**What is an element, and how is it defined in the IUPAC Gold Book?**

By Eric Scerri

This article concerns the IUPAC definition of the concept of an element. Before taking up the current definition in order to suggest an amendment, I will provide a very brief historical review of how our understanding of this central concept in chemistry has developed [1].

As is well known, the idea that all substances are comprised of a few most fundamental parts, or elements, was first discussed by the pre-Socratic philosophers who concluded that the elements consisted of earth, fire, water, and air and that the particles of each of them possessed the shapes of the then known Platonic solids, namely the cube, octahedron, icosahedron and octahedron respectively. When a fifth Platonic solid, namely the dodecahedron, was discovered, a fifth element, known as the ether, was postulated. These elements were thought to exist as underlying principles as opposed to concrete entities that one generally associates with in modern times. This view has sometimes been described as a metaphysical understanding of the nature of the elements.

Moving forward some three thousand years or so, Lavoisier is said to have founded modern chemistry when, among other things, he defined elements concretely to mean the last stage of chemical decomposition of any compound. He also produced his famous list of 33 simple substances, as he called them. This turn away from a metaphysical understanding of elements as principles was enormously productive and contributed to the banishment of alchemy as a viable path to knowledge. Nevertheless, the thinking of elements as underlying principles was never completely forgotten but was only highlighted once again by Dimitri Mendeleev, the leading discoverer of the periodic system. Indeed, Mendeleev went to some lengths to emphasize the need for a dual sense of the concept of an element, namely as Lavoisier’s simple substances but also as underlying principles [2].

Even more surprisingly, perhaps, Mendeleev claimed that his understanding of the periodic system was primarily based on the second meaning of what an element consists of, namely, elements in an abstract sense. In addition, Mendeleev drew attention to the fact that when two simple substances, such as mercury and oxygen, combine to form mercury oxide, the simple substances do not persist in the compound. What persists are the elements as basic substances, which, for Mendeleev, were characterized exclusively by their atomic weights.

It is useful in this sense to make a clear distinction between the conception of an element as a separate homogeneous substance and as a material but invisible part of a compound. Mercury oxide does not contain two simple bodies, a gas and a metal, but two elements, mercury and oxygen, which, when free, are a gas and a metal. Neither mercury as a metal nor oxygen as a gas is contained in mercury oxide; it only contains the substance of the elements, just as steam only contains the substance of ice, but not ice itself, or as corn contains the substance of the seed but not the seed itself [3].

Moving forward to the 1910s, the discovery of isotopes by Soddy and others required a rethinking of the nature of elements. The fact that carbon, to take an example, occurs as three main isotopes of 12C, 13C, and 14C implies that elements could no longer be characterized by their atomic weights. As it later turned out, the required criterion for elementhood was the possession of the same atomic number. The initial reaction from some chemists, such as Fajans, was that the period system had encountered a serious challenge and that it might not survive. Others attempted to expand the existing periodic table to accommodate the profusion of new isotopes that were being discovered, in the belief that they represented genuine new elements.

The eventual resolution to this impasse was provided by the Austrian radiochemist Friedrich Paneth, who returned to Mendeleev’s notion of a dual concept of element [4]. Moreover, the dual nature of elements is to this day enshrined in the IUPAC definition as can be found in the Gold Book. However, we wish to propose that Paneth’s resolution has not been fully embraced in the current definition and that it may be time to revisit the issue. Alternatively, it may be that Paneth’s resolution has become somewhat distorted since he first proposed approximately 100 years ago [4]. The fact remains that the current IUPAC definition differs rather markedly from what Paneth proposed and elaborated upon in an article written in 1931. A philosophically nuanced version of Paneth’s proposal that appeared later was first translated into English in 1962 [5].

Let me now turn to the way that the Gold Book currently attempts to capture the meaning of ‘element’ by way of a dual definition,

1. A species of atoms; all atoms with the same number of protons in the atomic nucleus.

2 A pure chemical substance composed of atoms with the same number of protons in the atomic nucleus. Sometimes this concept is called the elementary substance as distinct from the chemical element as defined above, but mostly the term chemical element is used for both concepts.

The above definitions are rather unclear, since the second one essentially repeats the first one before appealing to “elementary substance,” which is presumably intended to mean Paneth’s abstract sense of an element. We suggest that the abstract nature of an element is not captured by either of the definitions, and we will proceed to explain why such an understanding may still be important.

**Why is the abstract sense of element also needed in modern chemistry?**

It is easy for a modern chemist to dismiss any notion of an abstract understanding of the concept of an element and to consider that we should only think of elements in the traditional sense of the 118 concrete entities that are classified in the current periodic table. Here is why we believe that the distinction made by Mendeleev and, more recently, by Paneth, still has an important role to play, and why it may be appropriate to consider a modification to what is already a dual definition according to the current Gold Book.

First of all, consider what is meant when somebody utters the word “carbon”. Is this name, or that of any other element, intended to mean one particular isotope of the element? Of course, the answer is that it is meant to represent a kind of superposition of all the isotopes of the element. There is no concrete instantiation or any unique case of a concrete atom of carbon in this general sense. This is why the element should also be considered as an abstract entity, as well as the more familiar concrete understanding. Similarly, when somebody utters the word “carbon”, is the intention diamond, graphite, or C60? As in the case of isotopes, the word carbon represents a combination of all three allotropes and cannot be uniquely instantiated by any particular substance. Again, the element carbon is best considered in an abstract underlying sense, which has no specific properties.

Finally, consider the following case, which is very much in the spirit of Mendeleev’s example concerning mercury oxide. When the grey poisonous metal sodium combines chemically with the green and highly poisonous gas chlorine, the result is the white crystalline substance sodium chloride, which is essential for life. Neither the simple substance sodium nor chlorine is literally present in sodium chloride. The simple substances seem to have disappeared. What survives of these two components is the element as an abstract or basic substance, just as their individual atomic weights survive in the compound.

We therefore propose a modification to our current definition of element that is more in keeping with Paneth’s suggestion, namely,

I suggest that we should use the term “basic substance” whenever we want

to designate that which is indestructible in compounds . . . and that we should

speak of a “simple substance” when referring to the form in which such a basic

substance, not combined with any other, is presented to our senses [5].

The reader may well think that this talk of the need for abstraction and a second definition is unwarranted since we now consider that the macroscopic behavior of elements is governed by the movement of atoms and molecules, which are unobservable but which one would still not wish to describe as abstract. Needless to say, the literal existence of atoms and molecules was a matter of debate at the time of Mendeleev. This might be taken as a reason why Mendeleev appealed to a mysterious-sounding notion of abstract elements. As a matter of historical fact, Mendeleev is known to have objected to the existence of atoms, as many authors have pointed out [6].

On the other hand, Paneth was writing in the 1930s, by which time the reality of atoms had become well-established, as had the usefulness of quantum mechanics in providing fundamental explanations for chemical phenomena. Indeed, Paneth was a personal friend of many of the pioneers of quantum theory, including Niels Bohr. Furthermore, Panth was involved in the research in which Bohr used quantum mechanics to supposedly predict whether the yet undiscovered element 72 would be a rare earth or a d-block element [7].

The point I am making is that the dual definition of the word “element” was never intended merely to distinguish between macroscopic samples and their underlying atomic components. Instead, it was intended to refer to the one single aspect that is preserved when an element, as a simple substance, reacts with one or more other elements, also as simple substances, to form a compound, namely its atomic number. The notion of abstraction that Mendeleev and Paneth subsequently stressed, and which has been the focus of much attention in contemporary philosophy of chemistry, is not simply a matter of the reduction of macroscopic phenomena to their fundamental components. It is a question that is independent of that of reduction to unobservable entities, in the same way that it is independent of the realism versus anti-realism debate, as to whether microscopic entities such as electrons and protons truly exist. It is rather a question of the remaining need to consider abstraction and the role of metaphysical suppositions, even if we can explain virtually everything in chemistry by appeal to the microscopic components and accompanying theories, such as quantum mechanics.

To return to the question raised in this article, the precise wording of any modified definition of the word “element” remains to be formulated, and we believe, should make reference to their abstract sense as discussed above. Finally, the author welcomes suggestions from readers, including chemical educators, as to how this might best be achieved.

**References and further reading**

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2025. See chapter 4 on the discovery of hafnium.

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