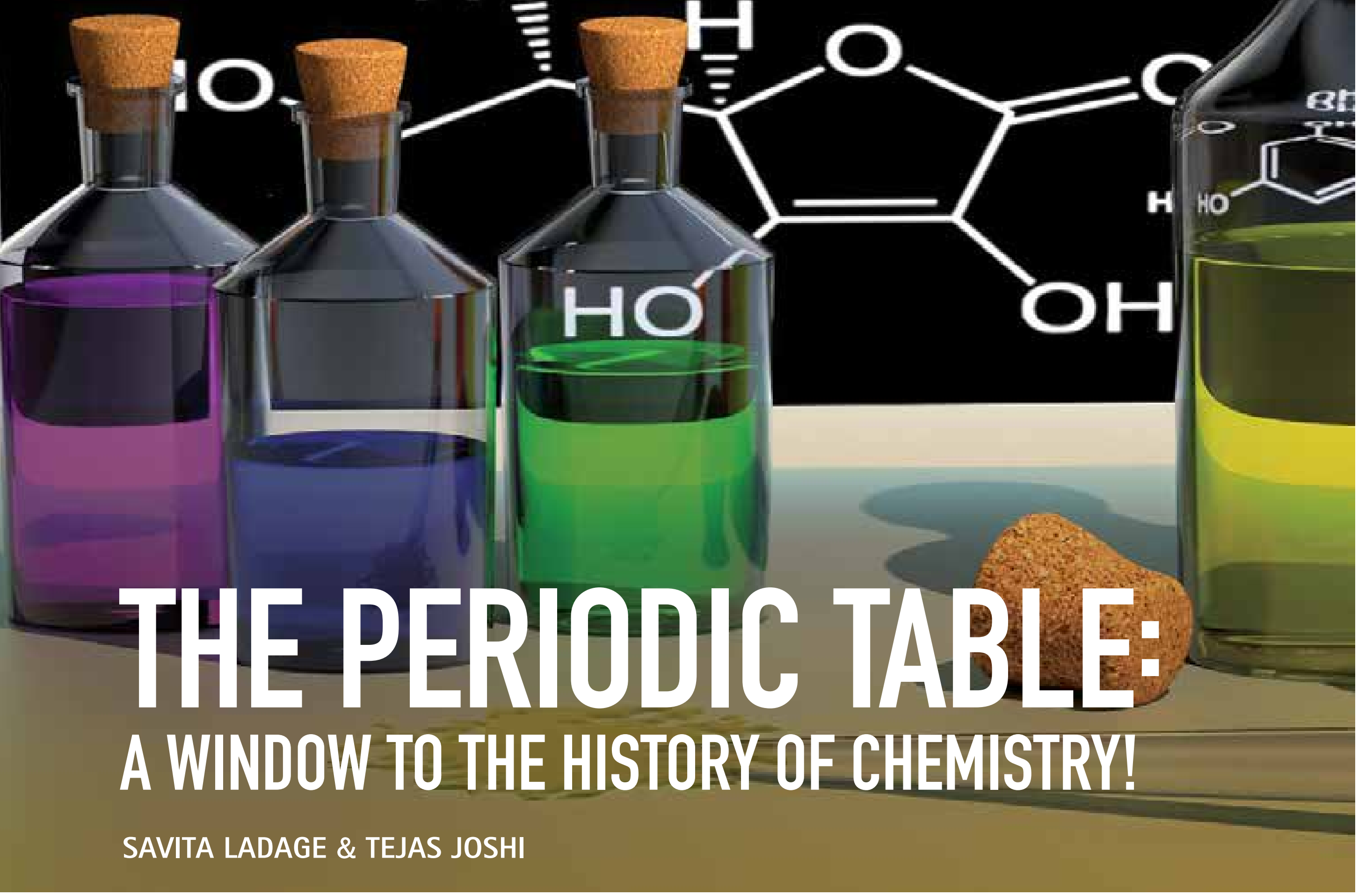

THE PERIODIC TABLE:
A WINDOW TO THE HISTORY OF CHEMISTRY!

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The periodic table is central to chemistry education, and it can be just as central in exploring the inspiring history and evolution of chemistry as a subject. This article embarks on this historical journey, with the objective of showcasing its value for both teachers and students.

The periodic table is an integral part of the chemistry we study today. But, have you ever wondered how elements were discovered? Or, how the periodic table has evolved to its present structure and format – especially in the absence of advanced analytical techniques, instruments or accessible literature? The answers to these questions lie in the unflinching human quest for knowledge, a logical approach, and a great deal of foresight. As lucid and organized as it may appear today, the periodic table is in fact a reflection of the challenging and uphill evolution of the very subject of chemistry. Thus, learning about its history is as invaluable for a teacher as it is for a learner...

Early attempts to identify natural elements

The belief that all matter in the world around us is made up of a limited pool of building blocks has persisted since ancient times. This has led to numerous attempts, from different civilisations, to identify these building blocks.

One such attempt identified four elementary substances – Water, Air, Fire and Earth. Aristotle added one more element – 'Aether', the element of the heavens, to this list. These finite building blocks were put together in a preliminary, but convincing, 'table' – becoming one of the first efforts to classify elements. Even back then, these elementary substances were used to make sense of natural phenomena (refer Fig1)!

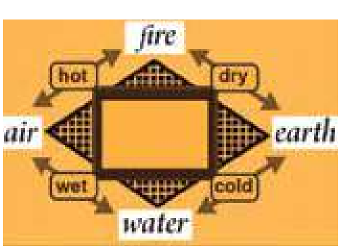


Fig. 1. A preliminary table of natural elements. This very old precursor, by Aristotle, to the modern periodic table might have been a modest beginning, but it worked well in explaining natural phenomena. For example, the presence/absence of fire explained hot and cold respectively. The absence of water implied a solid. Thus observing ash and experiencing heat following the burning of wood, wood was believed to be made up of earth and fire.

This simple, but reasonably rational, classification prevailed for many centuries. However, beginning with the work of alchemists (ancestors of modern chemists), and later as a result of progress in experimental sciences, the concept of chemical elements began witnessing a considerable change.

What are chemical elements?

The discovery of chemical elements dates back to prehistoric times, when humans observed charcoal (Carbon) being left behind from the burning of wood in forest fires.

An awareness of as many as seven metals – Gold, Silver, Copper, Lead, Iron, Tin and Mercury, and the non-metal Sulphur (apart from Carbon) – can be traced back to ancient times. This may have been because many of these elements occur naturally, either in free (elemental) forms or in ores like sulphides and oxides, and are easily decomposed by simple heating or heating in the presence of charcoal. It is also possible that once they were discovered, their utility or importance to humans may have driven their further identification. However, we have little documentation of either – their discovery, or their recognition as elements.

In this context, the history of Gold is particularly significant. Due to its attractive lustre, Gold (along with Silver) became a symbol of wealth (ornaments) and beauty, gradually assuming significance as a medium of exchange and international trade. Consequently, many alchemists began to seek this 'Philosopher's Stone' by attempting to convert other base metals, like Iron, into Gold. It was these attempts by alchemists from the Middle Ages that led to the discovery of many other elements, like Antimony, Arsenic and Bismuth. It also led to the development of a variety of glassware as well as the discovery of three major acids – sulphuric, hydrochloric and nitric, all of which have been crucial for subsequent experimental research.

However, the first written record documenting the discovery of an element dates back to 1669. The element it describes is Phosphorus, discovered from urine, a natural source of phosphates.

While it is possible that many more elements were discovered in this period, it is difficult for us to establish the existence of this knowledge. Alchemists of this period relied heavily on trial and error. Also, given the potential economic benefits that their discoveries might bring them, they tended to refrain from disclosing their learning. This meant that knowledge was more likely to remain isolated, and its development did not progress methodically.

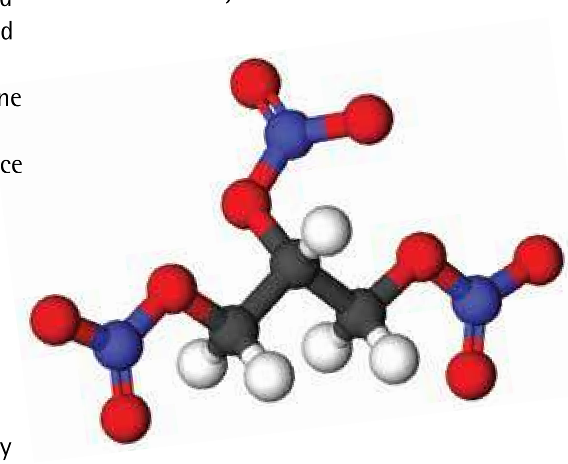
Experimental science and the new concept of the element

The first significant shift in our ideas about elements came from the work of Robert Boyle in the seventeenth century. Boyle defined an element as being a substance that could not be broken down into simpler constituents, and could combine with other elements to form a mixture (today's compound). Extensive work by scientists like Henry Cavendish, Joseph Priestley and Antoine Lavoisier in the eighteenth century demonstrated this concept experimentally.

Cavendish discovered a flammable gas (produced by the reaction of acid and metal), christened Hydrogen, at around the same time that Priestley discovered a gas, christened Oxygen, which supported burning. Lavoisier's milestone synthesis of water using the two was the first major blow to Aristotle's choice of elements. Lavoisier also established the conservation of mass in chemical reactions and provided a basis for writing chemical reactions.

An invention that played a vital role in the discovery of new elements was the construction of the Volta's cell in 1800. The Volta's cell provided a steady source of electricity and, thereby, a unique means of decomposition. It was successfully deployed by Sir Humphry Davy to isolate the extremely reactive Sodium and Potassium in 1807 and other alkaline earths like Calcium, Magnesium and Barium subsequently. The reducing ability of potassium, in turn, helped Jöns Jacob Berzelius discover Selenium, Silicon, and Zirconium etc.

The gradual increase in the number of known elements was accompanied by the evolution of ideas regarding the atom and atomic mass in the early nineteenth century. Both these aspects became important stepping stones in subsequent attempts to classify elements. The atomic theory proposed by John Dalton in the beginning of the nineteenth century is particularly significant in this context. Dalton suggested that elements were made up of indivisible particles, called 'atoms'. His idea that all atoms of a particular element were identical – in terms of their mass, size and properties – focussed attention on the important concept of atomic mass. According to Dalton, the exact value for the atomic mass of an element could be thought of as being the signature of that element. This idea led to the question: how do we calculate the atomic mass of an element? Dalton displayed remarkable foresight in calculating this value relative to another element whose mass was known (i.e. Hydrogen as a reference element to predict relative masses of other elements).



Box 1. Atoms or molecules?

Remarkably, at this point of time, the chemical formulae of compounds was not known, nor was the concept of valence. However, the law of conservation of mass (Lavoisier) and the law of constant proportion (Proust) had already been established. The law of constant proportion by Proust states that irrespective of its source, a particular compound (say water) is made up of the same elements (hydrogen and oxygen) present in a constant mass ratio (1:8) throughout. Keeping hydrogen as a reference, and assuming the simplest formula of water to be HO, Dalton concluded the atomic mass of oxygen to be 8.

Gay-Lussac was working with chemical reactions in gaseous phase, and suggested that atoms need not be the smallest particles in an element to have independent existence. Gay-Lussac's results were in conflict with Dalton's postulate of the indivisibility of an atom. This conflict was finally resolved by Avogadro who proposed the idea of 'molecules'.

The concept of atomic mass and its determination was further developed in the period between 1800 and 1860 by Gay-Lussac, Amedeo Avogadro, Berzelius, Jean Stas and Stanislao Cannizzaro. Berzelius changed the reference element from Hydrogen to Oxygen, broadening the canvas of chemical assays by making use of readily available oxides. This historic notion of using some reference for calculating atomic masses is still very much in use – with the 12C isotope being the standard today.

Box 2. Developing the idea of atomic weights.

The development of the idea of atomic weights is an amazing story in itself, which has been discussed in detail in an article titled – The Saga of Atomic Weights (Pg. 78) in the first issue (Nov 2015) of **i wonder...** We'd recommend a quick read!

Thus, by the mid-nineteenth century, almost 60 elements had been discovered, and their atomic masses had been calculated. However, this knowledge was still largely unknown within the scientific community, and wasn't particularly accessible to everyone. As a result many conceptual ambiguities regarding valence, molecular masses, equivalent masses continued to prevail.

The necessity for contemporary chemists to come together to resolve these ambiguities resulted in the first international Congress held at Karlsruhe, Germany in 1860. Cannizzaro's values of atomic masses and his rationale for calculating them, based on Avogadro's hypothesis, was presented at the Congress. This landmark gathering thus laid the foundation for serious and concerted efforts to reflect on existing knowledge about elements and their properties.

Box 3. Triads of elements.

Even though most attempts at classifying elements happened after the Karlsruhe Congress, there were some noteworthy attempts prior to it, notably Dobereiner's work. Dobereiner's categorization of elements was based on their chemical similarity: he arranged a group of three similar elements in an increasing order of (their then known) atomic masses. When this was done, he noticed that the atomic mass of the middle element was close to the average of the mass of the other two. He published his 'Law of Triads' in 1829, leading to the subsequent identification of ten such triads by 1843.

Fig. 2. Examples of some triads of elements.

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However, this preliminary classification could not be used to organize all known elements; neither was this grouping perfectly robust: for example, some tetrads, and even one pentad, were identified later!

Periodicity in chemical properties of elements

Following the 1860 Congress, the considerable number of known elements (63) and clarifications about their atomic masses, valence etc. provided the appropriate reference points needed to organize this information.

John Newlands was the first to identify a certain 'periodicity' in the chemical properties of elements. Newlands observed that when arranged in order of their increasing atomic masses (as calculated by Cannizzaro), every eighth element to appear in sequence from a given starting element in his arrangement was similar to each other (refer Figure 2). He called this peculiar property the 'Law of Octaves' given its similarity to the musical octave.

The fact that Newlands relied more on atomic masses of elements, rather than their physical and chemical properties, resulted in some limitations in his arrangement. This was partly because some of the atomic mass values that were in use at that time were incorrect, leading to their incorrect placement. Additionally, Newland did not leave gaps for undiscovered elements in his table.

Mendeleev solves the puzzle

Even though Newlands identified periodicity, his attempt at classifying elements was not taken seriously by chemists, and thus he did not pursue his ideas further. It was Dmitri Mendeleev, who in 1869, and later in 1871, published his version of a periodic table. This elegant system of classification not only established the periodic law convincingly; but, also anticipated some undiscovered elements by virtue of logical foresight, accommodating them by actually leaving gaps!

What makes Mendeleev's efforts, in the development of the perioidic table, transformational?

Li^{2} 7	Be^{3} 9	B^{4} 11	C^{5} 12	N^{6} 14	O^{7} 16	F^{8} 19
Na^{9} 23	Mg^{10} 24	Al^{11} 27.5	Si^{12} 28	P^{13} 31	S^{14} 32	Cl^{15} 35.5

Fig. 3. A portion of Newlands' periodic table. Newland's brave attempt in arranging elements and identifying periodicity is evident in this portion. Chlorine (Cl), the eighth element to appear in sequence from F (Fluorine) exhibits similar chemical properties to it. That they both belonged to the same group – of halogens – was established much later.

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1. Mendeleev's arrangement did not rely only on the atomic mass values calculated by Cannizzaro. Instead, he pursued his own analysis of compounds, identifying chemically similar or 'analogous' elements, and prioritised this chemical similarity in his arrangement. In fact, he used this information to question the atomic masses of several elements.

2. Mendeleev seemed to have taken knowledge available to him as a challenge –somewhat like a jigsaw puzzle that was supposed to be assembled. He, therefore, prepared individual cards for each element, attempting to sort them through multiple arrangements. While considering these arrangements in the vertical and horizontal directions, that we are familiar with (in today's table), he chose to use family likeness vertically, and increasing atomic masses horizontally.

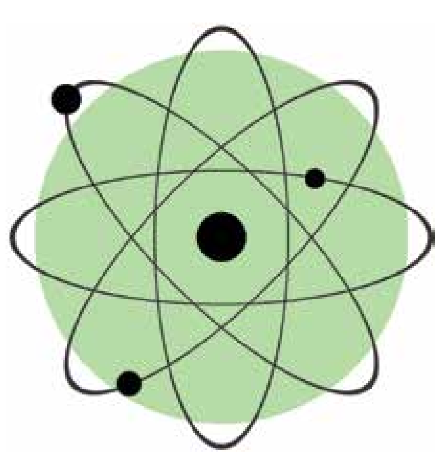
3. Mendeleev's conviction enabled him to confidently question existing knowledge (for example, incorrect atomic masses) and he resorted to re-calculating or re-positioning apparently incorrectly placed elements. This conviction and foresight were proved correct subsequently.

4. Possibly the most salient feature of Mendeleev's table are its blank spaces that were aimed at accommodating some undiscovered elements. But these were not just spaces, they were also accompanied by predictions of the properties these yet undiscovered elements were likely to exhibit (for example, having anticipated properties similar to aluminium, Mendeleev predicted the presence of an element that he called eka aluminium, and was later discovered and named Gallium). This visionary, and rather audacious, provision in Mendeleev's table allowed more elements to be incorporated. In fact, it also guided the search for new elements!

Amazingly, a strikingly similar periodic table was independently devised at around the same time by Lothar Meyer, a scientist who was later given almost equal credit for his contribution to the development of the periodic table as Mendeleev. Meyer's table drew more attention towards a progression in physical properties of elements, such as their atomic volumes.

A bigger problem: the surge in new elements and accommodating them!

Even as Mendeleev's periodic table offered a formidable organization of the 60-odd elements known at the time, it was soon threatened by the discovery of many new elements.



The first of these challenges came with the discovery of rare earths, i.e. lanthanides, using a spectroscope, invented by Robert Bunsen and Gustav Kirchoff in 1859. The spectroscope is an instrument that allows us to detect very small quantities of elements in any substance, without chemically isolating them. For the rare earths, which were chemically very similar and difficult to separate, therefore, the spectroscope was apt. As many such rare earths were being discovered post 1870, placing them in Mendeleev's periodic table was proving to be a challenge. Their chemical similarity was at odds with the fact that one of the main attributes of Mendeleev's classification was a progression in chemical properties. In 1905, Alfred Werner successfully resolved this problem by placing the rare earths between alkaline earth metals and transition elements in his very long periodic table, comprising 33 columns! Isn't it remarkable that Werner was able to rightly place the rare earths without any knowledge of their electronic configuration?

Another challenge came with the discovery of the first inert gas – Argon, in 1894, by William Ramsay and Lord Rayleigh. This discovery was unwelcome to most chemists, as chemically unreactive Argon seemed to threaten all that we had discovered and understood about elements. The subsequent discovery of other inert gases like Helium, Neon, Krypton and Xenon, amplified this complication – culminating in the creation of a unique group in the table, placed between the halogens and alkali metals.

In 1898, Marie Curie and her husband, Pierre, discovered Polonium and Radium, and by 1911, almost 30 radioactive elements were known. These discoveries presented yet another challenge to the conceptual understanding of elements – mainly because some of them had identical chemical properties, but different atomic masses. This naturally

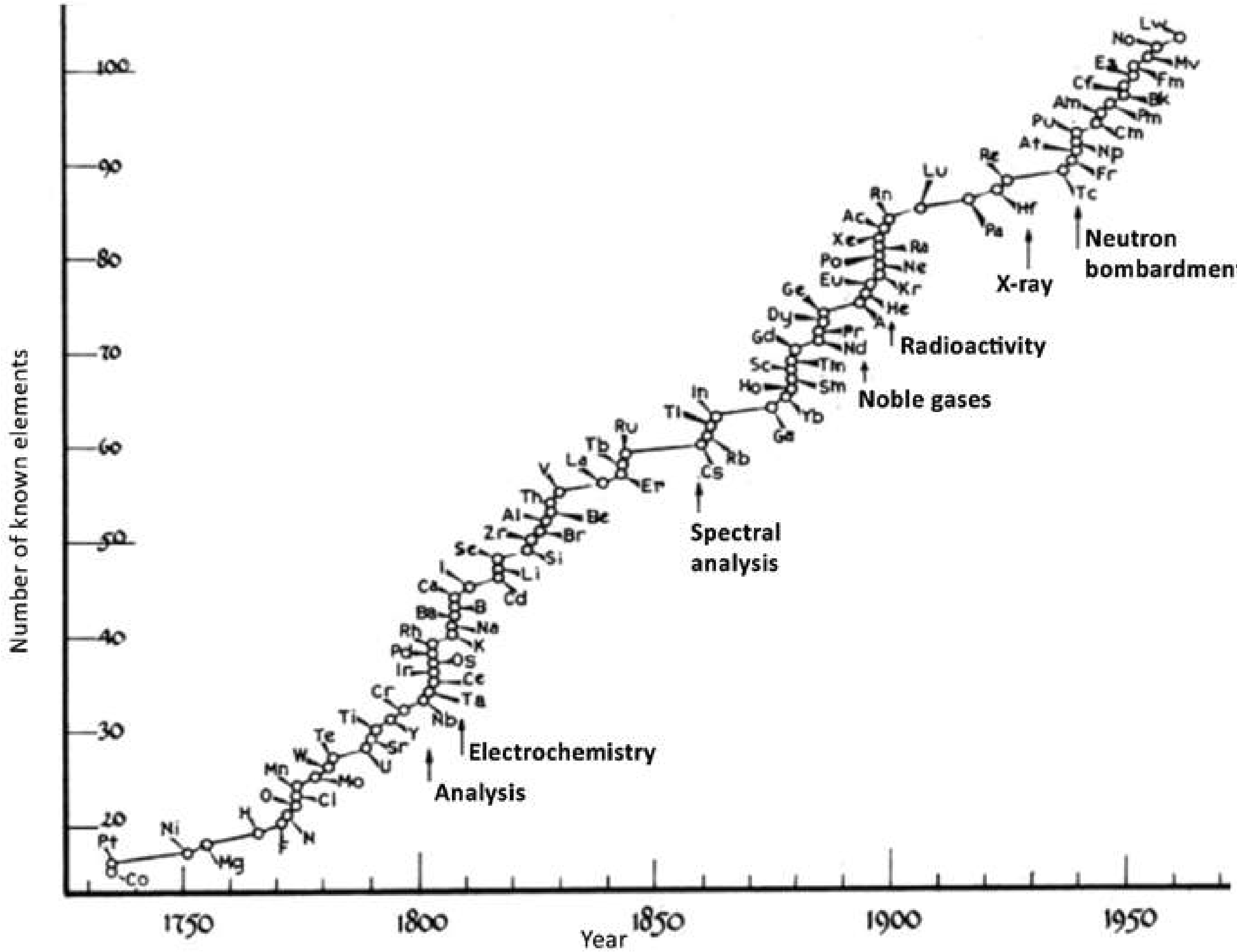


Fig. 4. An overview of the discovery of the elements.

Credits: Adapted by Tejas Joshi from Goldwhite, H., & Adams, R. C. (1970). Chronology of the discovery of elements. Journal of Chemical Education, 47(12), 808.

led to the problem of how and where to place these new elements in the periodic table. Frederick Soddy and Kazimierz Fajans resolved this problem by suggesting that all isotopes (elements with identical chemical properties) of an element must be placed along with it, in one single place, despite having different atomic masses.

Atomic number: the new signature of an element

Henry Moseley's work in 1913 showed that there exists a systematic mathematical relationship between the placement number of an element in the periodic table and X-rays produced by the element. Thus, he could measure the atomic numbers of several elements for the first time. Because of his work, atomic number (that is, number of protons present in the nucleus of the atom), instead of atomic mass, is now considered the signature of an element. Moseley's work also conclusively showed that there were 14 rare earths, with the two, till then missing, elements Hafnium and Rhenium being discovered soon after, by the X-ray method.

The latest addition to the periodic table is that of new elements created by humans. As a result, the concept of elements evolved from being limited to naturally occurring ones to including those created in laboratories by the transformation of matter on nuclear bombardment. Neptunium was the first element to be synthesized. The creation of this trans-uranium element in 1940 by Edwin McMillan and Philip Abelson, at the Berkeley Radiation Laboratory was followed by extensive syntheses of transuranium elements by Glenn Seaborg and his co-workers. Accommodating these newly created elements in the periodic table was yet another challenge, as nobody had anticipated them! By 1944, Seaborg, who christened this set of elements as the 'Actinide' group, had developed an updated version of the table with these elements placed below the rare earths (Lanthanides). This was based on the discovery that the actinide group of elements were analogous to their corresponding lanthanides, and subsequently aided the identification of many more synthetic elements.

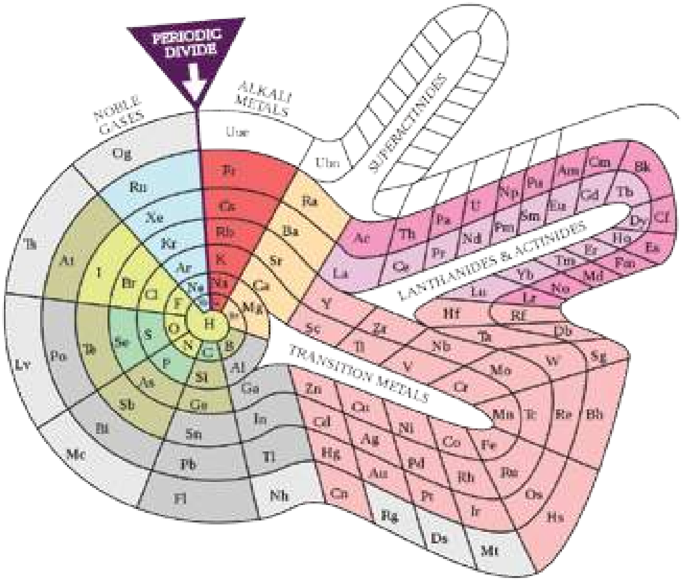


Fig. 5. Could the periodic table look different? Presented in this image is one example of a significantly unusual format – a spiral table developed by Theodor Benfey. With hydrogen placed at the centre of the spiral, the emergent spirals expand into eight segments, housing transition elements, lanthanides and actinides. The spiral and helical models are not new – the Telluric Screw model proposed by Chancourtois in 1862 was a prominent example of a helical model. To explore other such formats, collected from across the world, visit Mark Leach's online collection at http://www.meta-synthesis.com/webbook/35_pt/pt_database.php.

1. The first resource is an infographic flyer presenting the milestones in the development of the periodic table and introduces scientists who contributed to it. This article is inspired by this resource.
2. But this flyer opens up (unfolds) into a large, incomplete activity-based periodic table with hints and spaces, which the reader completes!
3. The second resource is a pack of 114 visual information cards, one for each element.
4. Color-coded and illustrated, each card has the element 'talk' to the reader, sharing myriad information about itself across themes, details of which are available on the portal.

The portal **www.bit.ly/lmtce** takes you to a detailed description about these resources, and hyperlinks to many useful sources of information for you to pursue.

Fig. 6. Resources developed at the Homi Bhabha Centre for Science Education.

Box 4. Resources

An extensive list of print and web-based resources on the periodic table that we have referred to for this article, as well as some teaching resources developed by us, are openly accessible online at www.bit.ly/lmtce under the 'Important References and Resources' section on the portal.

We recommend visiting the portal, which was built to make available educational resources for multiple audiences, some of whom might not be able to access teaching aids or international books in print. We are sure that some of these resources will inspire and support you in your practice – whether it is through designing activities for your students, directing them towards self-learning, or encouraging them to question and seek answers. We also offer print versions of a set of learning resources designed to act as lucid starting points for inculcating an appreciation for the periodic table and its elements among your students. These resources are available on purchase, and details for the same can be obtained by writing to us.

The periodic table as an educational tool

So here we are today, with the widely recognized long-form of the periodic table. A lengthy journey, right? And one that has not yet ended – efforts to improve the functionality and format of the periodic table continue (refer Figure 4 for one such example)!

All revisions in the periodic table are documented and updated by a global body called the International Union of Pure and Applied Chemistry (IUPAC). These revisions could involve changes in technical information, or the addition of new elements. The most recent version of the table (January 2016), a standard reference for educators, incorporates four new elements that have been in the news, and are known simply as 113, 115, 117, and 118.

What makes the periodic table invaluable for chemistry, and science education in general, is its extraordinary depiction of the dynamic but gradual process by which scientific knowledge progresses, and how pushing this progress is a constant human endeavour.

We present this historical journey in the hope that it broadens your perspective on the periodic table (or anything that you study in science for that matter). Rather than seeing it as a completed product, we hope you can now see the periodic table as the result of an on-going, and rather captivating, story with characters who were curious, hard-working, and pursued questions with no obvious answers through logical contemplation.

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