# The Periodic Table: Highlights from the History of an Icon

## Abstract

The periodic table is an icon of chemistry—one of the few visual images that makes anyone who sees it think of chemistry. The periodic table has even branched out beyond its chemical roots as an arrangement for vegetables, desserts, and the like. Back to chemistry: where did it come from? When? How? What chemistry had to be known before the table could be discovered? (For that matter, was it discovered or invented?) These are just a few of the questions to be touched on in a whirlwind tour of the history of the periodic table from its devising to the present, including various shapes and sizes it has assumed over the years.

## Introduction

The periodic table is instantly recognizable to anyone who has had a course in chemistry, and even to many who never had such a course. That is what makes the table an icon. The pattern of little boxes arranged in a roughly rectangular pattern, slightly higher on both sides than in the middle practically screams “periodic table” even if the table is not of the elements (as in this table of desserts). This photo, showing student chefs of Sally Mitchell’s, had both the elements and actual desserts, so it satisfied both the mind and the taste buds.

## Periodicity

But we are here to look at **the** periodic table, the one of the chemical elements. Let’s look at the words: the **periodic** **table** of the **elements**. What do these terms even mean? Let’s unpack this phrase from the end back to the beginning. By elements, we mean chemical elements, like these for example. A table is simply an orderly arrangement. And in math, periodic functions are repeating functions, like this cosine or this more complicated combination of sines and cosines. A periodic function is one that repeats, or alternates. It has a regular pattern of ups and downs.

That is what periodic means in the periodic table, as well, although the alternation of ups and downs is not quite as regular. When the elements are arranged in a certain order, many of their properties show a repetition of high and low values. These include chemical properties like electronegativity, physical properties like molar volume, and properties relevant to both the physics and chemistry of an element like ionization energy.

## Before the Periodic Table

These graphs display modern data, but this talk is about the **history** of the periodic table, so let’s go back in time a couple of hundred years or so to see how we got here. What would scientists have had to know before they could put together a *periodic table of the elements* based on graphs like the one we just saw? While you are thinking about what information is needed, let me show you a graph from 1870 published by one of the pioneers of the periodic table, Julius Lothar Meyer. This is a graph of “atomic” volume (what we would call molar volume).

Here is the list I came up with. First you would need the concept of element, and then lists of examples of elements. You need information about the properties of the elements, preferably quantitative information. You would have to figure out which property to use as the independent variable (*x*-axis) when plotting one property against another. (Don’t forget: the remarkable thing about the periodic table is that practically **every** property shows periodicity when plotted against **the same** independent variable.) And you would have to have enough elements discovered and characterized for patterns to emerge.

At this point, I ought to tell you that scientists were not exactly trying to find chemical periodicity. They were not exactly waiting for data to be accumulated so that they could say, “Let’s graph properties and see if any patterns emerge.” The periodic table **actually** came out of attempts to **classify** chemical elements, basically to organize elements and their properties in a coherent way. But the information necessary to make a comprehensive classification was basically what we have just identified.

For a scientific, empirical concept of element, we go back to Robert Boyle in the 17th century, and his book *The Sceptical Chymist*: “I now mean by Elements ... certain Primitive and Simple, or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the Ingredients of which all those call’d perfectly mixt Bodies are immediately compounded, and into which they are ultimately resolved.” Late in the 18th century, Antoine Lavoisier wrote “If we apply the term elements, or principles of bodies, to express our idea of the last point which analysis is capable of reaching, we must admit, as elements, all the substances into which we are capable, by any means, to reduce bodies by decomposition.” Lavoisier, 100 years later, not only defined elements, he included a list of them, and started to classify them, mainly by qualitative chemical characteristics. Lavoisier was not always correct: you may notice light and caloric (or heat) on his list of elements, and he was not always consistent as he included elements that had not yet been isolated (like the ones we know as chlorine, fluorine, and boron). I point out Lavoisier’s mistakes because not even the father of modern chemistry was always right. Lavoisier deserves a lecture of his own—as would any chemist beheaded in the French Revolution and whose portrait belongs to the Metropolitan Museum in New York—but we have to move on.

In the first decade of the 19th century, John Dalton proposed his atomic theory. He was not the first to propose that matter was ultimately discrete, that it came in the form of tiny particles he (and we) called atoms. What was most important about his theory (and not just for our story today) is that it focused on a property of atoms that was actually measurable with the technology of the time, namely their relative weights (or technically masses). Determining atomic and molecular weights and the formulas of chemical compounds became the main activity in chemical research for about the next 50 years. The Italian chemist Stanislao Cannizzaro is generally credited with reconciling most of this work into a coherent and widely accepted set of atomic weights around 1860.

## The First Periodic Classifications

Science is a cumulative activity. The periodic table could not have been formulated before reliable atomic weights, and many more properties, had been measured for a large number of elements.

Some groupings of elements into families with similar properties were carried out in the first half of the 19th century. In 1829, Johann Wolfgang Döbereiner noticed that several trios of elements that had similar chemical properties had atomic weights such that the weight of the middle element was the average of the weights of the highest and lowest. I’ve arranged these trios vertically, in boxes, and perhaps that makes these trios, or triads as they were called, look more like pieces of the periodic table we know. But neither Döbereiner nor I have put these isolated triads into any relationship with each other.

In the 1860s, several scientists discovered chemical periodicity independently, but only the last couple had much influence in the development of the periodic table.

The first of these was a geologist and mineralogist—not a chemist—Alexandre-Émile Beguyer de Chancourtois. He proposed a spiral arrangement of the elements. When he plotted atomic weights on a 45° line that he picked up and restarted at the atomic weight of oxygen, he found that elements lined up on top of each other, as you can see in this simplified version of his graph. **√**The graph, however, contains not just elements, but what he called “radicals” (and what we would recognize as polyatomic ions, like cyanide and ammonium). There were also examples of the same element appearing in multiple places on the graph. It is apparent that de Chancourtois found chemical periodicity. The graph, however, contains not just elements. He found chemical periodicity, but it is not at all clear to me that he was aware either of its limitations or its irregularities.

In the middle 1860s, an analytical chemist who worked in the sugar industry in London proposed several arrangements of the elements. John Newlands started by extending Döbereiner’s work. His best arrangement ended up using atomic weights as the ordering principle, but instead of looking for numerical relationships among the masses themselves, he simply assigned an ordinal number to each element. Sometimes he assigned more than one element to the same number, if their atomic weights were identical or nearly identical. In this way, Newlands found a repetition of chemical properties with every eighth element, more or less, and he called this observation the “law of octaves.” **√**When he presented this classification to the Chemical Society of London in 1866, they were not impressed. One of the audience asked, only half in jest, if he had tried arranging the elements in alphabetical order instead. Here we can see some of the strengths and the weaknesses of the arrangement. **√**In this row, we see the alkali metals, and even the elements that are not alkali metals frequently form singly-charged cations. **√**But in this row, we have an example of two elements occupying one spot, and we have both the oxygen group and several noble metals and iron all lumped together.

In 1864, the German Julius Lothar Meyer published a table containing about half of the elements known at the time that showed family relationships among main group elements. It emphasized valence and relationships among atomic weights. In 1868, he prepared a more comprehensive table that he never published. In 1870 he published a still different arrangement, which was better in several respects than the table Dmitri Mendeleev had published the year before. When the periodic system of elements came to be recognized as an icon of chemistry, Meyer’s contributions were recognized.

If there is one name associated with the periodic table, it is that of the Russian chemist Dmitrii Mendeleev. Mendeleev was not the first to recognize chemical periodicity, and his first table (of 1869) was arguably not as good an arrangement as Meyer’s of 1870. But Mendeleev deserves his reputation as father of the periodic table. **√**Here are two photos of Mendeleev, the one on the right near the end of his life, and the one on the left considerably earlier. Here are a draft and the published versions of his first periodic table, presented in 1869 to the Russian Physical-Chemical Society. Notice that the groups of elements are horizontal in this table, not vertical as we are used to, but here are several consecutive main group families. Note also the gaps left for as yet undiscovered elements. The text that accompanied this table explicitly predicted elements like aluminum and silicon in these positions. Two years later, Mendeleev published a very long and detailed article on his periodic classification, including this table, which has many features of the modern table. The groups are now vertical, as in the tables we are used to. This table has group designations, and it starts with hydrogen and the alkali metals. It has headings that emphasize chemical properties like valence. There is some distinction between main group and transition elements (by offsetting). We see spaces for three elements that were to be discovered over the next 15 years or so (gallium, scandium, and germanium), and the properties of these then unknown elements were quite accurately predicted in considerable detail. We also see spaces for many other elements, though, that do not exist. Mendeleev’s table was the best, but it was not perfect. Neither he nor anyone else at the time knew what to do with the lanthanides (or rare earth elements, as they were then called). Fortunately, not too many of them were known at the time to mess up the patterns! Again, fortunately, most of the main group elements **were** known, so that the most regular and evident periodicity was there to be discovered.

## After Mendeleev

This next slide was designed to make a rhetorical point about the nature of scientific knowledge: it changes as we learn new things. But the main reason I am using it here is that it is actually a good summary of how the periodic table has changed since it first became widely accepted in chemistry. (By the way, the bit about Mendeleev being a bigamist is true. His first marriage wasn’t dissolved until a month after his second marriage.)

Now about that whole added column. You may have noticed that none of the tables shown so far included any noble gas elements. That is because no members of that family were known (on earth, anyway) until 1894. Lord Rayleigh and William Ramsay isolated the first noble gas, argon, in 1894, and how they found it is an interesting story in itself. (These are drawings of Rayleigh, left, and Ramsay, right, that appeared in *Vanity Fair* around the turn of the 20th century. Ramsay is pointing to the noble gas group on a periodic table.) Argon posed some interesting problems once it was discovered and characterized as well, mainly how to fit it in the periodic system of the elements. Measurements of the density of argon led to the conclusion that its “molecular” weight was just under 40 units. (I put molecular in quotation marks because, as we are about to find out, if we didn’t already know it, a “molecule” of argon consists just of a single atom. Gas density measurements are sensitive to the mass of whatever form the material takes in the gaseous state, however many atoms are stuck together.) Other measurements, involving heat capacities, led to the conclusion that argon was monatomic, unlike the other common elementary gases like oxygen and nitrogen. An atomic weight just under 40 would place argon between potassium (39) and calcium (40), which was a big problem, because argon was nothing like those elements. Remember that periodicity means variation in properties, so something between potassium and calcium ought to have properties intermediate between those elements; however, the unreactive gas argon was nothing like those two very reactive metals! This dilemma for a while led chemists and physicists to question different pieces of evidence about the newly characterized element. Some physicists were willing to throw out the periodic table, or at least to accept an exception to it. After all, no one knew why the table worked, and it sure didn’t seem to work in this case of an element unlike any other that didn’t fit in the table. Some chemists weren’t willing to accept the highly mathematical physical theory that led to the conclusion that argon was monatomic. Maybe it was diatomic, in which case its atomic weight would be just under 20. In that case, it would go between fluorine and sodium, and an unreactive element would do just fine there between highly electronegative fluorine and electropositive sodium. Some chemists thought it might even be triatomic nitrogen (N3), although that would require a molecular weight of 42.

Anyway, shortly after the discovery of argon was announced, Ramsay was told about a similarly inert gas found trapped in some minerals. The spectrum of this trapped gas was taken, and it didn’t match argon, but instead matched the spectrum of an element that had been named helium but never before isolated. (The name helium comes from the Greek word for the sun, helios, because the sun’s spectrum contained some lines that matched no element known on earth. Helium was a sort of placeholder name for whatever element matched that spectral line, and it was the gas investigated in 1895.)

Before long, helium was characterized. Like argon, it was unreactive and monatomic. Its atomic weight was 4, which placed it between hydrogen and lithium. Now that there were two such elements, some chemists were feeling more confident in chemical periodicity (which, after all, says that elements come in families or groups). In 1896, William Ramsay placed argon and helium in the column we know as the noble gas column, and predicted that there were other monatomic inert gases as yet undiscovered. He set about looking for them, and he and his assistant Morris Travers found neon, krypton, and xenon in 1898.

Ramsay’s solution to the problem of argon meant that argon should come before potassium, even though its atomic weight was greater. This was unusual, but not unprecedented. Does anyone know of other elements in the table that are out of atomic weight order? Atomic weight order is pretty good, but it is not perfect. Today we order the periodic table by atomic number rather than atomic weight.

What is atomic number, anyway? We know it as the number of protons in the nucleus of an atom. It was discovered in 1913 by a young Englishman named Henry Moseley. Moseley found an absolutely regular progression in the positions of certain lines in the X-ray spectra of a large number of elements, and this regular progression corresponded to steps in the positive charge in the nucleus. Once atomic numbers were known, exceptions in atomic weight order became less worrisome, and it became absolutely clear where there were still gaps in the list of known elements.

There were two main sets of changes to the periodic table in the middle and later 20th century, and Glenn Seaborg was an important figure in both sets. At left is a picture of a younger Seaborg, and he was a relatively young man (under 40) when he won the Nobel Prize in 1951. At right is a photo of Seaborg in his 80s in the 1990s. This is what he looked like when I met him in the late 1990s. I was lucky enough to have lunch with him and his wife Helen and Eric Scerri at an unmemorable restaurant in Las Vegas between sessions of an ACS conference.

Seaborg won the Nobel Prize for his work in the chemistry of the transuranium elements. He used to say that he won the award for moving the actinides. Before World War II, the elements actinium through uranium were usually placed as the start of another transition metal row, such that uranium sat under tungsten as in the table shown here. The extensive work done with uranium during the Manhattan project, not to mention the discovery of transuranium elements like plutonium and americium, led Seaborg to conclude that the actinides were analogous to the lanthanides rather than the transition metals.

In the modern table, shown here in its familiar form, the actinides and lanthanides are shown detached from the main body of the table, mainly to save space. Besides that arrangement, you will notice many more elements at the bottom of the table. There is an entire actinide row, followed by a full transition row and the completion of a main group row. Seaborg and co-workers were responsible for discovering, or rather synthesizing many of these elements. For the last year or so of his life, he was the only living person to have an element named after him. Seaborgium, element 106, was discovered by Seaborg’s colleagues Al Ghiorso and others at Berkeley, and look, **that’s** the element that belongs under tungsten. And that is what Seaborg was pointing to in the picture I showed earlier.

## Conclusions

I hope I’ve shown you that the development of the periodic table is a story full of characters, insights, and some wrong turns as well—like science in general. It also illustrates how science develops as a cumulative activity of human beings using their judgment about evidence. As we saw, an awful lot of data had to be accumulated before one could even hope to classify the elements in a coherent manner.

Let me close with a few unusual forms designed to illustrate chemical periodicity. The left-step periodic table was first published by Charles Janet in 1928. Its advantages include regularity of shape. Columns still represent families of elements, and the blocks of elements are clearly evident. It even had uranium in the right place! But note that the rows do not correspond to periods as in the standard table.

Cycles and loops are natural forms for illustrating periodic phenomena, and there are several creative arrangements of this sort. Here is one from a mural in the early 1950s, and a more recent similar design adapted to evoke a spiral galaxy. And here is one by the English scientist William Crookes, published shortly after the discovery of neon and krypton but before xenon. Note that the noble gases (zero valence) lie at the crossing point of the track. This is a drawing of an actual physical model.

I’ll close with another physical model, a periodic coffee table, or as Theodore Gray prefers to call it, a periodic table table.

I’ll put up a few resources while I thank you for your interest and your attention. I’ll be glad to field questions.