Chronicles of a chemical chart

As the International Year of the Periodic Table draws to an end, we reflect on how it has prompted chemists to explore the past, present and future of this chemical icon.

Chemists — especially those active on social media — would have been hard-pressed not to notice that 2019 was the International Year of the Periodic Table (IYPT), marking the 150th anniversary of Dmitri Mendeleev's early arrangement of the then-known elements. One of the aims of this year-long celebration is to raise the profile of chemistry with the wider public and better explain its importance — in particular for global challenges related to human health and sustainable development. The IYPT has also prompted many chemists to take a closer look at the table, from a variety of different angles, and share what they have learned; the pieces we have published on this topic periodically throughout the year are gathered together in a collection (https://www.nature.com/collections/jksxfggtbd).

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As chemistry has evolved over the past century and a half, so has the periodic table. The discovery of new elements — combined with a deeper understanding of their properties and how they relate to each other — has seen this iconic chart go through a number of iterations to arrive at the standard version we know today. And it hasn't just been a simple case of plugging gaps as new elements were found in nature or created in the lab; some proposed entries turned out not to be elements after all and their coveted place at the table had to be given up. In a Comment article published early in the IYPT, Michelle Francl ponders on these 'phantom elements' that never were.

Early developments in the table are, understandably, not as well documented as more recent ones and we're still learning new things about its history. This is nicely illustrated by the 'tale of two tables' from the late 1880s (or thereabouts), recounted by Pilar Gil and Eli Zysman-Colman in a Thesis article. After an old periodic table was discovered at the University of St Andrews, some detective work involving the university's archives and financial records from the late 19th century suggests that it is currently the earliest known example of a classroom wallchart. Meanwhile, analysis of a different table printed in French but found in the German city of Koblenz is a "testimony to turbulent times in the past" — including the periods of French occupation that the city went through after both World Wars.

Gender bias has long been a major problem in chemistry (and science in general) and more needs to be done not only to redress the balance but also to look back and acknowledge the significant contributions made by women throughout its history that were often overlooked at the time (and since). In the context of the IYPT, a conference entitled 'Setting their table' focused on the contributions of women to the development of the periodic table and the ongoing exploration of the elements. In a Meeting Report covering this event, Claire Murray conveys why this bias harms not only individual chemists but also the field as a whole, and concludes "Let's stop waiting for things to get better and do something together to fix them".

Another issue that has also been prominently highlighted during the IYPT is that of raw elemental resources being depleted. Rapid technological progress has meant that we rely on an increasing number of elements, some of which are not only scarce, but are being consumed at rates that mean it won't be long before we run out of them. Demand for indium and gallium, for example — both recognized as 'critical elements' — has recently skyrocketed owing to their use in flat-screen TVs and mobile phones. In a Thesis article, Bruce Gibb looks at how remaining resources of elements and their minerals are assessed and monitored by governments.

Not only is 2019 a special year for the periodic table, but it also marks the 100th anniversary of the International Union of Pure and Applied Chemistry (IUPAC), which was founded in Paris in July 1919 with the aim to standardize notations and promote international collaboration within the field. Centenary celebrations were held this July at the 47th IUPAC World Chemistry Congress in the same city, as described in a Meeting Report by Yi Yan Yang and Julien Nicolas. They highlight how it reflected the breadth and depth of the field by bringing together chemists from a wide variety of areas who are working collaboratively towards "tackling today's and tomorrow's societal challenges". In a Comment article, Javier García-Martínez relates the involvement of IUPAC in recognizing new additions to the periodic table — a role that would include far more adjudicating than anyone could have foreseen — as well as in establishing a common language in chemistry, one that now needs to be read and understood by computers. García-Martínez also points out that there isn't simply one 'true' form of the periodic table. Over the years, the elements have been arranged into charts of various shapes, from spiral to pyramidal to three-dimensional, to capture the elements' chemical similarities and account for their periodicity.

Nevertheless, it is the familiar, roughly rectangular, seven-period-deep table (with the lanthanide and actinide series usually floating on their own at the bottom) that adorns labs and classrooms the world over. It is an incredibly useful teaching tool — though Martyn Poliakoff and co-workers wonder in a Comment article whether it would benefit from being flipped upside down! The team of chemists and psychologists propose that filling the table from the bottom up — as you would a graph, with values increasing as you get closer to the top — may make its underlying principles easier to grasp. They report that this simple, yet bold, proposal was met with a "surprisingly positive reception" from the chemists they consulted. As someone remarked to Poliakoff and colleagues, it does also have the added merit of making the periodic table look much more like, well, an actual table.

This is not to say that all chemists find all of the elements exciting all of the time. In a somewhat light-hearted Comment piece, Rebecca Jelley and Allan Blackman muse on what the most boring element might be — spoiler alert, despite the missed alliteration opportunity it's neither boron nor bohrium. And although they do come up with one elemental candidate, and recognize that chemists often think their own area of chemistry is the most important, they ultimately conclude that the IYPT is a time for us to "be revelling in the astonishing diversity of all the elements". Beyond the very varied elements that do exist, the idea of an 'almighty element' has also captured the imagination of scientists and non-scientists alike, and has often appeared in works of fiction. In a Comment article, Suze Kundu explores how these fictional elements may not actually be all that different from well-known terrestrial substances.

In any case, despite a few remaining quibbles — such as the location of the first and last members of the lanthanide and actinide series — the periodic table as it now stands is widely accepted. Yet it has never simply been just a catalogue of all the known elements and their characteristics. From its early days, it has served as a tool for element discovery, and this is still true. In recent years, however, the elements that have been added to it are rather exotic: their atoms are so huge that they decay nearly as soon as they form (to be recognized as an element, an atom only needs to have a lifetime of at least 10^{-14} s). Their nuclei are so big that electrons surrounding them move at relativistic speeds, causing significant deviations from the expected periodic trends.

These newest, ephemeral elements, often referred to as 'superheavy', have attracted much attention — including from the wider public — in particular since 2016 when the names of the four latest tiles added to the current periodic table were officially approved by IUPAC. The recent developments in superheavy science prompted Kit Chapman to embark on a journey retracing the discovery of the transuranium elements. All of them were first identified as a result of human activity — whether made in a laboratory or in the aftermath of a nuclear explosion — although some do occur naturally in very small amounts. It's quite difficult to pin down what the heaviest naturally occurring element actually is, but Brett Thornton and Shawn Burdette give it their best shot in a Comment article from earlier this year. In this issue, in her Books & Arts review of the book Chapman wrote following his explorations, *Superheavy*, Rebecca Abergel conveys the "deep and mesmerizing sense of excitement at the idea of crafting nature's building blocks" and reflects on how these endeavours are intricately linked to geopolitical events.

When it comes to nuclear chemistry, experiments typically involve large teams of people with a range of different expertise. The synthesis of superheavy elements consists of firing atoms at a target in the hope that their nuclei will meet, at exactly the right place and the right speed, and fuse. This is no mean feat, Chapman explains — "as Ernest Lawrence would later say, if an atom was the size of a cathedral, the nucleus was a fly. Lawrence didn't mention that it would have to be an insanely dense mutant fly that made up 99% of the cathedral's mass." Nevertheless, the most difficult part comes after that: any superheavy atom formed then needs to escape the target, be successfully separated from any other products that may have also been created, carefully collected and characterized. The characterization in itself is also a rather peculiar process. All of the elements heavier than 101 were first identified by their decay chain; this means that information is captured as the desired element decomposes, and its identity is deduced retrospectively once it has fizzled out of existence. In an In Your Element essay, superheavy-element hunter Yuri Oganessian — who lends his name to element 118, oganesson, which sits in the very last spot on the current periodic table — recounts the creation and identification of one of the other heaviest known elements: moscovium.

In this issue, we feature a Q&A with nuclear scientist Jadambaa Khuyagbaatar about his research at this crumbling edge of the periodic table and what led him down this particular career path. After hesitating between a profession in science and one in sports, he chose to focus on the superheavy (element discovery) rather than the heavy (weightlifting). He explains why, despite their ephemeral existence as a handful of atoms at a time, these elements are worth investigating. Khuyagbaatar invokes, first and foremost, fundamental insight, and points out that there is no guessing what practical advances may result from this work. There are also the technical advances required to handle these elements, one atom at a time, in ultrafast set-ups — a point also made by Hiromitsu Haba in a Comment article published earlier this year about current efforts to make elements even (super)heavier than oganesson.

Beyond expanding the boundaries of the periodic table as it currently stands, studying these short-lived isotopes may well lead to a better understanding of the Universe. We are, of course, inherently limited to viewing the elements from our perspective, restricted by the conditions that exist here on Earth, but some long-lived isotopes of superheavy elements may be produced in astrophysical processes. Studying their short-lived counterparts created in the lab may be a stepping stone to finding such species. In a Thesis essay, Michelle Francl also muses on the importance — and the sheer abundance — of the isotopes contained in the seemingly two-dimensional periodic table. The familiar chart made of the current 118 tiles is indeed very much enriched by some 3,380 identified isotopes.

With the formal recognition of oganesson, the blanks in the familiar framework of the periodic table with its seven periods have now been completely filled. Where will heavier elements fit and how will they alter the structure and the periodicity of the table? In a sense, these questions pertaining to the essence of nuclear structure, atomic shell structure and chemical properties of the new elements aren't too dissimilar to those posed in the early days of the periodic table and throughout its evolution. We admit that we don't find this one bit boring, and very much look forward to further developments at the very edges of this iconic chemical chart. ❐

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