classification of flowers by their color or petal number.

The periodic table on the website of the International Union of Pure and Applied Chemistry avoids making a decision about whether La and Ac or Lu and Lr are group 3 elements.

“You’ve got to go for something fundamental,” Scerri says, like electronic configuration. “Just to amass properties is never going to give you a definitive answer.”

Not that electronic configuration is perfect either, as Scerri will tell you. Exceptions have been made for some elements in the periodic table in terms of how their orbitals are filled, like copper. By the periodic table’s logic, all d-block elements should have filled s orbitals. But copper defies that logic. It should have the electron configuration [Ar] $3d^9\ 4s^2$. Instead, its 4s atomic orbital remains unfilled, and one electron goes in its 3d shell, leading to the configuration [Ar] $3d^{10}\ 4s^1$, which is more stable.

Scerri does prefer electronic configuration to what he calls “gross physical characteristics” for organizing the table. But he sees an even simpler logic to solve the group 3 problem: arrange by atomic number. If Scerri has his way, we’ll all have to get used to a newly arranged table.

Going wide

“My suggestion is simply this,” Scerri says. “Represent the periodic table in a 32-column format.”

Scerri calls 32 columns a more natural form for the periodic table and attributes the current dominance of 18 columns to convenience only. A 32-column table uses the atomic numbers as its logical foundation. Not only would it solve the group 3 question, but Scerri says 32 columns would be more correct because it puts the f-block in its rightful place: inside the table rather than floating below for convenience.

Related: Seventh Row Of The Periodic Table Is Now Complete With Addition Of Four Elements

In a 32-column table arranged by ascending atomic number, lanthanum (atomic number 57) follows barium (number 56) to start the f-block, with actinium below it. That makes lutetium the first element in the third row of the d-block, with scandium and yttrium above it and lawrencium below to form group 3. Strict adherence to atomic number satisfies Scerri's desire for a fundamental organizing principle and neatly sidesteps questions about chemical or physical properties.

Another table similar to the 32-column version has been proposed, but it uses electronic configuration rather than atomic numbers as its primary guide. French scientist Charles Janet's left-step periodic table, devised in 1928, isn't likely to make it into textbooks anytime soon, however. Janet moves the s-block to the right side of the table and includes helium at the top of group 2 because its s orbital, like other elements in that group, is filled.

Most tables place helium atop the noble gases. Scerri thinks helium's demotion in the left-step table is one reason the table never got more traction, though **recent experiments showing helium can form stable bonds** help Janet's argument that it belongs in a group with other reactive, rather than inert, elements.

The left-step periodic table, invented by Charles Janet, is strictly based on atomic orbitals and electron-filling order.

Regardless, read from top to bottom and left to right, the left-step table more correctly conforms to the Madelung rule, which states that electrons must first fill the lowest-available electron levels before filling higher ones, Scerri says. It has a regularity that current tables don't: two periods of 2 elements, two of 8 elements, two of 18, two of 32. And when element 121 is discovered, it will begin the g-block and two new periods of 50 elements.

Relative difficulty

The filling order that most chemists are used to might not hold up for much longer, however. Some calculations show the Madelung rule breaks down at higher atomic numbers because of relativistic effects. Electrons in large atoms move so fast that their behavior—and the properties of the atoms they belong to—begin to change.

Fans of relativistic effects will be happy to know there's a table for them too. Pekka Pyykkö, a theoretical chemist at the University of Helsinki, calculated electron configurations up to element 172 and made a table for them (*Phys. Chem. Chem. Phys.* 2010, **DOI: 10.1039/c0cp01575j**). Pyykkö doesn't bother with the group 3 question. His table leaves a hole under yttrium and has three 15-element rows in an f-block floating beneath the main table. Nor is he so constrained by atomic numbers. For instance, element 164 is followed by elements 139, 140, and then 169. According to Pyykkö's calculations, 139 and 140 are the first elements with electrons in the 8p orbital.

This table is, of course, largely hypothetical. Scientists have not yet synthesized any elements beyond 118, and while several groups are working to do so, it's possible we will reach the limits of our abilities to forge new elements well before element 172 or even 139.

Pekka Pyykkö proposes a periodic table that goes all the way up to atomic number 172 and is based on electronic configurations, which he calculated by taking relativistic effects into account.

"This is open land," says Peter Schwerdtfeger, a theoretical chemist at Massey University studying superheavy elements. He calls Pyykkö's calculations a "very good approximation" of the electron configurations but says more calculations are needed to pin down the precise characteristics of these elements. Pyykkö agrees. He too is waiting for more detailed calculations to show how wrong or right his table is.

And there are still other configurations of the elements that scientists are arguing for. Some tables look like rings or spirals. Some are 3-D, with lobes or stacks of element blocks. It seems less likely any of these will challenge the basic shape of the current table.

But Restrepo encourages scientists to think beyond just one table. "There's a lot of discussion about if this table is good or bad, if this shape is better or worse," he says. He prefers to focus on the periodic system rather than on the table. In a sense, he says, the system is like a sculpture, and the tables are shadows cast by lights shone from different angles. He says that allows chemists to find the periodic table or tables that are most useful to them, whether they're looking for new elements or trying to understand properties in detail.

Gordin agrees on historical grounds. The periodic tables of the 19th century, he says, were made "to be flexible." But he understands the resistance to radically different periodic tables, comparing new periodic tables to Pluto's demotion from the ranks of planets. "The table you grew up with is the table you like."

Related: Reviewing The Periodic Table

That raises a question about how much scientists and others should worry about these debates. "There's a little group that argues over which [periodic table] is best," Ball says. He believes the IUPAC group's work is important because the current situation, with several competing tables, is confusing. But Ball says there's no reason to think one table can capture the whole picture. "This notion of periodicity was so important for chemistry when the periodic table was first put forward and in the subsequent decades to make sense of this chaos of elements," he says.

But today it should be more of a rule of thumb rather than a law of nature, Ball adds, arguing that there's room for more than one periodic table: "Chemistry is about compromise."

CORRECTION:
This story was updated on Jan. 8, 2019, to correct the left-step periodic table. Its s-block was aligned incorrectly.

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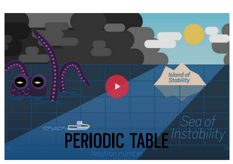
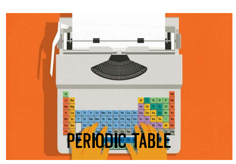
Exploring the superheavy elements at the end of the periodic table



Video: What lies at the end of the periodic table?



How the periodic table changed my life

COMMENTS

Gerald Eadie
(January 8, 2019 3:33 PM)
For proponents of the Left Step periodic table, it is not necessary to calculate g-block and the matching s-p-d-f components. To see why this is so, check out the table "Periodic Group G.pdf" at:
https://drive.google.com/drive/folders/0ByxBrWNhiMIJWVkteTJSNFJscmc
for a tongue-in-cheek spoof of g-Block. The Pyykkö model (like most non-LST models) assumes that s-block is already full.

Reply »

Paul Eckler
(January 9, 2019 3:16 PM)
The periodic table is a popular symbol of chemistry. But why should we have only one? Why not allow those who specialize to design their own for their own purposes?
Reply »

Chuck Schroer
(January 9, 2019 3:37 PM)
I'm just wondering if there is a more three dimensional approach that needs to be developed to better show the elemental associations . A linear table might be too restrictive? Maybe a spherical concept or pyramidal one? Maybe an ellipsoid...
I think sometimes we get caught up in one way of looking at things when using another way could be more helpful. I am not an expert, I just have a feeling that those who are trying to build this puzzle are looking at it the wrong way.
Reply »

Eisa M
(March 15, 2019 12:39 AM)
Recently thought the same! Sadly think that the leading representation of data has to shift to 3D before it becomes 'the' "table".
Reply »

Robert Parsons
(January 9, 2019 4:08 PM)
I wonder if it might it not be more accurate (at least for now) to say that most of the transuranic elements were "invented" rather than "discovered." All these elements, after all, were synthesized by man rather than found in nature, and while the lower molecular weight elements among them have been found to occur naturally in very minute quantities, the higher molecular weight elements among them have not been found in nature, and indeed have existed only for mere fractions of a second before decaying into lower MW natural elements. While it is certainly possible that all these higher MW synthesized elements might exist naturally somewhere in the universe (perhaps within the hearts of stars), it is unlikely that any of them exist naturally on Earth and it is also possible that none of them exist naturally anywhere.
Reply »

Gary D Patterson
(January 9, 2019 5:12 PM)
The periodic table is best viewed as a paradigm of chemistry. The pictorial representation of this concept has varied over time and is still evolving. One of the rarely mentioned formulators of this paradigm is John F.W. Herschel in his book "Preliminary Discourse on the Study of Natural Philosophy," (1851). In case anyone doubts that he was a chemist (he was the son and collaborator of William Herschel and received many awards in astronomy and geology), he was the Chair of the Chemistry Section of the British Association for the Advancement of Science. He was one of the developers of photography(every pun intended) and was the father of chemical spectroscopy. A paper on his contributions to the periodic table concept will be given at the San Diego ACS Meeting in August.
Reply »

Valery Tsimmerman
(January 9, 2019 10:19 PM)
According to some physicists the end of the periodic table is near. See Phys. Rev. Lett. 120, 222001 – Published 31 May 2018. University of Toronto physicists Bob Holdom, Jing Ren, and Chen Zhang predict that nuclei of elements with atomic masses slightly heavier than 300 might not be composed of familiar protons and neutrons, but would rather be up and down quark matter matter, or udQM. This would mean punctuation mark in the periodic table near or at element 120.
On a different note, I agree with Scerri's position. Modern periodic table should not depart too far from spectroscopic and quantum mechanical data. It should remind users that periodic table blocks s, p, d, and f correspond to angular momentum quantum numbers l=0,1,2 and 3 and the length of the blocks should be 4l+2, as quantum theory dictates. Fifteen element f-block flies in the face of what QM teaches.
Reply »

Paul C. Li
(January 9, 2019 11:10 PM)
Dear Honorable Editors in Chief @ C&E News:
I used the “I Ching’s hexa grams” in co-circular forms extended from the middle point to layers after layers which satisfies nearly perfect shape with side branches observable in the chemical identities.
I shall pick it back to my own purpose as entertainment. For entertainment it does more fun than mind buckling as what it is now to outstanding scholars. Life is a string of better chemistries strung together shaped like what we are dwelling. Submitted to your attention with highest level of respect. Dr. Paul C. Li a life long enthusiastic chemist.
Reply »

René Vernon
(January 10, 2019 4:40 AM)
The problem could be resolved by picking the format with the least number of block membership discrepancies. For example, Gd is in the f-block but has a "d" differentiating electron, so that’s a discrepancy.
On this basis, the "winner" is a table with He over Be, and La and Ac under Y, for a total of 11 discrepancies. Next is the left step table, with He over Be, at 12 discrepancies.
Effectively no one will like He over Be. That leaves a table with He over Ne, and La and Ac under Y, also with 12 discrepancies. This is the table most commonly seen in the literature.
A table with Lu and Lr under Y has 13 discrepancies; the IUPAC table has 14.
Each table has its uses but the most popular table, with He over Ne, and La and Ac under Y continues to serve the chemistry community well.