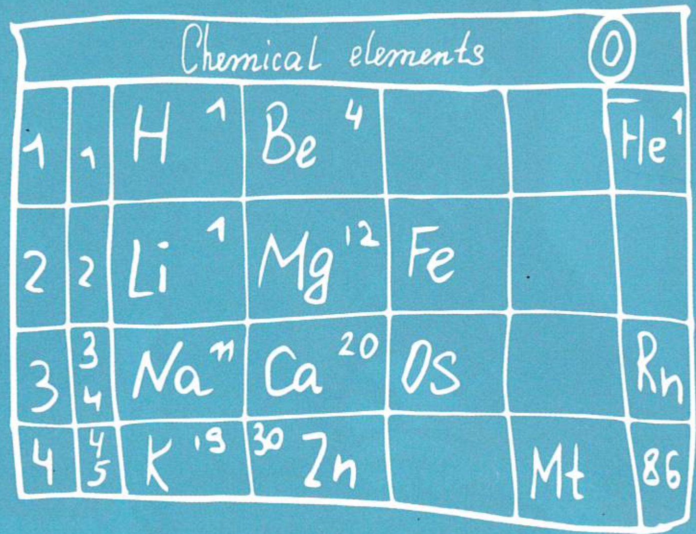
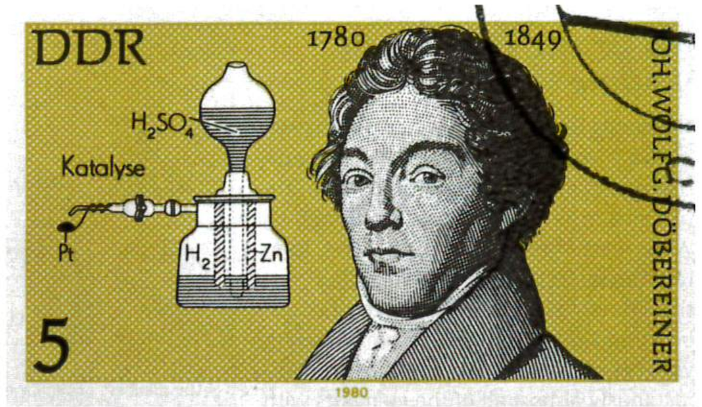
CRACKING
the Periodic Law



We have known for a long time about how the properties of elements depend on their atomic masses. But only in the 19th century did the scientific community begin active attempts to crack open the periodic law. This law explains what the properties of atoms depend on and which reactions are characteristic for different elements — despite the fact that they are all composed of the very same electrons and protons.

Döbereiner's Table

If the German chemist Johann Döbereiner had brought the idea of the ordering of the elements to its logical end, then, perhaps, the periodic law would bear his name. At the beginning of the nineteenth century, he was one of the first to try to systematize fifty-five elements that had been discovered by that time and explain the difference in their properties. Döbereiner noted that bromine (Br) is in between iodine (I) and chlorine (Cl) and, moreover, that the atomic mass of Br is the arithmetic mean of the atomic masses of Cl and I. The same relationship was observed in two more groups: calcium, strontium, and barium; and sulphur, selenium, and tellurium. Such congruence could not be accidental and Döbereiner took up the search for similar triads among the remaining known elements. A few more triplets were discovered: lithium, sodium, and potassium; and phosphorus, arsenic, and antimony.



A German postal stamp from the 1980's with an image of Wolfgang Döbereiner

DÖBEREINER TRIAD

Li	7
Na	23
K	39

$$\frac{7+39}{2} = 23$$

Cl	35.5
Br	80
I	127

$$\frac{35.5+127}{2} = 81.25$$

S	32
Se	78
Te	128

$$\frac{32+128}{2} = 80$$

P	15
As	33
Sb	51

$$\frac{15+51}{2} = 33$$

By 1829, he published his ideas, however, the scientific community responded to them with scepticism. At first, it seemed that atomic mass was not able to influence the physical properties of elements. Secondly, the **"Döbereiner triad"** was not enough: the remaining elements did not obey this rule. As a result, the first attempts to crack the great chemical law were rejected, but the foundation for future discoveries had been laid.

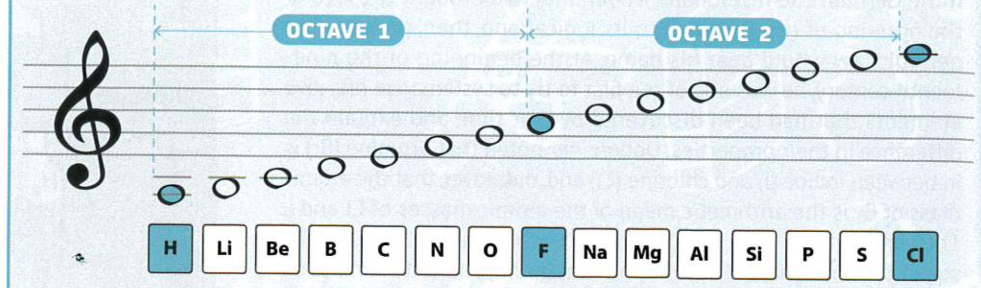
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Ca	Ga	Ge	As	Se	Br	Kr
Rb	Sr	In	Sn	Sb	Te	I	Xe
Cs	Ba	Tl	Pb	Bi	Po	At	Rn

A distinctive characteristic of the Döbereiner triads was the element in the middle of each triad, whose atomic mass is the arithmetic mean of the two outer elements

Music and the Atomic Volume

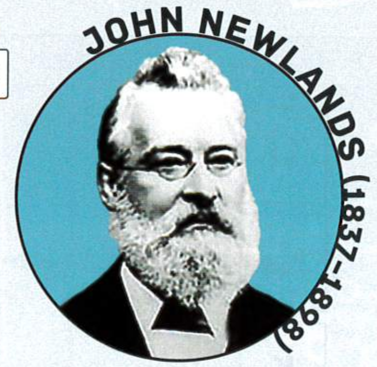
Newlands Law of Octaves has gone down in the history of chemistry as, perhaps, the most curious attempt to explain the structure of the world of elements. What were these octaves? In 1864, **John Newlands**, from London, suggested that the known elements at the time could be arranged by increasing atomic mass in vertical columns of seven each. And, miraculously, almost all of the elements with similar properties happened to "fit" into the very same corresponding horizontal rows! As a result, we obtained a table which specifically describes the *periodic* dependence of properties on their structure – a direct predecessor of Mendeleev's law. Newlands called the law that he discovered the **Law of Octaves**, in an analogy to the seven notes which form a musical octave, in which each eighth note almost entire repeats the first and begins a new octave. Sound familiar? The English chemist practically laid out all of the necessary tools to crack the mystery, but he needed to have gone a little further to complete the final step. Scientists laughed at Newlands' idea, pointing out that not all of the rows were filled with similar elements (which means that those coincidences that were revealed were just that – random), and during his presentation to the London Chemical Society, it was sarcastically suggested to him that he try to arrange to elements alphabetically and try to find any patterns. Nonetheless, many years later, in 1887, Newlands received an award for "the discovery of the periodic law of chemical elements." Paradoxically, the exact same medal was given to Russian scientist Dmitri Mendeleev for the exact same purpose.

NEWLANDS' LAW OF OCTAVES

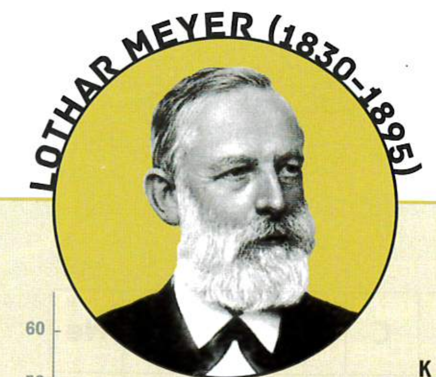


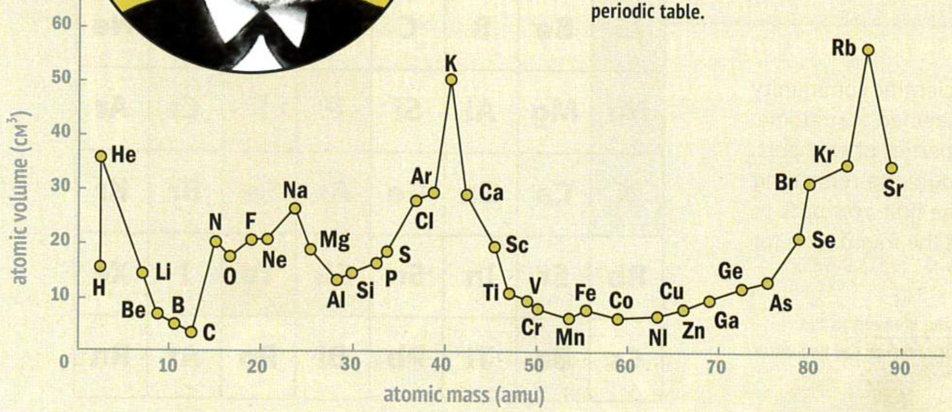
The numbers of similar elements, as a rule, differ either by an integer number of seven or by multiples of seven; in other words, the relationship between members of the same group mimics the relationship between the extreme notes of one or more octaves in music.

1	2	3	4	5	6	7	8
1 H	8 F	15 Cl	22 Co, 22 Ni	29 Br	36 Pd	43 I	50 Ir, 50 Pt
2 Li	9 Na	16 K	23 Cu	30 Rb	37 Ag	44 Cs	51 Os
3 G	10 Mg	17 Ca	24 Zn	31 Sr	38 Cd	45 Ba, 45 V	52 Hg
4 Bo	11 Al	18 Cr	25 Y	32 Ce, 32 La	39 U	46 Ta	53 Tl
5 C	12 Si	19 Ti	26 In	33 Zr	40 Sn	47 W	54 Pb
6 N	13 P	20 Mn	27 As	34 Di, 34 Mo	41 Sb	48 Nb	55 Bi
7 O	14 S	21 Fe	28 Se	35 Ro, 35 Ru	42 To	49 Au	56 Th



German chemist **Julius Lothar Meyer** decided to measure the volumes that occupy the fixed weights of various elements – and there he struck gold in chemistry (no, not literally). Meyer arranged these values in ascending order on a two-dimensional plane graph, in which the x-coordinate (the abscissa) corresponded to the atomic mass, and the atomic volume increased on the y-coordinate (the ordinate). This resulted in a curve which reached its peak values for alkali metals – sodium, potassium, rubidium, and caesium. In addition, each peak and trough of the plotted line corresponded to a period in the modern periodic table of elements. In fact, Meyer had created an analogue of the periodic table by 1870, but in the form of a two-dimensional sawtooth wave. Interestingly, the second and third periods contained the elements from the Newlands' octaves. As you can tell, the idea of the periodicity of properties of elements was in the air in the 19th century.



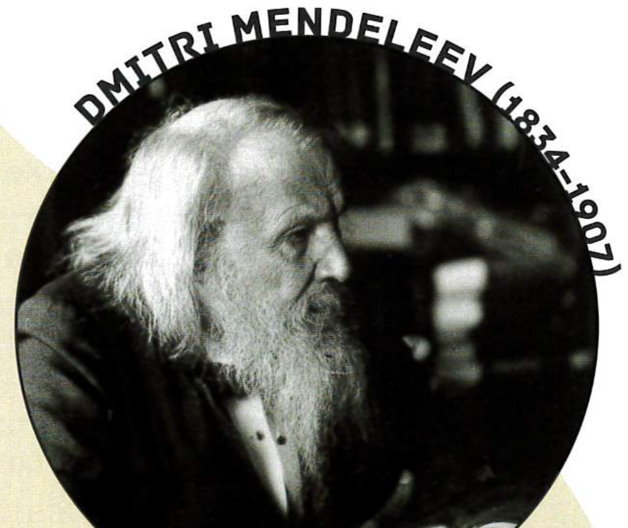


Every fall and rise in the Meyer graphic equalled one period in the modern periodic table.

The Element Predictor

Dmitri Mendeleev knew about his predecessors and, in the development of the periodic law, took their shortcomings into account. He did not draw a graph like Meyer and abandoned the strictly equal periods that Newlands had insisted upon. As a result in 1869, when 35-year-old Mendeleev published his ideas in the *Journal of the Russian Chemical Society* and became a groundbreaking actor in the field of chemistry. He placed all of the elements in order of their atomic masses with the same valences in columns but did not adjust the facts to fit the theory and put some elements with larger weights in front of the lighter ones. For example, tellurium, which has an atomic mass of 127.6, turned out to be in front of iodine (which has an atomic mass of 126.9). The boldest part was Mendeleev's statement that his table contained "blank spaces" which would eventually be filled by undiscovered elements! This, without a doubt, caused a stir in the scientific community of that time. Mendeleev named the future elements the prefix "eka" (which means "one, or the next" in Sanskrit) – *eka-aluminium, eka-silicon, eka-boron*. In 1870, the scientist predicted the properties of eka-aluminium (Ea): "The properties of this metal in all respects must represent a transition from the properties of aluminium to the properties of indium, and it is very likely that this metal will be more volatile than aluminium, and therefore, one can hope that it will be discovered through spectral research."

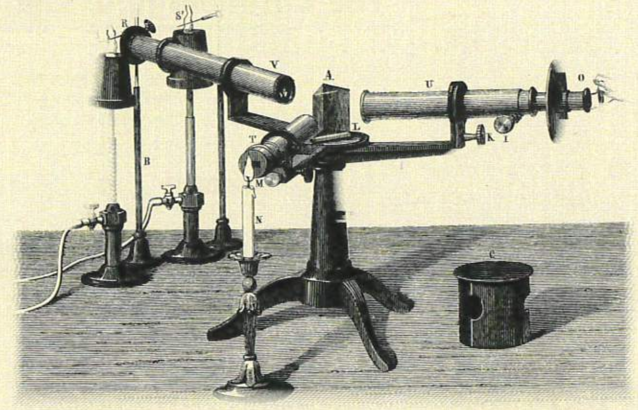
Five years later, Paul Emile Lecoq de Boisbaudran discovered a bright violet line in the spectrum of a mineral containing zinc, something never seen before. It turned out to be the predicted eka-aluminium, which was later called gallium! Eka-boron (Eb), as Mendeleev called it, should have had an atomic mass of about 44, an oxide formula of R_2O_3, and the external appearance of a colourless salt. Refer to the periodic table and you will learn that this element is scandium, discovered in 1879 by the Swede Lars Fredrik Nilson. But the most detailed prediction of periodic pioneer Mendeleev's was in relation to eka-silicon, which he indicated would have an atomic mass of 72, an oxide formula of RO_2 with a specific gravity of 4.7. He also calculated the composition of the chloride RCl_4.



MENDELEEV'S TABLE, 1870

elements known to Mendeleev; Döbereiner triad

	H 1.01									
He 4.00	Li 6.94	Be 9.01	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0			
Ne 20.2	Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5			
Ar 40.0	K 39.1	Ca 40.1	Sc 45.0	Ti 47.9	V 50.9	Cr 52.0	Mn 54.9	Fe 55.9	Co 58.9	Ni 58.7
	Cu 63.5	Zn 65.4	Ga 69.7	Ge 72.6	As 74.9	Se 79.0	Br 79.9			
Kr 83.8	Rb 85.5	Sr 87.6	Y 88.9	Zr 91.2	Nb 92.9	Mo 95.9	Tc (99)	Ru 101	Rh 103	Pd 106
	Ag 108	Cd 112	In 115	Sn 119	Sb 122	Te 128	I 127			
Xe 131	Cs 133	Ba 137	La 139	Hf 179	Ta 181	W 184	Re 180	Os 194	Ir 192	Pt 195
	Au 197	Hg 201	Tl 204	Pb 207	Bi 209	Po (210)	At (210)			
Rn (222)	Fr (223)	Ra (226)	Ac (227)	Th (232)	Pa (231)	U 238				



An illustration of a spectroscope from 1874 from the French magazine Magasin pittoresque

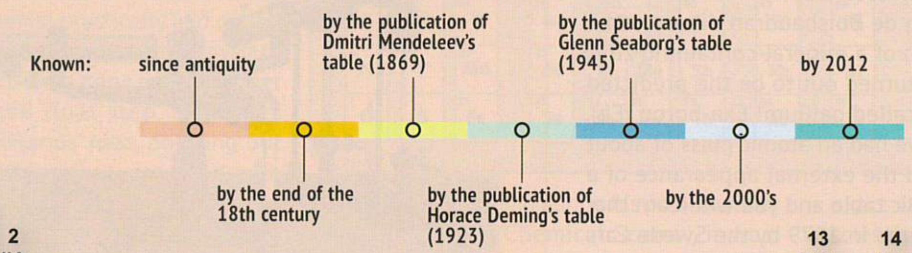
Mendeleev went further and mentioned the dual nature of the chemical properties of the undiscovered element, and about its ability to create organometallic compounds. Have you guessed what we are talking about? Germanium, of course, which was discovered during Mendeleev's life by the German chemist **Clemens Winkler** in 1888. Other elements that Mendeleev had predicted were discovered after his death: hafnium, rhenium, francium, and radium. The Great Predictor left blank spaces for all of these. What's more, Mendeleev was so confident in his work that he decided to correct the atomic masses of the elements known at that time. First up was beryllium, which had its atomic mass decreased from 14 to 9.4, which did not violate the harmonious structure of the periodic table of elements. In addition, the atomic masses of eight other elements on the table were ascertained, and, accordingly, received their rightful places. Concrete confirmation of the scientist's daring ideas came much later; for example, the mass of the titanium atom was only corrected in 1885 – fifteen years later.

The Many-Faced Table

Mendeleev's tremendous successes were recognized at many levels. In 1882, along with Lothar Meyer, the scientist received the Davy Medal "for the discovery of the periodic ratios of atomic weights" from the Royal Society of London and certainly deserved the then-young Nobel Prize in chemistry. It was at the beginning of the 20th century that the periodic law passed one of its most serious tests – the discovery of inert gases. Argon and helium were the first on this list, but there was no space for them in the table. Their zero valence and the monoatomic nature of their molecules made finding a location for them very difficult, a fact which was "weaponized" by Mendeleev's scientific opponents. There was an outpouring of accusations that the periodic law was invalid, but the scientist retorted elegantly by simply creating a special zero-group, where he put the castaway elements. In the future, new inert gases were added to the list in the table and became the main subgroup of the Group VIII elements. The periodic law received its fundamental confirmation, and at the beginning of the 20th century, Mendeleev was nominated for the Nobel Prize three times – in 1905, 1906, and 1907. In the first two cases, the Swedish Academy of Sciences considered the works of Adolf von Bayer and Henri Moissan more significant, and, in 1907, when it was practically a given that Dmitri Mendeleev would receive the prize, he passed away.

At the moment, the Periodic Table of Elements exists in several variants – short-period, long-period, and extended-period. The short form is considered the classic, and it was in this format that the scientist originally published the work in 1871, but in 1989, the *International Union of Pure and Applied Chemistry* (IUPAC) abolished it, replacing it with the long form. In this form, there are 18 groups, while the series, subgroups, and families are absent, which simplifies working with the table. The extended table is unofficial and consists of 32 columns, 14 of which are only occupied by two elements each. Not only the shape changes but the contents, too! Most recently, the numbers 113, 115, 117, and 118 were formally inducted into the table as nihonium, moscovium, tennessine, and oganesson. And scientists from world centers focusing on the synthesis of new elements are full of energy for new achievements in the search for the ultimate element of the periodic law. Cracking the periodic law, as we can see, is in full swing.

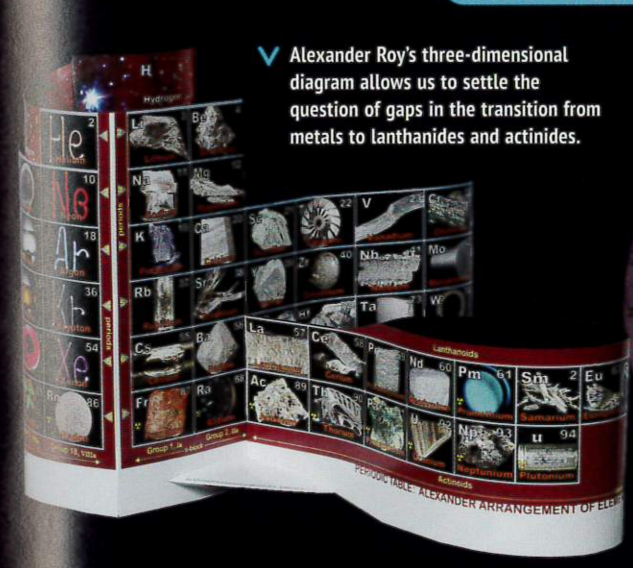
The Chronology of the Discovery of Elements



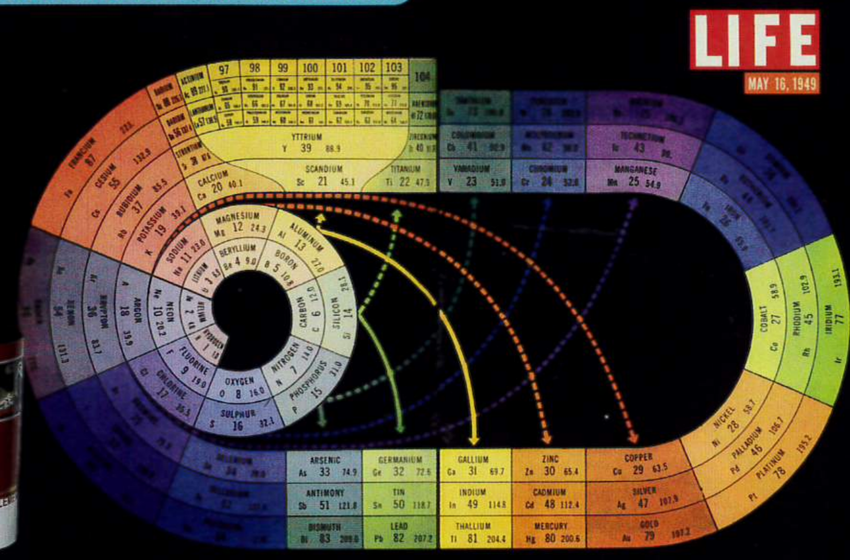
	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Gy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

ALTERNATIVE FORMATS OF THE PERIODIC SYSTEM OF ELEMENTS



Alexander Roy's three-dimensional diagram allows us to settle the question of gaps in the transition from metals to lanthanides and actinides.

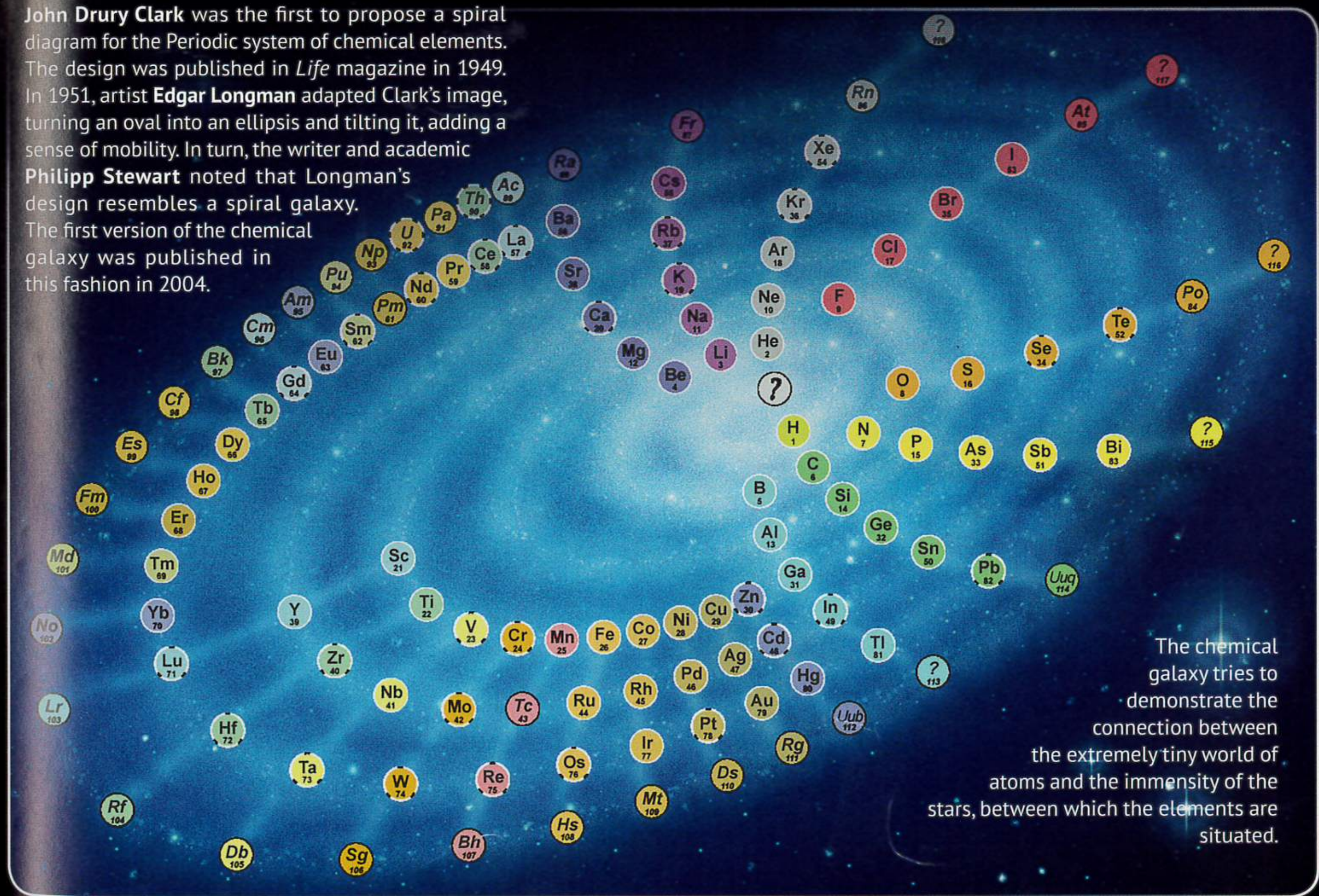


John Drury Clark's diagram, published in Life magazine in 1949

The history of the chemical galaxy

John Drury Clark was the first to propose a spiral diagram for the Periodic system of chemical elements. The design was published in *Life* magazine in 1949. In 1951, artist **Edgar Longman** adapted Clark's image, turning an oval into an ellipsis and tilting it, adding a sense of mobility. In turn, the writer and academic **Philipp Stewart** noted that Longman's design resembles a spiral galaxy. The first version of the chemical galaxy was published in this fashion in 2004.

Philip Stewart's Chemical Galaxy



The chemical galaxy tries to demonstrate the connection between the extremely tiny world of atoms and the immensity of the stars, between which the elements are situated.