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The Development of the Periodic Table and its Consequences

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Abstract. Chemistry is fortunate among the sciences in having an icon that is instantly recognisable around the world: the periodic table. The United Nations has deemed 2019 to be the International Year of the Periodic Table, in commemoration of the 150th anniversary of the first paper in which it appeared. That had been written by a Russian chemist, Dmitri Mendeleev, and was published in May 1869. Since then, there have been many versions of the table, but one format has come to be the most widely used and is to be seen everywhere. The route to this preferred form of the table makes an interesting story.

Keywords. Periodic table, Mendeleev, Newlands, Deming, Seaborg.

INTRODUCTION

There are hundreds of periodic tables but the one that is widely reproduced has the approval of the International Union of Pure and Applied Chemistry (IUPAC) and is shown in Fig.1. How chemists arrived at this iconic table makes an intriguing story and it can be traced back more than 250 years. However, it has become invariably linked to a man who lived in St Petersburg in the mid-ninteenth century: Dimitri Mendeleev.

EARLY ATTEMPTS TO BRING ORDER TO THE ELEMENTS

The great French chemist, Antoine Laurent de Lavoisier (1743–1794) was interested in the elements and, in 1789, he sought to bring order to them in his book *Traité Elémentaire de Chemie* (*Elements of Chemistry)*[1]. In this he listed 33 substances which he regarded as elements – see Fig. 2.

Lavoisier separated them into four categories that we could describe as *Gases,* which comprised light, heat, oxygen, nitrogen, and hydrogen; *Nonmetals,* which consisted of sulfur, phosphorus, carbon, chloride, fluoride, and borate; *Metals,* this was the largest group with antimony, arsenic, bismuth, cobalt, copper, gold, iron, lead, manganese, mercury, molybdenum, nickel, platinum, silver, tin, tungsten, and zinc; and *Earths,* which were lime, mag-

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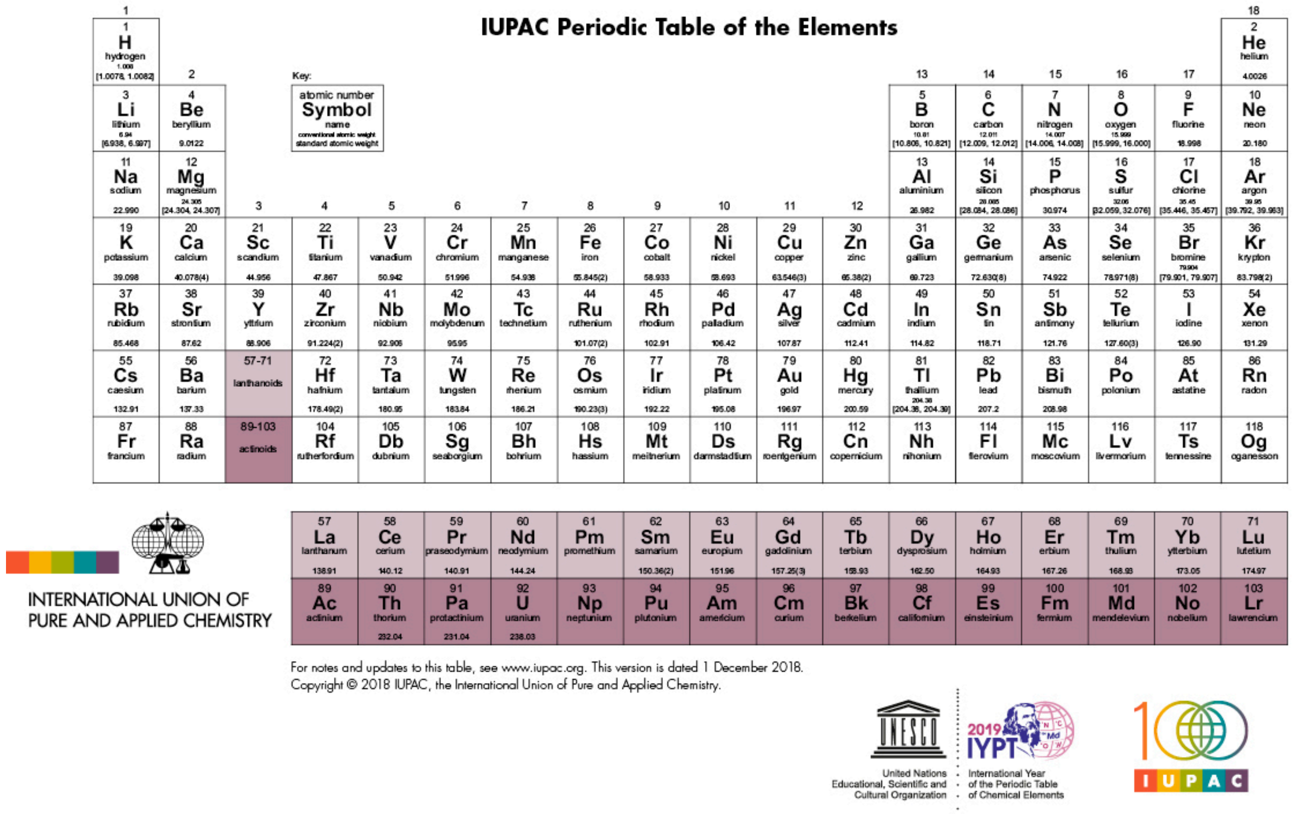

IUPAC Periodic Table of the Elements

Key:
atomic number
Symbol
name
conventional atomic weight
standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.008 [1.0078, 1.0082]																	2 **He** helium 4.0026
3 **Li** lithium 6.94 [6.938, 6.997]	4 **Be** beryllium 9.0122											5 **B** boron 10.81 [10.806, 10.821]	6 **C** carbon 12.011 [12.009, 12.012]	7 **N** nitrogen 14.007 [14.006, 14.008]	8 **O** oxygen 15.999 [15.999, 16.000]	9 **F** fluorine 18.998	10 **Ne** neon 20.180
11 **Na** sodium 22.990	12 **Mg** magnesium 24.305 [24.304, 24.307]											13 **Al** aluminium 26.982	14 **Si** silicon 28.085 [28.084, 28.086]	15 **P** phosphorus 30.974	16 **S** sulfur 32.06 [32.059, 32.076]	17 **Cl** chlorine 35.45 [35.446, 35.457]	18 **Ar** argon 39.95 [39.792, 39.963]
19 **K** potassium 39.098	20 **Ca** calcium 40.078(4)	21 **Sc** scandium 44.956	22 **Ti** titanium 47.867	23 **V** vanadium 50.942	24 **Cr** chromium 51.996	25 **Mn** manganese 54.938	26 **Fe** iron 55.845(2)	27 **Co** cobalt 58.933	28 **Ni** nickel 58.693	29 **Cu** copper 63.546(3)	30 **Zn** zinc 65.38(2)	31 **Ga** gallium 69.723	32 **Ge** germanium 72.630(8)	33 **As** arsenic 74.922	34 **Se** selenium 78.971(8)	35 **Br** bromine 79.904 [79.901, 79.907]	36 **Kr** krypton 83.798(2)
37 **Rb** rubidium 85.468	38 **Sr** strontium 87.62	39 **Y** yttrium 88.906	40 **Zr** zirconium 91.224(2)	41 **Nb** niobium 92.906	42 **Mo** molybdenum 95.95	43 **Tc** technetium	44 **Ru** ruthenium 101.07(2)	45 **Rh** rhodium 102.91	46 **Pd** palladium 106.42	47 **Ag** silver 107.87	48 **Cd** cadmium 112.41	49 **In** indium 114.82	50 **Sn** tin 118.71	51 **Sb** antimony 121.76	52 **Te** tellurium 127.60(3)	53 **I** iodine 126.90	54 **Xe** xenon 131.29
55 **Cs** caesium 132.91	56 **Ba** barium 137.33	57-71 lanthanoids	72 **Hf** hafnium 178.49(2)	73 **Ta** tantalum 180.95	74 **W** tungsten 183.84	75 **Re** rhenium 186.21	76 **Os** osmium 190.23(3)	77 **Ir** iridium 192.22	78 **Pt** platinum 195.08	79 **Au** gold 196.97	80 **Hg** mercury 200.59	81 **Tl** thallium 204.38 [204.38, 204.39]	82 **Pb** lead 207.2	83 **Bi** bismuth 208.98	84 **Po** polonium	85 **At** astatine	86 **Rn** radon
87 **Fr** francium	88 **Ra** radium	89-103 actinoids	104 **Rf** rutherfordium	105 **Db** dubnium	106 **Sg** seaborgium	107 **Bh** bohrium	108 **Hs** hassium	109 **Mt** meitnerium	110 **Ds** darmstadtium	111 **Rg** roentgenium	112 **Cn** copernicium	113 **Nh** nihonium	114 **Fl** flerovium	115 **Mc** moscovium	116 **Lv** livermorium	117 **Ts** tennessine	118 **Og** oganesson

57 **La** lanthanum 138.91	58 **Ce** cerium 140.12	59 **Pr** praseodymium 140.91	60 **Nd** neodymium 144.24	61 **Pm** promethium	62 **Sm** samarium 150.36(2)	63 **Eu** europium 151.96	64 **Gd** gadolinium 157.25(3)	65 **Tb** terbium 158.93	66 **Dy** dysprosium 162.50	67 **Ho** holmium 164.93	68 **Er** erbium 167.26	69 **Tm** thulium 168.93	70 **Yb** ytterbium 173.05	71 **Lu** lutetium 174.97
89 **Ac** actinium	90 **Th** thorium 232.04	91 **Pa** protactinium 231.04	92 **U** uranium 238.03	93 **Np** neptunium	94 **Pu** plutonium	95 **Am** americium	96 **Cm** curium	97 **Bk** berkelium	98 **Cf** californium	99 **Es** einsteinium	100 **Fm** fermium	101 **Md** mendelevium	102 **No** nobelium	103 **Lr** lawrencium

INTERNATIONAL UNION OF
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For notes and updates to this table, see www.iupac.org. This version is dated 1 December 2018.
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United Nations
Educational, Scientific and
Cultural Organization

2019 IYPT
International Year
of the Periodic Table
of Chemical Elements

100 IUPAC

Figure 1. The periodic table.

nesia, barytes, alumina, and silica. Lavoisier and his colleagues suspected that the 'earths' were probably capable of being broken down further and he wrote: 'We may even pressume that the earths may soon cease to be considered as simple bodies.'

Clearly light and heat were wrongly classified as elements, and borate was boron-with-oxygen, as were the earths which were the oxides of calcium, magnesium, barium, aluminium and silicon. Technology of the time could not decompose them further. Heating a mineral with carbon in a furnace would generally remove all the oxygen as CO_2, but for some minerals this did not happen, hence Lavoisier's belief that these were fundamental elements.

In all, his list included 26 that we now know to be true elements. However, he made no attempt to organise his list into elements with similar properties, so his list cannot be regarded as a fore-runner to the periodic table, although he might have eventually listed the elements in other ways, had he not been guillotined in 1794.

Meanwhile chemistry was undergoing a major shift with the writing of John Dalton who, in 1805, not only proposed that elements must exist as single atoms but he calculated their relative weights.

The next attempt to bring order to the elements was a theory put forward in 1815 by 30-year-old William Prout (1785–1850). He submitted a paper entitled 'On the Relation between the Specific Gravities of Bodies in their Gaseous State and the Weights of their Atoms' and he asked that it be published anonymously, although it became known he was the author.[2]

In this paper he proposed that all elements had relative weights, so-called 'equivalent weights', which were multiples of the weight of hydrogen, taken as 1. His theory would explain why so many weights were whole numbers, or nearly so. It was a far-sighted suggestion, and today we know the explanation is that 99.98% of the mass of an atom resides in its nucleus which is made up of protons and neutrons both of unit mass. Because the majority of elements have one dominant isotope, this explains why their weights are whole numbers. However, there were several important exceptions, such as chlorine (35.5), copper (63.5), and zinc (65.4) which have a variety of isotopes.

Charles Daubeny (1795-1867) was appointed Professor of Chemistry at Oxford University in 1822. He

	Noms nouveaux.	Noms anciens correſpondans.
Subſtances ſimples qui appartiennent aux trois règnes, & qu'on peut regarder comme les élémens des corps.	Lumière	Lumière.
	Calorique	Chaleur. Principe de la chaleur. Fluide igné. Feu. Matière du feu & de la chaleur.
	Oxygène	Air déphlogiſtiqué. Air empiréal. Air vital. Baſe de l'air vital.
	Azote	Gaz phlogiſtiqué. Mofète. Baſe de la mofète.
	Hydrogène	Gaz inflammable. Baſe du gaz inflammable.
Subſtances ſimples non métalliques oxidables & acidifiables.	Soufre	Soufre.
	Phoſphore	Phoſphore.
	Carbone	Charbon pur.
	Radical muriatique	Inconnu.
	Radical fluorique	Inconnu.
	Radical boracique	Inconnu.
Subſtances ſimples métalliques oxidables & acidifiables.	Antimoine	Antimoine.
	Argent	Argent.
	Arſenic	Arſenic.
	Biſmuth	Biſmuth.
	Cobalt	Cobalt.
	Cuivre	Cuivre.
	Etain	Etain.
	Fer	Fer.
	Manganèſe	Manganèſe.
	Mercure	Mercure.
	Molybdène	Molybdène.
	Nickel	Nickel.
	Or	Or.
	Platine	Platine.
	Plomb	Plomb.
	Tungſtène	Tungſtène.
	Zinc	Zinc.
Subſtances ſimples ſalifiables terreuſes.	Chaux	Terre calcaire, chaux.
	Magnéſie	Magnéſie, baſe du ſel d'epſom.
	Baryte	Barote, terre peſante.
	Alumine	Argile, terre de l'alun, baſe de l'alun.
	Silice	Terre ſiliceuſe, terre vitrifiable.

Figure 2. Lavoisier's classification of the elements.

produced a panel listing 20 elements with their relative weights, which still exists, and his listing was reproduced in the third edition of E. Turner's *Elements of Chemistry*, published in 1831. However, the list in no way corresponds to a periodic table.

Another chemist to make a contribution to classifying the elements was Johann Döbereiner (1780 – 1849). In 1829 he announced his Law of Triads.[3] He called it 'an attempt to group elementary substances according to their analogies'. He had noticed that of three chemically similar elements, the weight of the middle element was the average of the lighter and heavier members. Lithium-sodium-potassium formed such a triad, and others were chlorine-bromine-iodine and sulfur-selenium-tellurium. By 1843, ten such triads had been identified.

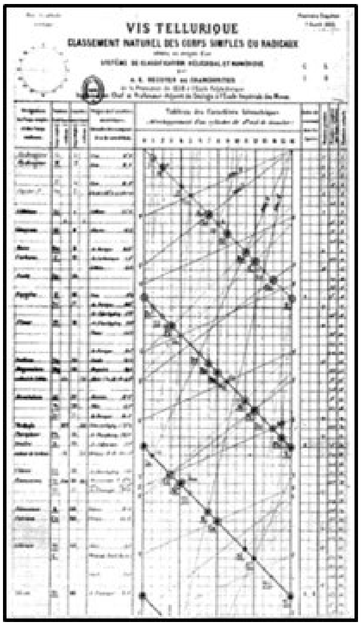


Figure 3. Chancourtois' listing of the elements [Reproduced by kind permission of the Master and Fellows of St Catherine's College, Cambridge].

The first attempt to arrange all known elements in a regular pattern was made in 1862 by a French geologist Alexandre-Émile Béguyer de Chancourtois (1820–1886). He wrote a list of them on a piece of tape, in order of weight, and then wound this spiral-like around a cylinder. The cylinder surface was divided into 16 parts, based on the atomic weight of oxygen. Chancourtois noted that certain triads came together down the cylinder, such as lithium, sodium and potassium whose atomic weights are 7, 23 (7+16), and 39 (23+16). This coincidence was also true of the tetrad oxygen-sulfur-selenium-tellurium. He called his model the *Vis Tellurique* (Telluric Screw) and published it in 1862[4] – see Fig.3. This was the first formulation which revealed the periodicity of the elements.

A boost to element discovery came with the development of atomic spectroscopy in 1859 by Bunsen and Kirchhoff in Germany. This revealed that each element had a unique pattern of lines in its visible spectrum. Because an element always gave the same pattern, no matter its source, it was realised that here was a technique for uncovering new elements. Merely submitting a mineral to atomic spectroscopy, immediately showed whether a new element was present. As a result, rubidium, caesium, and thallium were announced in the years 1860-1863.

In 1860, the Italian chemist Stanislao Cannizzaro (1826–1910) presented a paper to the First International

Chemical Congress, at Karlsruhe in which he gave the *atomic* weights of the known elements.[5] A young Russian chemist, Dimitri Mendeleev, who was doing postgraduate research in Germany, was in the audience and picked up a copy of the list and took it back to St Petersburg when he returned there in 1861. Previously, chemists had used so-called equivalent weights determined from their oxides, and which were variable.

An attempt to classify the elements was made by an Englishman, 27-year old John Alexander Reina Newlands (1837–1898). In 1863 and 1864 he had published papers dealing with relative weights and in 1864 he gave a talk entitled 'The Law of Octaves' at a meeting of the London Chemical Society. He had arranged 56 elements into groups and noted that there seemed to be a periodic repetition of similar properties at intervals of eight. The title of his talk was chosen by analogy with octaves in music. It was an inappropriate choice, and it is said that one member of his audience sarcastically asked Newlands whether he had ever thought of arranging the elements in alphabetical order instead. The society's journal refused to publish his talk as a paper. However, he wrote accounts in *Chemical News*, in 1864[6]and 1865,[7] so we know what he was proposing. Eventually, the Royal Society of London awarded him its prestigious Davy Medal in 1887 in belated recognition of his achievements, and given 'for his discovery of the periodic law of the chemical elements'.

Also, in London at the time was William Odling (1829–1921), who was at the Royal Institution. He also came near to devising the first periodic table. He published a paper in 1864 in the *Quarterly Journal of Science* entitled: 'On the proportional numbers of the elements'. He arranged the known elements in the same way as Mendeleev was to do, and he too even left gaps where there were missing elements. However, unlike Mendeleev, he didn't have the confidence to predict their existence and physical properties. Odling even left gaps that were later to be filled by helium and neon, long before the noble gases had been discovered.

Periodicity among all the elements had been noticed by the German chemist Julius Lothar Meyer (1830–1895). He drew a graph of atomic volumes of the 49 elements then known versus their atomic weights which showed a periodic rise and fall: Fig. 4. He also devised a periodic table of elements. He wrote a paper and gave it to a colleague, Professor Adolf Remelé, (1839–1915), asking for his comments. Unfortunately, these were slow in coming, and before he could submit it for publication, Mendeleev's definitive paper had appeared. Meyer's version was eventually published in 1870,[10] only a few months after Mendeleev's paper.

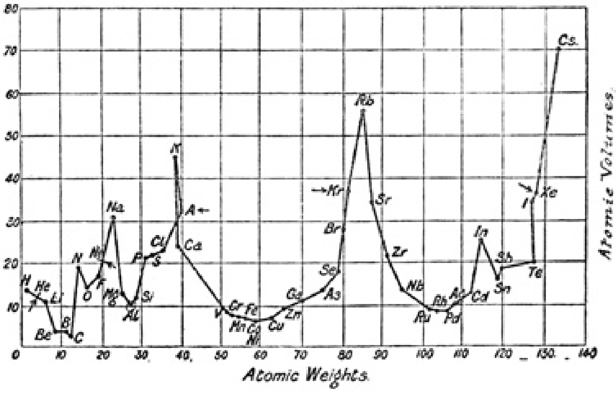


Figure 4. Lothar Meyer's graph showing periodicity.

DMITRI IVANOVICH MENDELEEV (1834–1907)
ДМИТРИЙ ИВАНОВИЧ МЕНДЕЛЕЕВ

In 1867, 35-year-old Dmitri Ivanovich Mendeleev began to write a textbook: *The Principles of Chemistry*. (This was published as a two-volume work in 1869 (vol.1) and 1871 (vol.2), and was translated into other languages.) He wondered how best to deal with the many elements with their diverse properties. He became obsessed with bringing some kind of order to the 63 elements then known, and he told his colleague A.A. Inostrantcev that he had spent sleepless nights wrestling with the problem.

Mendeleev's discovery of the periodic table is said to have occurred on February 17th. This was the date based on the ancient Julian calendar still in use in Russia. For the rest of Europe, using the Gregorian calendar, it was March 1st. On that day he had planned to visit a local cheese factory, but decided instead to work in his study.

He had written details of every element and its physical properties on pieces of card, including its atomic weight, and the formulae of any hydrides and oxides which it formed, these indicating its valency or oxidation states. He then began to arrange the cards in various ways, until one arrangement seemed to him to be the best and he wrote that down on an envelope which still exists: see Fig. 5. Its printed version is Fig. 6, from a paper he submitted to the *Russian Journal of Chemistry*, this was a new publication of the Russian Chemical Society which he had helped to set up. It appeared in May of that year.[9]

What Mendeleev had done eventually made him one of the most famous scientists of all time. He also sent copies of his table of elements to other chemists, calling it '*Essai d'une systeme des elements d'après leur poids atomiques et fonctions chemiques*' (Assessing a system of elements according to their atomic weights and chemical functions.) He wrote in French because this was the for-

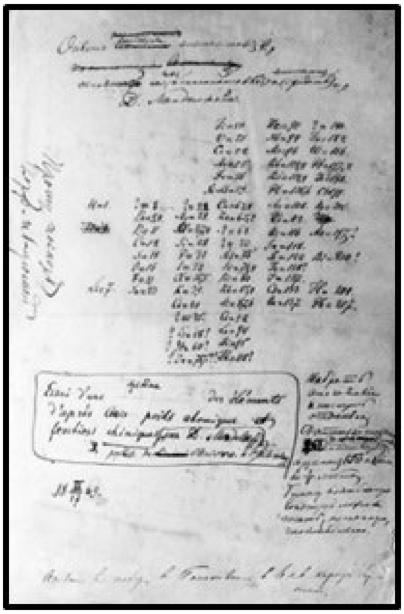


Figure 5. Mendeleev's envelope with the first periodic table.

Figure 6. The periodic table in Mendeleev's first paper.

eign language he had been taught at school and he had spent a little time in Paris when he was doing a postgraduate course in Germany under Robert Bunsen.

What Mendeleev had announced was fundamental to chemistry and science. In effect he was saying that the chemical elements conformed to a pre-determined pattern of relationships which we now call the periodic table. What followed was to transform a large part of chemistry from a disorganised jumble of facts into a disciplined science.

Mendeleev's periodic arrangement of the elements might easily have gone unnoticed, but his paper was summarised in the leading German journal, *Zeitschrift für Chemie*, and so got wide publicity. By 1872 his table had been rearranged so that the groups were vertical rather than horizontal – see Fig 7. Also, Mendeleev's first table had some elements in the wrong place because he had ranked them in order of atomic weights and these were not always reliable. These faults were soon corrected.

Mendeleev was so sure that he was right in his concept of a periodic table, that he could see there were elements missing. He predicted that these must exist and for some of them he gave their likely physical properties, such as melting point, density, and basic chemistry.

The first of these was discovered in 1875 by Paul-Émile de Boisbaudran (1838–1912) and he called it gallium. He measured its properties, including the density, which he said was 4.7 g/cm^3. He was then told that his new element was the missing one in group III of Mendeleev's table and that he had predicted its properties, for which its density would be 5.9 g/cm^3. Boisbaudran was alerted to this by Mendeleev and so checked his measurements and discovered he had made an error; the correct density was 5.956 g/cm^3 just as Mendeleev has said.

In 1879, the Swedish chemist, Lars Nilson (1840–1899), discovered scandium. It too had the properties Mendeleev predicted. It was also in column III and came below boron, and he had referred to it as eka-boron. Its atomic weight was 44 (Mendeleev predicted 44) and its density was 3.86 g/cm^3 (Mendeleev predicted 3.5 g/cm^3).

Finally, in 1886, the German chemist, Clemens Winkler (1388–1902), discovered germanium, which was almost exactly as Mendeleev had predicted for the element below silicon in group IV, right down to the density of its oxide which he said would be around 4.7 g/cm^3 and turned out to be 4.703 g/cm^3. He said that the boiling point of its chloride would be a few degrees below 100°C. It was 86°C.

Mendeleev's table had eight columns with the Roman numerals I to VIII, corresponding to the chemical valencies (oxidation states) of the elements. This property was revealed by the chemical formula of the highest oxide. Yet it brought together elements that were quite dissimilar, such as metals and non-metals. For example, in group V we find vanadium and phosphorus, which have almost no chemistry in common. Mendeleev consequently split the columns of his periodic table into two sub-groups labelled A and B. Vanadium was in VA, phosphorus in VB. The same pattern was repeated in the other columns with the exception of group VIII which

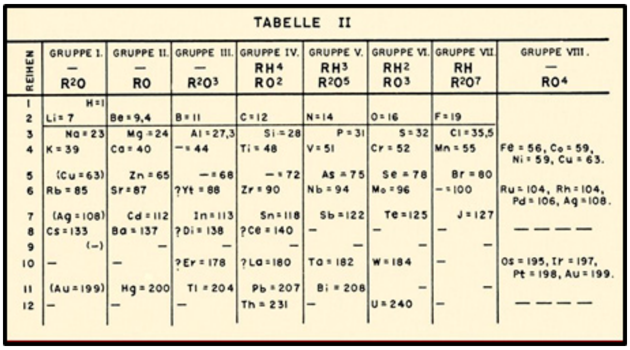
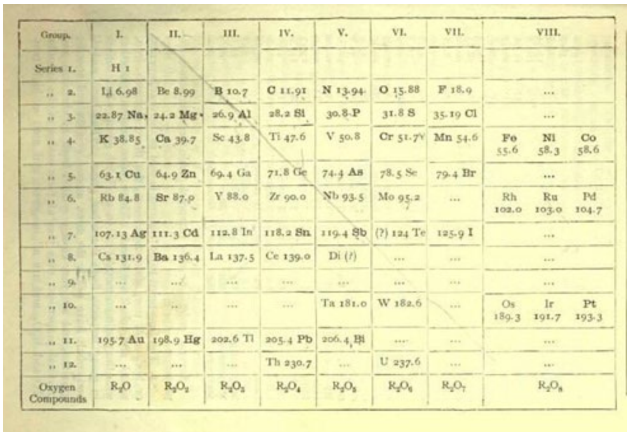


TABELLE II

REIHEN	GRUPPE I. — R^2O	GRUPPE II. — RO	GRUPPE III. — R^2O^3	GRUPPE IV. RH^4 RO^2	GRUPPE V. RH^3 R^2O^5	GRUPPE VI. RH^2 RO^3	GRUPPE VII. RH R^2O^7	GRUPPE VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Figure 7. The first periodic table with vertical groups.



Group.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
Series 1.	H 1							
,, 2.	Li 6.98	Be 8.99	B 10.7	C 11.91	N 13.94	O 15.88	F 18.9	...
,, 3.	22.87 Na	24.2 Mg	26.9 Al	28.2 Si	30.8 P	31.8 S	35.19 Cl	...
,, 4.	K 38.85	Ca 39.7	Sc 43.8	Ti 47.6	V 50.8	Cr 51.7	Mn 54.6	Fe 55.6 Ni 58.3 Co 58.6
,, 5.	63.1 Cu	64.9 Zn	69.4 Ga	71.8 Ge	74.4 As	78.5 Se	79.4 Br	...
,, 6.	Rb 84.8	Sr 87.0	Y 88.0	Zr 90.0	Nb 93.5	Mo 95.2	...	Rh 102.0 Ru 103.0 Pd 104.7
,, 7.	107.13 Ag	111.3 Cd	112.8 In	118.2 Sn	119.4 Sb	(?) 124 Te	125.9 I	...
,, 8.	Cs 131.9	Ba 136.4	La 137.5	Ce 139.0	Di (?)	...	...	...
,, 9.	...	...	...	...	...	...	...	...
,, 10.	...	..	...	...	Ta 181.0	W 182.6	...	Os 189.3 Ir 191.7 Pt 193.3
,, 11.	195.7 Au	198.9 Hg	202.6 Tl	205.4 Pb	206.4 Bi	...	...	...
,, 12.	...	...	...	Th 230.7	...	U 237.6	...	...
Oxygen Compounds	R_2O	R_2O_2	R_2O_3	R_2O_4	R_2O_5	R_2O_6	R_2O_7	R_2O_8

Figure 8. Textbook version of the periodic table – 1913.

contained metals that were very similar and which occurred in sets of three. These were iron-cobalt-nickel, ruthenium-rhodium-palladium and osmium-iridium-platinum.

Mendeleev was to become a celebrity chemist. He visited many other countries, and won many awards such as the Copley Medal of the Royal Society of London, their highest award which had been founded in 1737. (The list of scientists given this award includes Charles Darwin, Dorothy Hodgkin, and Albert Einstein.)

For reasons that are still unclear, Mendeleev failed to gain a Nobel Prize despite being nominated three times, in 1905, 1906 and 1907, the year before he died. Had he lived another year or two it is more than likely he would eventually have been rewarded this way, but Nobel prizes can only be given to living scientists.

EARLY PERIODIC TABLES AND NEW ELEMENTS

Basically, there have been two approaches to devising a periodic table. The first lists all the elements in a continuous line, rather like the numbers on a tape measure, and this is then looped in such a way that like elements come together. The second version chops the tape into segments and stacks these in rows or columns so as to bring together elements with similar chemical properties. The former approach is what Chancourtois had used in 1862 for his telluric screw, and what many others have done since. The table versions are direct descendants of Mendeleev's table.

An example of an early periodic table – Fig.8 – can be found in the book by Henry Roscoe (1833–1915) and Carl Schorlemmer (1834-1892) called a *Treatise on Chemistry*. This was a comprehensive two volume text of 2400 pages, which first appeared in 1878 and was reprinted many times.[12] This did not sub-classify elements into A and B columns, although it placed them in alternative rows as in later editions.

Although Mendeleev did not realise it, there was a group of elements missing from his table. These were the noble gases, and when they were discovered 30 years later, they were to exert an influence on the way the table was perceived. Roscoe and Schorlemmer's later editions contained these elements.

The lightest noble gas, helium, had in fact been reported the year before Mendeleev produced his table. It had been detected by the French astronomer, Pierre J. C. Janssen (1824–1907), on Tuesday 18th August 1868. He had travelled to India to study the total eclipse that would be observed there. Thankfully the sky was not overcast with clouds, and he was able to record the corona spectrum, which clearly showed an unknown element was present. Later that same week, two British astronomers, Norman Lockyer (1836–1920) and Edward Frankland (1825–1899), viewed the sun through a London fog and observed the same spectrum. Lockyer expected the new element to be a metal and so he called it helium, deriving the name from Helios, the ancient Greek sun god. Some chemists thought he was being presumptuous in finding a new element on the Sun and having the effrontery to name it. However, they were wrong – and so was he. It was a new element, but it was not a metal; it was a gas.

Helium is also present in the Earth's atmosphere but only in infinitesimally small amounts – 5 p.p.m. – as it is continually being lost to space. It is also present in uranium minerals that emit alpha particles which are the nuclei of helium atoms. In 1888, the US geologist William Hillebrand (1853-1925) noted that the mineral uraninite (UO_2) gave off bubbles of gas when dissolved in acid, but he could not identify it. Per Teodor Cleve

(1840–1905) at Uppsala, Sweden, in 1895, confirmed that the gas was helium.

Another unreactive gas was discovered in 1894, by Lord Rayleigh (1842–1919) and William Ramsay (1852–1916). They were intrigued by the discrepancy in the density of nitrogen gas that was extracted from air, compared to that which was formed by the decomposition of ammonia. The difference was a mere 0.05% but Rayleigh did not believe his density measurements were wrong and deduced that the nitrogen produced from air must be contaminated with another gas. He went on to isolate this and it was essentially argon which constitutes around 1% of the air and it is formed when the potassium isotope ^{40}K undergoes radioactive decay.

Ramsay now realised that helium was not a unique element, but was head of a group that was missing from the periodic table. He began the search for them and discovered three gases: neon (atomic weight 20), krypton (84) and xenon (131), which he extracted from liquid air. The element at the bottom of the group is radioactive radon, whose longest-lived isotope is ^{222}Rn with a half-life of only 3.8 days. This element was discovered by Friedrich Ernst Dorn (1848–1916) in 1900, and he discovered it as the gas which collected in sealed ampules containing radium.

Although the first inclination of chemists was to place the noble gases at the left-hand side of the periodic table because their valency was 0, they are now on the right-hand side and this is the logical location when we regard the rows of elements as additions to the various electron shells surrounding the nucleus, each being completed with a noble gas.

Moseley's system of numbering the elements – see below – revealed that those of atomic number 43, 61, 72, 75, 85, 87 and 91 were as yet unknown. These are all radioactive elements with short half-lives. Technetium (43) was first obtained in 1937 when Emilio Segrè (1905–1989) and Carlo Perrier (1886–1948) at the University of Palermo in Sicily separated it from a sample of molybdenum which had been bombarded with deuterons in the cyclotron at the University of California, Berkeley. (Segrè was to be dismissed from his academic post in 1938 because he was opposed to Mussolini's fascist regime, so he emigrated to the USA.)

Promethium (61) was claimed in 1938, by a group at Ohio State University but they lacked chemical proof that it was the missing element and, at that time, such proof was deemed as essential to support a claim for a new element. Then, in 1945, a group at Oak Ridge, Tennessee, USA, were able to separate isotope-147 of element-61 and so were able to confirm it as required. Element 61 was also made using a cyclotron to bombard neodymium with atoms of deuterium.

Element 78 (francium) was extracted from actinium in 1939 by Marguerite Perey (1909–1975) at the Curie Institute, Paris, France.

Element 85 (actinium) had been discovered by Andre Debierne (1874–1949) in 1899 and he extracted it from the uranium ore pitchblende. It was later made by bombarding bismuth (element 83) with alpha particles in a cyclotron, and this was achieved by a group at Berkeley which now included refugee Segrè. The isotope produced had a half-life of 8.3 hours which they named astatine from the Greek word *astatos* (unstable).

A dilemma of the periodic table in its earliest form was that some elements did not fit the strict sequence of ordering by atomic weight. Why did some elements have higher atomic weights than others which came after them in the table? The best example of this was the tellurium/iodine conundrum, with the former having atomic weight 127.6 while the latter's atomic weight is 126.9. Mendeleev was sure that the atomic weight of tellurium had to be wrong; it had to be less than that of iodine, so he used a value of 125, that had been determined by a Czech chemist Bohuslav Brauner.

In 1911, the English radiochemist Frederick Soddy (1877–1956) proved that elements had isotopes, which finally resolved the issue of pair reversal, thereby allowing an element of larger atomic weight legitimately to occupy a position in the table before its neighbour.

Transuranium element 93 had been wrongly claimed but never confirmed before it was finally produced in 1939 by Edwin McMillan (1907-1991) and Philip Abelson (1913-2004) at Berkeley in 1940. It had a half-life of 2.3 days. The named it neptunium based on the planet which comes beyond Uranus after which uranium (element 92) had been named. This element occurs naturally in uranium ores as a result of radioactive decay processes. Its longest-lived isotope is Np-237, with a half-life 2.14 million years.

Elements beyond uranium were produced in various ways using nuclear processes in the 1950s, 1960s… and in the current century. Eventually a group of Russian and American scientists, working at the Joint Institute for Nuclear Research in Dubna, near Moscow, were able in 2002 to produce atoms of the element at the end of the bottom row (7p) of the periodic table which is oganesson.

THE LONG FORM OF THE PERIODIC TABLE

From the time of Mendeleev's first periodic table in 1869, it has undergone several changes, although we can still recognise some of Mendeleev's original groups such as the halogens (now group 17). Despite advances in atomic theory, Mendeleev's 8-column periodic table remained in use for almost a hundred years. Eventually, the so-called long-form gradually displaced it as man-made elements were announced and interest focussed on the final row.

Today the standard version is the long-form: Fig.1. This was first advocated by the Swiss inorganic chemist Alfred Werner (1866-1919) in 1905, and had 18 columns, with two rows for the lanthanoids and actinoids. (These were previously referred to as lanthanides and actinides.)

So why did the long-form periodic table become the preferred one, compared to the hundreds of others which have been suggested? The answer is that it is logical, easy to understand, and to extract information from.

When designing a periodic table of elements, the primary data which determines their arrangement is atomic number. Clearly such a linear sequence of elements has to be organised in some way, and the most obvious guideline is the one which Mendeleev used, i.e. to place elements with similar properties in table format, with lightest elements at the top and with increasing atomic weight as you descend the group.

Although Mendeleev was not aware of it, he had based his table on the two basic properties of an element: the number of protons in its nucleus and the occupancy of its electron shells.

Understanding the periodic table came only with the discovery of the electron in 1896 by J.J. Thompson (1856-1940), the proton in 1911 by Ernest Rutherford (1871-1937), and the neutron in 1932 by James Chadwick (1891-1974). In 1904 a Japanese scientist, Hantaro Nagaoka (1865-1950), put forward the theory that atoms consisted of a central nucleus around which electrons circulated. In 1909 Ernest Rutherford proved that the nucleus was tiny and positively charged, which he did by bombarding a piece of very thin gold foil with alpha particles, and observed almost all of these passed through and that very few encountered an atom. It appeared that atoms consisted of a tiny, positively-charged nuclei in which almost all the mass was concentrated.

In 1913, the physicist Henry G.J. Moseley (1887–1915) formulated the property of atomic number in his paper[8] entitled 'The high-frequency spectra of the elements.' This we now know to be the number of protons of positive charge in the nucleus. He showed that the sequence of elements in the periodic table was really in the order of their atomic numbers. Sadly, he was shot by a sniper in World War I. That same year, Niels Bohr (1885–1962) linked the form of the periodic table to the atomic structure of atoms.

The electronic composition of the elements explains today's arrangement of the periodic table with its s, d, p, and f blocks. These reflect the occupancy of electron orbitals around the atomic nucleus, these being 2 (s), 6 (p), 10 (d), and 14 (f). The order in which these are filled, results in the extended long-form of the periodic table with rows of 2, 8, 8, 18, 18, 32, and 32 elements. Combinations of these numbers give rise to 8 (= 2+6), 18 (= 2+6+10) and 32 (= 2+6+10+14) which are the lengths of the various rows of the table.

The orbital nearest the nucleus is just a single orbital and labelled 1s, the next is a pair of orbitals labelled 2s and 2p, the next is a trio of orbitals, 3s, 3p and 3d, and so on. However, these begin to overlap, so that the next one, 4s, is actually occupied before the 3d sub-orbital..

The sub-orbitals can hold increasing numbers of electrons and these are the basis of the various blocks of the periodic table. The s-block consist of two groups (numbered 1, the alkali metals, and 2, the alkaline earths), the p-block elements consist of six groups (numbered 12 to 18), some of which have also got names such as the chalcogens (group 16) and the halogens (group 17). The d-block elements have ten groups (numbered 3 to 11), and the f-block elements consist of two rows 4f and 5f which are not given group numbers.

At first approximation, the order of occupancy of orbitals is as follows: 1s / 2s, 2p / 3s, 3p / 4s, 3d, 4p / 5s, 4d, 5p / 6s, 4f, 5d, 6p / 7s, 5f, 6d, 7p. It still remains to be satisfactorily explained by quantum mechanics.

If the elements are arranged in rows of increasing atomic number, and in columns having the same electron outer shell, then we arrive at the long form of the periodic table. Across a row of the periodic table we are adding electrons to a particular shell until that shell is full when we arrive at one of the noble gases. Consequently, these represent a natural break in the table.

However, the long-form of the periodic table predates our knowledge about electron configuration, and it first appeared in 1923 when the American chemist Horace G. Deming (1885–1970) created it for his textbook *General Chemistry* – see Fig. 9.

He placed the lanthanoids at the bottom of the table. He referred to them as 'rare earths' although some are relatively abundant. The value of Deming's table was soon appreciated, and within a few years it was widely used. The pharmaceutical company Merck employed it in its advertising. It was also distributed to American schools as a teaching aid.

In an internal document of the Lawrence Berkeley Laboratory of the late 1930s there is a periodic table closely resembling the modern form (Figure 10). However, it places thorium below hafnium, protactinium below tantalum, and uranium below tungsten.

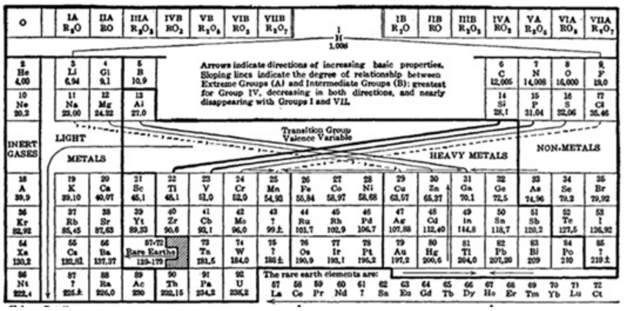


Figure 9. The Deming periodic table of 1923.

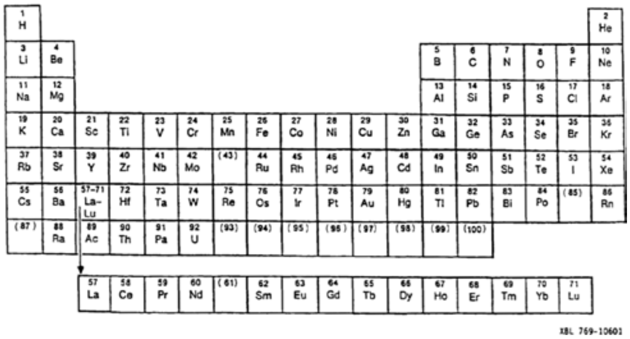


Figure 10. The Lawrence Berkeley periodic table of the 1930s.

In 1929, the amateur French chemist Charles Janet (1849–1932) came up with an extended long form of the table – see Fig. 11.

Mendeleev knew of thorium and uranium, and their chemistry made them suitable to place in his groups IV and VI respectively. And so, things remained, until synthetic elements started to be produced in the 1940s. Then, in 1942, the American chemist Glenn T. Seaborg (1912–1999) drew the table in the form we know today with the f-block elements shown as a separate group below the d-block. Seaborg's colleagues at the University of California advised him not to publish his table as it was mere speculation, but he went ahead anyway and today we have names for all 15 of these elements. Eventually the number of artificially produced elements has extended the periodic table to element 118 (organesson); atoms of this lasted all a fraction of a millisecond. (Its half-life is 0.89 milliseconds.) Whether physicists can extend the table further remains to be seen.

Seaborg avoided the controversy of which elements should go below scandium and yttrium in group 3 – lanthanum and actinium, or lutetium and lawrencium. He put all of them in the f-block, giving it 15 elements instead of the 14 which theory demands, and this is the table that the International Union of Pure and Applied Chemistry (IUPAC) has on its website – see Fig 1. Seaborg was eventually to be honoured by having element 106 named after him: seaborgium.

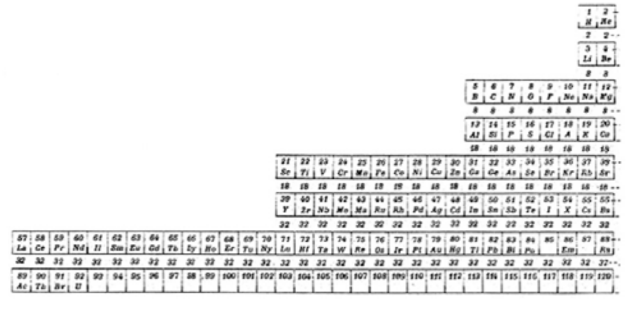


Figure 11. Charles Janet's table of 1929.

NUMBERING OF THE GROUPS

The normal periodic table has 18 columns numbered 1 to 18, but it was not always so. Before IUPAC judged this to be the preferred configuration, there were other conventions, including Roman numerals and letters.

The change-over from the 8-column periodic table to the modern form was not without its difficulties. When Mendeleev's periodic table of 8 groups was turned into the long form of 18 groups, the Europeans numbered the groups on the left-hand side IA to VIII, and on the right-hand side they were numbered IB to VIIB, thus:

IA, IIA, IIIA, IVA, VA, VIA, VIIA, VIII, IB, IIB, IIIB, IVB, VB, VIB, VIIB, VIIIB

However, the American journals favoured a different classification:

IA, IIA, IIIB, IVB, VB, VIB, VIIB, VIII, IB, IIB, IIIA, IVA, VA, VIA, VIIA, VIIIA

which was more in keeping with Mendeleev's notation. Both systems numbered the alkali metals groups IA, and the alkaline earth metals IIA but after that they diverged.

The Scandinavians preferred a system based on letters rather than Roman numerals:

M1, M2, T1, T2, T3, T4, T5, T6, T7, T9, M2', M3, M4, M5, M6, M7, M8

With M standing for main groups and T for transition metals. When the American Chemical Society also decided to drop Roman numerals, they use a simple numbering system but differentiated the transition metals groups with a 'd' thus:

1, 2, 3d, 4d, 5d, 6d, 7d, 8d, 9d, 10d, 11d, 12d, 13, 14, 15, 16, 17, 18.

The numbering of groups was tackled in *New Scientist* in January 1984 when readers were asked to comment on the various systems and to suggest alternatives. The response was overwhelming and came from all over the world. Hundreds of letters were received and the consensus was that simply numbering the columns 1 to 18 was best. The International Union of Pure and Applied Chemists (IUPAC) preferred the groups simply be numbered this way and, after much heart searching, the American Chemical Society (ACS) agreed. The f block does not fit into the numbering system but this poses no problem since the 4f and 5f periods of elements are best dealt with as separate rows below the table.

PROBLEMATIC ELEMENTS

We may think that the arrangement of the periodic table has finally been determined, but there are five elements whose position in the table is still debated. They are hydrogen (element atomic number 1), helium (2), lanthanum (57), lutetium (71), and actinium (89).

Hydrogen and **helium.** Because hydrogen has a single s-electron, logic says that it should be in group 1 of the s block, but the other elements in that group are the alkali metals and clearly that is not what hydrogen is. Helium has two s-electrons and so should be in group 2 but it's not a metal either. Helium is a noble gas and so placed at the top of group 18 while hydrogen sits incongruously at the head of group 1. However, helium is not a p-block element so it is out of place in that part of the periodic table. It has been possible for helium to form stable chemical bonds, so maybe Janet was right to put it above beryllium and this is where it is to be found in some tables.

There are tables which place hydrogen by itself, or with helium, in the very centre of the table, floating free above the other elements. Others place hydrogen above fluorine, although it shares little in common with the halogen gases. Some tables give it double billing and place it above both lithium and fluorine. There are other ways of deciding how to place these elements based on their atomic radii or 1st ionisation potentials.

Lanthanum and lutetium. The lanthanoids, elements of atomic numbers 57-71, posed a problem for the early periodic table since only a few of these had been discovered, and yet all seemed to prefer the oxidation state 3 so should come in group III of the periodic table.

The story of rare-earth discoveries began with yttrium in 1794. This metal was contaminated with traces of other rare-earths. First erbium and terbium we extracted from it in 1843, and then erbium yielded holmium in 1878, thulium in 1879, and so on, until finally lutetium was identified in 1907. This came as a result of painstaking work by the French chemist, Georges Urbain (1872-1938) at the Sorbonne in Paris. He called the element lutecium, later changed it to lutetium.

For these elements to be incorporated into the periodic table, they had either to be placed as in the unwieldy extra-long form of the table, or be located in rows beneath the table. The question then arose as to which element should occupy group 3, below scandium and yttrium, with lanthanum (element 57) being the most obvious on as it follows immediately from element 56 (barium), with actinium (element 69) below it.

In 1982, William B. Jensen (1948–) of the University of Wisconsin-Madison took issue with this arrangement. He gave chemical reasons why the element in group 3 of the main table should be lutetium,[11] and many agreed with his point of view. This being so, then the lanthanoids were lanthanum to ytterbium.

Some periodic tables fudge the issue and have both lanthanum and lutetium as part of a 15-member list at the bottom of the table, indicating this with La-Lu in group 3. However, this jars somewhat as there cannot be 15 f-electrons, but this is the arrangement in the IUPAC table of Fig. 1.

In 1902 the Czech chemist Bohuslav Brauner (1855–1935) had said that there should be an element 61, coming between neodymium and samarium. This was confirmed by Moseley in 1914. Attempts were made to discover it and, in the 1920s, chemists in Italy and in America, claimed to have found it. The difficulty with promethium is that the isotope with the longest half-life is Pm-145, and that is only 17.7 years. There was no way that this element could be successfully extracted from terrestrial sources. Tiny amounts do occur in uranium ores as a result of fission, but the calculated amount is around a picogram (10^{-12} g) per tonne of ore.

A more realistic claim to have obtained element 61 was made in 1938 by a group at Ohio State University. They bombarded praseodymium and neodymium with neutrons, deuterons and α-particles in a cyclotron and detected element 61 in the debris. They proposed the name cyclonium for the new element, but their detection of element 61 was not accepted as a discovery because *chemical* proof for the missing element was lacking.

Finally, such proof was forthcoming in 1945 from the work of J.A. Marinsky, L.E. Glendenin, and Charles D. Coryell at Oak Ridge, Tennessee, USA. They had the new technique of ion-exchange chromatography at their disposal and with it they were able to separate isotope-147 of the missing element and analyse it. They wanted to call the element clintonium after the Clinton

Laboratories in which the work was done, until Coryell's wife suggested promethium basing it on the Prometheus of Greek mythology who stole fire from the gods and gave it to humans, and this became its name.

Element 103: Both American and Russian physicists claimed to have been the first to make atoms of atomic number 103, and so complete the actinoid series, giving them the right to name it. In 1958 physicists at the Lawrence Berkeley National Laboratory bombarded curium-244 with nitrogen-14, and californium-252 with boron, and said they had identified it. They named it lawrencium.

Then, in 1965, physicists at the Soviet Union's nuclear research centre bombarded americium-243 with oxygen-18 and obtained atoms of it. They also repeated the Lawrence Berkeley experiment and failed to confirm what the Americans had claimed. The Russians proposed that element 103 be named rutherfordium. This dispute over names was part of a larger issue regarding the claims and names of various new elements in this part of the periodic table. The disputes were only resolved in 1992 when an international committee called the Transfermium Working Group (TWG) met to decide the issue of names. As regards element 103, they decided that the discovery of 103 had been made by both Russian and American laboratories and that the name should be lawrencium; rutherfordium was then to be the name of element 104.

Completing the bottom row of the periodic table became the province of atomic scientists and the strict chemical proof, that had previously to be met to confirm a new element, no longer applied.

CIRCULAR PERIODIC TABLES

Soon after Mendeleev published his table, other chemists suggested other ways of arranging the elements. Among the alternative types of table, a circular arrangement was common and indeed one such table appeared soon after Mendeleev's publication – see Fig. 12. This was proposed by a German mineralogist and chemist, Heinrich Baumhauer (1848–1926), in 1870. He continued to promote this version and produced a cobweb-like table in 1902 – see Fig. 13. Neither version became popular.

In 1957, the Latvian chemist Edward Mazurs compiled a complete list of all 700 known periodic tables and published them in his book: *Types of Graphic Representation of the Periodic System of Chemical Elements.* Today there are more than a thousand, although many are very similar, and logging on to Google images reveals many of them.

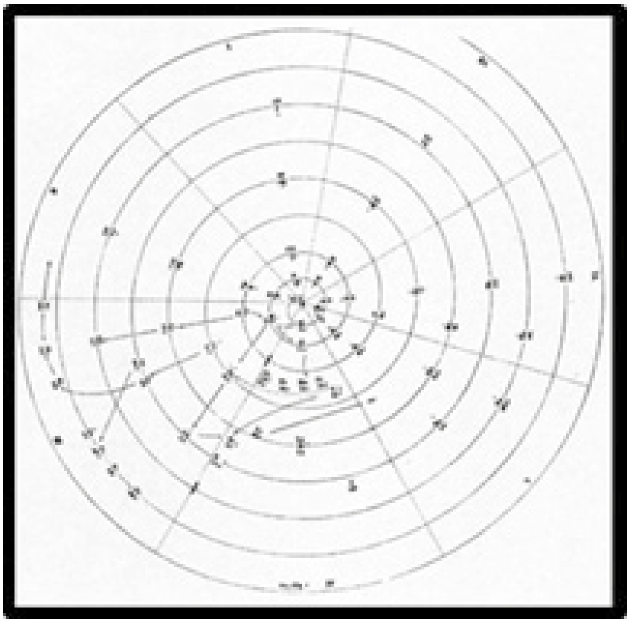


Figure 12. The first circular table.

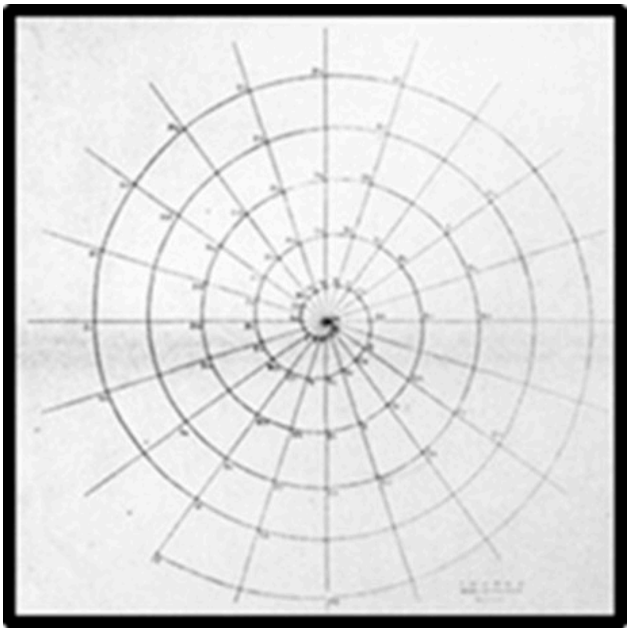


Figure 13. The 1902 table.

Most tables are two-dimensional, but there are several three-dimensional versions and these come in the shapes of cylinders, pyramids, spirals and even trees. These artistic versions can be very attractive and make ideal displays for science exhibitions, but they are not very practical when it comes to teaching chemistry and extracting information about the elements and their relationships.

One circular table which was well publicised was that drawn by Otto Theodor Benfey (1925-). He was born in Berlin but was educated in England, and eventually moved to the USA in 1947. In 1963 he became editor of the ACS magazine *Chemistry,* and in 1964 he published his own circular version of the periodic table in that journal. He justified it by saying that he wanted to highlight the continuity of the elements, and he referred to it as the periodic snail – Fig. 14. Part of his aim was to emphasise the lanthanoids and actinoids and also to include a section for the elements beyond the actinoids.

Circular versions of the periodic table continue to be proposed, but despite their elegance and the tantalising analogy with electrons in shells around a nucleus they all suffer the drawback of being difficult to read and to abstract the information from. Moreover, they tend to crowd together the more important elements at their centre while giving the less important elements more room at the periphery.

Some circular periodic tables verge on being works of art and one such is that devised by Philip J. Stewart of Oxford University which he published in 2007 and which he describes as a galaxy of elements;[12] Fig. 15.

If you want to examine all known tables consult Mark Leach of Manchester, England, who has a complete collection of periodic tables on his website meta-synthesis.com. There is also the website *Internet database* of periodic tables (address : https://www.meta-synthesis.com/webbook/35_pt/pt_database.php?PT_id=943) where there are hundreds of them of bewildering diversity.

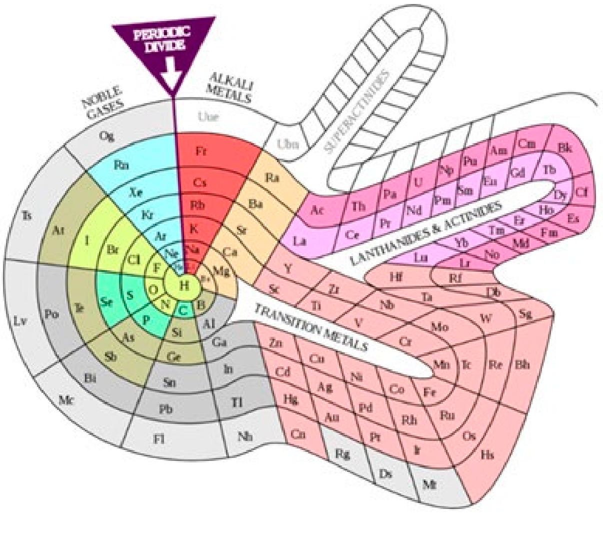


Figure 14. The 'snail' periodic table.

A FINAL WORD

It is probably impossible to say definitely that the periodic table which today appears everywhere, in books and lecture theaters, on T-shirts and ties, on TV programmes and in films, is the ultimate version. It will of course change slightly if new elements are produced. Since atoms of these will last for less than a second, then it may appear pointless to extend the table. In which case it is more than likely that the IUPAC table (Fig. 1) will still be the preferred version so long as there is chemistry. And Mendeleev's achievement has been acknowledged by naming an element in his honour: element 101 is Mendeleevium (Md). This was first made in 1955. It is highly radioactive with a half-life of 52 days.

Even if someday we communicate with another part of the universe, we can be sure that one thing both cultures will have in common is an ordered system of the elements that will be instantly recognisable. Perhaps the most artistic periodic table is that by the Glasgow artist, Murray Robertson, which is entitled 'Visual Elements' and for which he had created a stunning computer graphic for each element. This can be accessed, via the Internet, on the Royal Society of Chemistry's web site.

If you wish to access a more dramatic version online, there is the Periodic Table of Videos produced by Nottingham University (www.periodicvideos.com) with presenters Martyn Poliakoff and Pete Licence. Also accessible as an app is the periodic table of Theodore Gray which is also available in book format. Finally, if you want a real hands-on periodic table this is available from RGB Research and produced by Max Whitby and

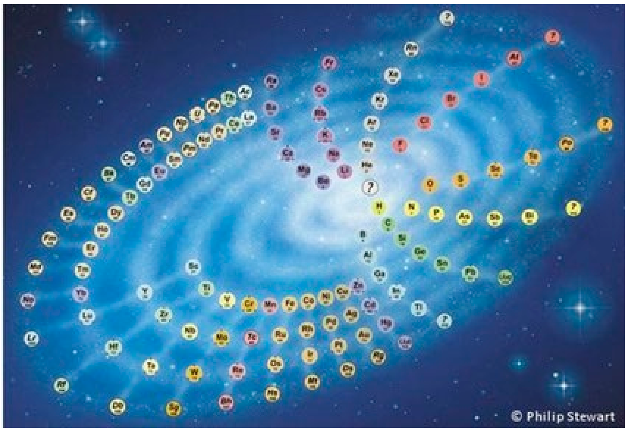


Figure 15. The Galaxy periodic table.

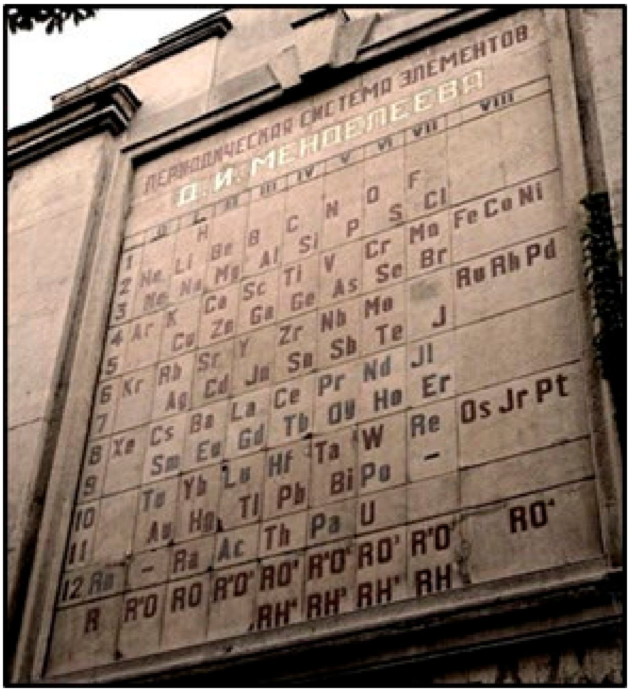


Figure 16. Periodic Table on a Wall. Saint Petersburg, Russia.

Fiona Barclay (https://periodictable.com/). It comes complete with a sample of each element that it is legally available. The larger versions of this kind of table of so-called 'Element Collections' can be seen at several institutions, such as the Science History Institute in Philadelphia, Pennsylvania, and at company sites such as the Dow Chemical headquarters in Michigan. Theo Gray is the author/web-master of the remarkable website https://periodictable.com/ and he has written a book: *The Elements.*

Today there is a permanent tribute to Mendeleev's discovery of the periodic table in the form of an impressive sculpture on the wall of the building where Mendeleev worked: Fig. 16.

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