Heroes of the Periodic Table

By Derek Marshall

A tribute to Mendeleev and the Periodic Table of the Elements in Bratislava, Slovakia. Notice the empty spaces for more elements around the edges.

Being Armed with the Scientific Method

The Periodic Table of the Elements was not conceived by one person, but was a product of many scientists. The discovery of the periodic system is an example of science and the scientific method at its very best. In order to begin investigating the scientific method, we must understand where it comes from and what is its basis in human inquiry.

In order to obtain knowledge, one must establish for themselves what knowledge is. Philosophy is the study of knowledge. It follows that one's philosophy determines the nature of what they consider truth. Here, we will be investigating one philosophy of knowledge, i.e. natural philosophy. Natural philosophy is practiced by employing the scientific method of inquiry. And science is the product of the Scientific Method.

The Scientific Method is the series of steps required to "do" science. Here are the steps we will be discussing that are cogent to our discussion. We will examine an example of each as they relate to the discovery of the Periodic Table.

Hypothesis: A hypothesis is a proposed explanation for an observed phenomenon. William Prout, a 19th century English chemist observed that the final mass of some chemical combinations of substances result in integer multiples of the individual mass of smallest substance he knew of at the time, "protyle". We know now that protyle was actually hydrogen, and his namesake hypothesis "All elements are made of protyle" was only partially correct. It required the research of many other scientists over many years to sort out Prout's Hypothesis, ultimately finding that each element indeed has a unique integer count of "protons", but the mass of the element is a complex mix of other sub-atomic particles.

Design of Experiment: In order to test a hypothesis, an experiment needs to be designed. In the late 18th century, the hypothesis that substances combined in definite proportions was first being considered. One investigator, Jeremias Richter, would add an acidic form of a known element, such as Sulfur to a base of other substance under test to determine how much base to took to neutralize the acid. If the acid and base were to combine proportionately, molecule for molecule, then any resultant weight differential of the two substances would imply that one was heavier than the other. Using this method, Richter developed a system of equivalent weights that allowed other scientists to perform more experiments, testing more substances to obtain more data. Richter's equivalent weights were used deep into the discovery of the Periodic Table.

Make observations: After performing the experiment, one must make observations. Just like experimental design, this step requires imagination. Observations made with the unaided eye are important, but we have four other senses that we may use to make observations. In addition, we have various instrumentation available with which other types of observations can be made. With these, extensive and intensive properties of observed materials can be established. In the early 19th century, Johann Dobereiner, used his keen observational powers, instrumentation and imagination to observe that the elements he was studying began to form in groups of 3, or "triads". Not only did a particular triad have similar chemical properties, such as acid forming, salt forming, etc, but if one took the average mass of the lighter and heaviest of the triad, one would obtain the mass of the middle element. These observations were among the first views into the vertical "groups" we see now in the modern periodic table of the elements.

Obtain Results: It is not enough to only make observations of an experiment. All of the data obtained must be analyzed, classified, and reported in a form that successfully conveys the findings to the intended audience. For some observations, this is straightforward, but for others, it takes more finesse. In the 19th Century, Max Pettenkofer noticed something similar to Dobereiner's triads but with a different flavor, causing him to reject the existence of the former. As he would analyze elements with similar properties from lightest to heaviest, and subtract the masses of one lighter from the heavier elements, that the same amounts of mass would be the result, or multiples thereof. These difference relationships of elements were so evident that their existence begin to imply periodicity. His research was one of the first views scientists had of the "periods" of the modern table of elements, and was noticed by Mendeleev himself when he put together the table we know today.

Draw Conclusions: Just like making observations during an experiment isn't the same as obtaining results, reporting those results, is not the same as drawing conclusions based upon those data. An investigator must decide whether those results support or refute the hypothesis. It is not until conclusions are drawn that findings can be reported. Dmitri Mendeleev is the scientist who gets most of the credit for the discovery of the Periodic Table of the Elements. Not because he performed all the brilliant science required to elucidate the table himself, but because he brought together that work product of other scientists, drew the proper conclusions and stood by those findings when they were put to the test for decades after his publications. I have found from my own experience as an engineer that it is the person who stands by and answers for their work, for good or for bad, who is the true designer: not the multitudes with ideas who have no little or no "skin in the game".

Peer Review: This was the most important aspect of the discovery of the Periodic Table. It took the work of dozens of scientists who were in communication networks with other scientists sharing their findings. Certain chemists liked other chemist's work more than others. Some liked Prout's Hypothesis, and tended to ignore the decimal points in their measurements. Some used Richter's equivalent weights and used precise measurements, while some others held on to incorrect beliefs for too long. One eventful meeting of these scientists in 1860 was the Karlsruhe Congress. This congress was famed for clarifying the existence of diatomic molecules and to present a standard for correct atomic weights. This conference was instrumental in pulling together the science behind the Periodic Table.

Next, we will do a more in-depth look at the Heroes; those prominent contributors to the discovery of the Periodic Table.

Lavoisier, the Father of Modern Chemistry (1743 -1794)

Antoine-Laurent de Lavoisier was born in Paris, France to a noble family during the French Enlightenment. With this advantage, he had the best educational opportunities available at that time and was immersed in the most progressive ideas in science and philosophy. He had many good influences in the sciences and excelled in chemistry and developed a passion for meteorology. His father was an attorney, and Antoine also ultimately received a law degree. He never technically practiced law but he was involved in social and political issues in order to further his research.

The chemical reaction theory of Lavoisier's day was that all substances contained phlogiston which was what allowed material to combust or burn. He opposed this antiquated phlogiston theory, thereby changing the science of chemistry from qualitative to a quantitative science. With his extensive experiments in combustion, he was the first to hypothesize that the same amount of matter exists before and after a material combusts. This is the conservation of matter theorem, later to be known as the First Law of Thermodynamics. Today, a "mass balance" is one of the most important aspects of Chemical Engineering.

There are varied attributions to Lavoisier, depending on the source, however, he was one of the first to produce a list of elements, and with that a system of chemical nomenclature and stoichiometry. He published these in his Traité élémentaire de chimie (Elementary Treatise on Chemistry), in 1789. Many consider this work as the first modern chemistry textbook and with this, he has the honor of being considered "The Father of Modern Chemistry". I believe that if it were possible for one person to discover the entire Periodic Table by themselves, Antoine-Laurent de Lavoisier of Paris, France would have done it.

John Dalton, Atomic Theory (1766-1844)

John Dalton was born in Cumberland, England into a Quaker family. In contrast to Lavoisier, the Dalton family was relatively poor and any schooling the young man was to receive would have to be from friends and family. Dalton was fortunate to have a wealthy Quaker patron who engaged the service of the young man and encouraged his studies in mathematics and meteorology. Because Dalton joined with his brother in running a Quaker school, he is often attributed the vocation of "English school teacher".

Although John Dalton was never formally trained in science, he did attain appointments at various colleges and universities and began publishing works as a meteorologist, chemist and physicist. As an experimentalist, he was doing cutting-edge research studying the expansion of gases. Another later mentor of Dalton was a philosopher and I believe this attributed to Dalton's theoretical works and writings.

Dalton's had plenty of contemporary inspiration for his atomic theory, including one Sir Isaac Newton who believed and wrote that "God in the beginning form'd matter in solid, massy, hard, impenetrable, moveable particles…" I will point out here that this creationist idea led to the truth of science. Here are the commonly listed tenets of the theory largely attributed to Dalton:

1. Elements are made of extremely small particles called atoms.
2. Atoms of a given element are identical in size, mass and other properties; atoms of different elements differ in size, mass and other properties.
3. Atoms cannot be subdivided, created or destroyed.
4. Atoms of different elements combine in simple whole-number ratios to form chemical compounds.
5. In chemical reactions, atoms are combined, separated or rearranged.

Another reason I include Dalton among the list of discoverers of the Periodic Table is because he published a tabulated list of elements with relative weights, and at least qualitatively presented the idea of multiple atoms forming polyatomic groups, later known as molecules.

Of course, I like to include in my descriptions of each scientist what they helped discover. But what they "missed" is also interesting. For Dalton, it was his "Rule of Simplicity". This is an example of a hypothesis that is partially correct; But, in science one must be consistent, so Dalton always employed this law. When taking measurements during an experiment, one may have at their disposal a rather blunt instrument. As long as all of the measurements are done the same way with the same imprecise tool, some measure of accuracy can still be achieved with a high enough quantity of samples. In closing, my favorite unit of measure is the Dalton. In biochemistry, 1 Dalton is 1/12 of the mass of a Carbon-12 atom.

Jöns Jacob Berzelius, Precise Weights (1779-1848)

Jöns Jacob Berzelius was a Swedish chemist and member of the Royal Swedish Academy of Sciences. He came from a very modest educational background but because of his interest and efforts in the areas of science and education as a tutor he was admitted into medical school where he was able to gain formal scientific training. He was known early in his college days as being able to reproduce other renown scientist's experiments, such as the discovery of oxygen and the voltaic pile, now known as the constant current battery.

His contributions to science and chemistry are numerous, and his timely contribution to the Periodic Table of the Elements in its infancy proved to be a major one. As discussed in the previous bio, John Dalton's "Law of Simplicity", and Prout's Hypothesis were generally accepted during this time, but Berzelius was not a fan. His precise measurements of the elements of his day not only furthered the case for the Periodic Table, but allowed him to discover two new elements, cerium and selenium. However, Berzelius incorrectly regarded all metals as dioxides, thus reporting incorrect mass values in his earliest tables for the alkali metals in first group of the periodic table.

Amedeo Avogadro, N_A (1776-1856)

Amedeo Carlo Avogadro was an Italian scientist born in Turin, Sardinia to a noble family, and was educated as an ecclesiastical lawyer. He also had a keen interest in math and physics and taught his philosophical findings in the local school. A few years later, in 1810, he published his hypothesis that equal volumes of gas contain equal number of molecules, inspired the work of other scientists finding that many chemical reactions of equal proportions rendered the same volume of gas. It is interesting to note that Avogadro was not the first to calculate the constant that bears his name "Avogadro's Constant", 6.022×10^{23}. Amounts of substances corresponding to their atomic weights contain an equal number of molecules. This quantity and Avogadro's Law is a very interesting result that applies to many scenarios in chemistry and physics. It works for substances in any of the 3 main phases of matter, gas, solid or liquid. If you know the atomic weight of a molecule, you can know how many atoms there are in your sample. Avogadro also made an invaluable contribution to the Karlsruhe Conference of 1860 by showing definitively that gaseous molecules are in fact atoms that are paired up in diatomic configurations. This allowed the distinction between atoms and molecule to be more widely understood.

Alfred Joseph Naquet, Families (1834-1916)

Alfred Naquet was French Professor of Medicine and Chemistry, born in Carpentras, France. He was active in the politics of the day and served as Defense Secretary during a time of revolution. In his 1867 textbook *Principles of Chemistry*, he grouped elements into "families", according to their chemical properties. These groupings were the precursors of the modern "groups" of the Periodic Table.

Naquet classified elements into two categories, metals and metalloids. The metals category was subdivided into families 1° through 6°, and the metalloids, 1° through 5°. It is interesting to note that these numerical family designators are related to the modern valences of atoms. For example, Cl, Chlorine is in metalloid family 1°, and has a valence of 1. This meant at the time that a 1° metal most often would combine with a 1° metalloid, in this example KCl, Potassium Chlorate. For oxides, 2° metal Zinc most would combine with a 2° metalloid oxygen to form Zinc Oxide. As we will see later, the modern groups are numbered differently, but are still listed in valence order. And although the classifications are more complex in the modern table, the groups are based upon 8 valence electrons in the outer shells of an atom, which are active in chemical bonding.

Stanislao Cannizzaro (1826-1910)

Stanislao Cannizzaro was an Italian chemist born in Palermo, Italy. He attended medical school but thereafter served as a chemistry research assistant instead of practicing medicine. He was a military officer during the Sicilian revolution, and that failed effort led him to Paris, France, where we began his research. Cannizzaro was a staunch advocate of his countryman Avogadro's work and helped the latter to express his theories more clearly during the Karlsruhe Conference of 1860. There were many different values of atomic weights and confusion over what was an atom and what was a molecule. Cannizzaro furthered his work distinguishing between atomic and molecular weights by sampling and measuring the weights of many different compounds containing the suspected element. For example, carbon combines with itself in a high degree in common organic substances such as methane, ethane and propane: These molecules feature one, two and three carbons, respectively. If an Avogadro's quantity, or 1 mole, 6.022×10^{23} instances of the carbon portion of each is a multiple of a constant mass, 12 grams in the case of carbon, that measurement can be regarded as carbon's atomic weight. Therefore, by Cannizzaro's Law, carbon can be regarded as an atom, not a molecule.

Alexandre-Émile DeChancourtois (1820-1886)

Alexandre-Émile DeChancourtois was a French geologist born in Paris, France. He attended one of the top engineering schools in France and studied under three renown scientists of the day. As a professor of a mining school in Paris, he worked on the collection and classification of minerals. This mindset of classifying minerals lent itself naturally to how DeChancourtois contributed to the discovery of a truly Periodic System of Elements.

In 1862, DeChancourtois produced a three-dimensional, periodic classification of the elements called the Telluric Screw of 1862. The screw was a cylinder of exactly 16 inches in circumference, based upon the atomic weight of oxygen. The data were presented as a series of diagonal lines, thereby forming a helix pattern much like a screw. We will read more about this first periodic table in the chapter "Variations of the Periodic Table". The Telluric Screw was published, but did not garner much interest because it did not include the all-important diagram. The table had shortcomings, maybe because DeChancourtois was a geologist, not a chemist. The best thing he said of his work was that "the properties of bodies are the properties of numbers".

John Newlands, Law of Octaves (1837-1898)

John Alexander Reina Newlands was an English chemist born in London, England. He was home-schooled by his mother and minister father and later attended the prestigious Royal College of Chemistry. Newlands had a short period during which he served as a volunteer solder during the unification of Italy. Upon returning, he helped run a sugar plant and made improvements to the sugar refining process. This got him noticed as an analytical chemist and he began publishing the results of his own investigations on the periodicity of the known elements of the day. He had the advantage of reading about Dobereiner's triads and other works grouping elements by properties and he produced the first table of elements listed in order of atomic weight. In 1863, he first presented several formal groups of elements, for example Group I, the Alkali Metals and Group II, the Alkaline Earth Metals, with these two groups bearing the same names today. He also generalized and tabulated elements using a specific pattern by what he termed as "The Law of Octaves". Unfortunately, his association of the elements with the musical scale put off many of his fellow scientists. His numbering of the elements foreshadowed the atomic numbers to come. His many revisions helped shape the table we know today.

William Odling, Periodicity (1829 -1921)

William Odling was an English chemist born in London, England. He was the son of a doctor, and Odling himself received his M.D. at London University at the age of 22. He taught chemistry and held several other positions in hospitals before ascending to the Fullerian Professorship at the Royal Institution where he changed his concentration from applied medicine to chemistry. Unlike Newlands, Odling had attended the Karlsruhe Conference of 1860 and had obtained that updated set of atomic weights which was so important in correctly ordering the elements. With this set of more accurate weights, Odling was able to publish a table that included 57 of the 60 known elements, including the reversal of Iodine and Tellurium. Odling's analysis of the periodicity of the elements was superior also, as he recognized several periodic increases of atomic weight on the order of 16 and 48, the former of which is the doublet of Newland's Law of Octaves. These additional periodicities of 40-48, for example, between Sulfur and Selenium and several others prompted Odling to isolate in his table some of what was to become the transition metals. This new periodicity also led him to leave unprecedented "gaps" in his tables, implying that new, undiscovered elements were perhaps hidden in those spaces.

Gustavus Hinrichs, Spiral Table (1836-1923)

Gustavus Hinrichs was a Danish scientist born in the Holstein region of what is now Germany. He attended the University of Copenhagen and was a prolific author. He was a true multi-disciplinary scientist with whom I find the most in common, because of the breadth of his ideas that he was able to correlate. Like the author, he discovered numerical and geometric patterns in the progression of the atomic weights of the elements. He characterized some groups of elements, namely the non-metals and metals as triangular and square (as he called them trigonoides and tetragonoides, respectively), based upon the geometric arrangement of quadratic formulas he devised. With these he could produce astonishingly accurate estimates of atomic weights. He was considered a Pythagorean because he noticed that ratios of atomic spectral line and planetary orbits formed a similar progression. He theorized that one could estimate the size of atoms based upon the "dark" lines of atomic spectra. His major contribution to the periodic system was an 11-spoke spiral diagram of the elements with each period being a rotation around the origin and each series being along the lines formed by the spokes. For example, he was the first to put copper, silver and gold in the same series.

Lothar Meyer, Periodic Law (1830-1895)

Julius Lother Meyer was another influential chemist from Germany. He born into a family of physicians and he and his siblings' educations were targeted towards medicine. However, his interests shifted to other fields in physics and chemistry. Lothar attended the famed Karlsruhe Conference in 1860 and was greatly influenced by Cannizzaro's work, even beyond the updated and more accurate atomic weights provided at the meeting. A strong argument can be made that Meyer published the Periodic system first; one complete with groups, valences, predictive gaps, listed in atomic weight order. His chemistry textbook of 1862 featured a table with 28 elements, in addition to 22 more elements in an adjacent table. This preceded Mendeleev's work by nearly 7 years. One main criticism of Meyer's work is that his table of 1864 was unclear in its references to atomic weights. Another major contribution of Meyer stemmed from his keen knowledge of atomic volumes. He published a chart in 1870 that illustrated how atomic volumes increase and decrease in a periodic manner as atomic weights increase. Meyer also began to theorize that non-organic atoms were comprised of consistent sub-units, just like organic compounds were made up of reoccurring molecular subunits, such as CH_4.

Dmitri Mendeleev (1834-1907)

Dimitri Ivanovich Mendeleev was a Russian chemist born in Tobolsk, Siberia. Mendeleev had the good fortune of attending a private school in St. Petersburg and studied science as well as how to teach and present information. Although contemporary chemists we have surveyed had already done so, Mendeleev independently listed the elements in the order of their atomic weights. At that time, other researchers seemed overly concerned about arrangement according to the element's properties and valences. This is not to say that Mendeleev was unconcerned with these important facets of the periodic system. He allowed himself to keep an open mind on these ideas because, for instance, he knew from his research that an element, such as iron, could have multiple valences. His novel contribution to the system can be seen in his periodic table of 1869, in which he arranged the elements in vertical columns and horizontal rows that were intertwined giving both periodicity and grouping in order of properties. He was somewhat slow to adopt Cannizzaro's atomic weights of 1860, but when he did, he discovered the periodicity of the elements by valence and properties fell into place, with few exceptions.

His in-depth knowledge of chemistry as well as a well-developed philosophical belief regarding what is simple substance versus what is an element allowed him to confidently state why he ordered the elements by their atomic weights. The distinction Mendeleev made is that an element, with its chemical properties will lose those same properties when becoming a molecule with another substance, but the former's mass does not change. Therefore, an element's mass is an unchanging property. Another accomplishment of Mendeleev over and above his contemporaries is that he predicted three elements, scandium, gallium and germanium. He predicted not only their atomic weights but their properties such as volume, specific gravity and similarity to aluminum and silicon.

With his mastery of the arrangement of the periodic system by atomic weight, by rows and columns, and accurate, multifaceted predictions of three elements, Mendeleev earned the right to claim that he was the first to claim discovery of the periodic system of elements. He further distinguished himself by publishing many versions of his tables and keeping with it for decades while other contributors moved on to other projects and pursuits. It was his love and passion.

Easy Table: Heroes of the Periodic Table	
LaVassier	List of elements, chemistry is quantitative
Prout	All elements are composed of “protyle”
Richter	Equivalent weights table wide early use
Dalton	Elements Combine in whole numbers
Berzelius	Precise atomic weights, not all whole numbers
Avogadro	Avogadro’s Number, N_A and Diatomic Compounds, such as O_2, H_2, N_2
Naquet	Grouped atoms by similar chemical properties, families
Cannizzaro	Distinction between molecular, atomic weights, first accurate atomic weights
Dobereiner	Triads of similar elements helping form Groups
Pettenkofer	Difference Relationships interpolate elements in Series
De Chancourtois	The first periodic system was a spiral table
Newlands	More Groups of elements by properties
Odling	Periodic table with gaps, predicting spaces for undiscovered elements to fill
Hinrichs	Relating spectra to atomic weights, spiral table, similar proportion to planet orbits
Meyer	Periodic table with groups and valences
Mendeleev	Tabulates elements by atomic weight, discovers group and series periodicity follows. Predicts 3 elements

QUESTIONS FOR STUDY

1. What is “protyle”? Discuss how Prout was both wrong and right in his hypothesis.
2. If one has 3.011×10^{23} atoms of Gold in their hand, how many grams will it weigh?
3. If an element is in a “family” with another, what does it mean?
4. How did Richter develop his system of “Equivalent Weights”?
5. What Period 1 element is missing from Mendeleev’s periodic table of 1869?
6. Why are Iodine and Tellurium seemingly reversed on the Periodic Table?
7. What are intensive vs. extensive properties of substances? Give examples.
8. How did a Creationist worldview help in the development of the Periodic Table?
9. Do you think we will discover any more elements beyond Ogannesson, (Og, 118)?

REFERENCES

Eric Scerri, 2020, *The Periodic Table: Its Story and Significance*. 2nd Ed, Oxford

Wikipedia

Encyclopedia Britannica

Encyclopedia.com