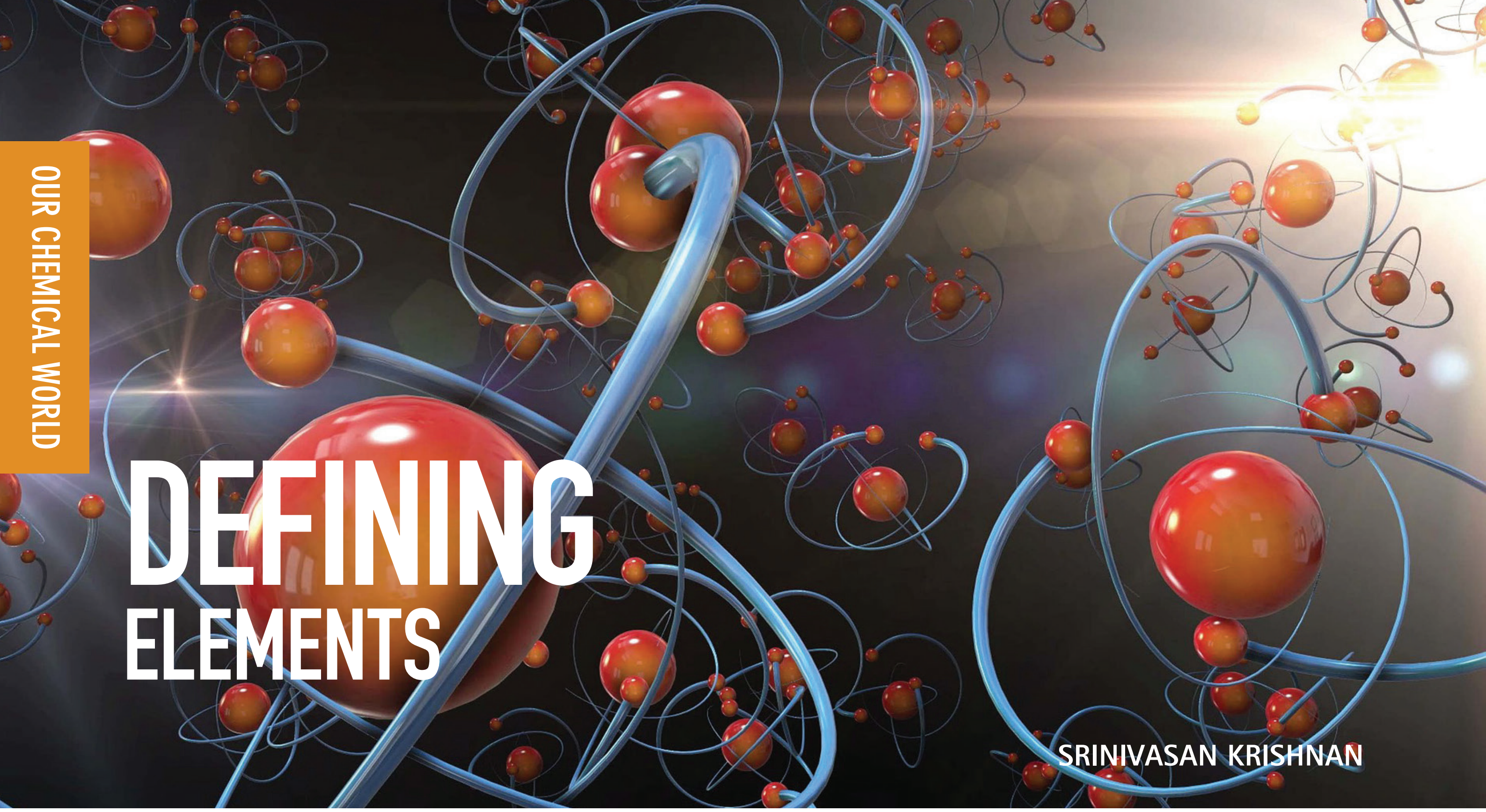


DEFINING ELEMENTS

SRINIVASAN KRISHNAN

When do we call a substance an element? How is the concept of an element linked to that of an atom? Are atoms real? Why are our definitions of elements prone to ambiguity and change?

We use our senses to observe the different substances that make up our world. And we use our powers of deduction and inference (dependent largely on existing technology and the robustness of intellectual structures) to discover new substances and categorize known ones in ever more suitable ways.

This inquiry into the world of matter also aids in the synthesis of new substances. From antiquity, humans have displayed the ability to make new kinds of substances by a combination or distillation of existing ones. Everyday examples of this ability include cooking a dish, mixing medicines and beverages, constructing buildings and tools, and so on. Our quest to make ever more complex substances and systems with 'desired' properties is based on our ability to answer the question—what are the basic substances out of which all other substances are made?

The idea that all substances on earth may be made up of the same unique and fundamental building blocks is not new. Many ancient civilisations have imagined the existence of these element-like substances (see **Box 1**). Some of them have also defined these 'elements' in terms of 'atom-like' indivisible particles (see **Box 2**). This suggests that the concepts of elements and atoms were inextricably linked in the ancient world. This understanding has evolved over time. Today, we classify 92 naturally occurring substances as elements and are artificially synthesizing many more (with atomic numbers greater than 92). This is possible only because our understanding of the relationship between atoms and elements is now robust enough to allow such creation. However, chemists still recognise a certain lack of certainty and precision with both these concepts that is rarely communicated in textbooks and other educational resources for teachers and students.

Box 1. Elements in ancient civilizations:

While many ancient civilizations believed in the existence of elements, there were differences in what each civilization classified as elements. For example, the ancient Greeks believed that there were just four elements—earth, air, fire, and water. The ancient Indians suggested an additional element—ether. The Chinese had a slightly different list of elements—earth, fire, water, wood, and metal.

Box 2. Atoms in ancient civilizations:

Many ancient civilizations believed that elements were made up of indivisible particles, similar to the concept of atoms. For example, Kanada, the founder of the Vaisheshika school of philosophy in the 6th century BC, suggested that all matter was composed of 'atoms' of four basic kinds, each corresponding to one of four elements—earth, water, fire, and air. He assigned different properties to the different kinds of atoms, and described complex rules to determine how they combined to produce all known substances. The Buddhist, Jain, Islamic, and Greek schools of thought also constructed the concept of atom-like particles as being the smallest units of elements, and the origin of all matter. While each school described these particles and their properties differently, all of them believed that these particles were eternal, indestructible, indivisible; and that particles of one kind were identical.[1]

Are atoms real?

The idea that elements are made up of atoms has had immense importance in the development of modern science. As the physicist Richard Feynman once wrote, *"If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world if just a little imagination and thinking are applied."* However, one could argue that atoms may not be real. After all, they are too fast and too small for us to 'see' them even under regular microscopes. Then why have we continued to believe in their existence? And how do we know that elements are really made up of such particles?

In 1905, Albert Einstein, then an unknown physicist working at the Bern patent office, was studying the second law of thermodynamics. At this point in time, the 'material existence' of atoms and molecules was the subject of a heated scientific debate. While some scientists, like the physicists J. Willard Gibbs and Ludwig Boltzmann, argued that heat was the effect of the non-stop agitated motion of atoms; other scientists, like the physicist Ernst Mach and the physical chemist Wilhelm Ostwald, denied the existence of such particles. It was in this year that Einstein published a path-breaking paper that offered unequivocal evidence for the existence of atoms and molecules. He recognised that any particle that was immersed in a bath of atoms/molecules would model the behaviour and kinetics of a large atom/molecule. Thus, using a microscope to observe pollen grains in water, Einstein showed that their Brownian motion would only be possible if the drop of water was made up of molecules. In the absence of such molecules, the suspended pollen grains would either bob in the water or move smoothly in different directions as the water jiggled and moved about. This was not the case—the pollen grains moved as if they were being randomly hit by other particles.[2] These other particles could only be molecules of water (see **Box 3**). That Einstein received the Nobel Prize in Physics in 1921 for this explanation reflects its significance for the scientific community.

But it is only since the 1980s that we have come close to seeing individual atoms.[3] The invention of scanning tunneling microscopes (STM) in 1981 has allowed us to map atomic positions on any surface through changes in current caused when its tip or probe encounters an atom.[4] In 2018, David Nadlinger, from the University of Oxford, photographed a single strontium atom that was illuminated by a laser beam.[5] In 2021, David Muller at Cornell University in Ithaca, New York, used an electron microscope to capture the highest-resolution image of an atom that we have so far.[6]

When do we call a substance an element?

Textbooks offer a variety of 'precise' definitions of elements. Surprisingly,

Box 3. 'Seeing' atoms indirectly through Brownian motion:

Put some pollen from a grass flower into a drop of water, and observe using a microscope. If the size of the pollen is right (neither too heavy nor too light), you will see it move or jiggle in a random manner as opposed to showing a continuous smooth motion. This random movement is called 'Brownian Motion', after the botanist Robert Brown who first described it (in 1827).

A harder experiment to conduct is to shine a bright light through some smoke particles captured in a glass cell and observe this through a microscope. Amidst swirling masses of smoke, one may occasionally spot smoke particles (that look like bright spots of light) showing Brownian motion.

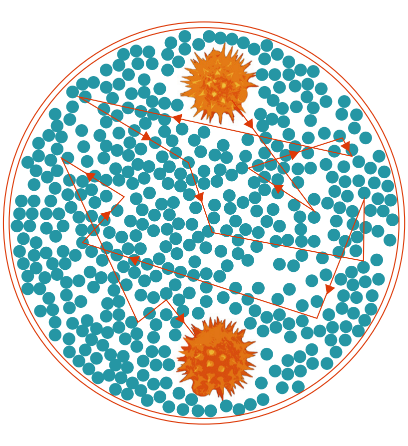


Fig. 1. The random motion of pollen in water is a result of the Brownian motion of the molecules of water.

Box 4. Dalton's atomic theory:

Dalton combined ideas proposed by many other scientists, including Cavendish and Proust, into a theory that could be measured and tested. This theory included five propositions:

1. All matter is comprised of tiny, definite particles called atoms.
2. Atoms are indivisible and indestructible.
3. Atoms of the same element have similar properties (like shape and mass) but are different from atoms of other elements.
4. The atom is the smallest unit of matter that can take part in a chemical reaction.
5. Atoms of different elements combine in fixed whole-number ratios to form compounds.

however, chemists are yet to arrive at an unambiguous, concise, and comprehensive definition for elements. Some of their challenges are related to nomenclature. For example, all of us may agree that oxygen is an element. But what do we really mean by that? Are we referring to an isolated oxygen atom or molecular oxygen gas or triatomic ozone? Or does the term 'element' refer to all of them?

More important challenges are related to our lack of certainty about whether what we call an element today will be broken down into more 'basic' substances in the future. For example, one common definition is that an element is 'a substance that cannot be decomposed into simpler substances'. This means that if a substance X can be broken down into two or more different substances, which when recombined produced substance X, then X is definitely not an element. This was one of the first useful definitions because it allowed scientists to identify what was **not** an element. It is, however, impossible to use this definition to conclusively prove that a substance is **really** an element since our ability to decompose a substance depends largely upon the technology and methods currently available to us. Thus, there is always a possibility that a substance that is not decomposable now may become decomposable when more advanced technologies and methods become available. Another, more useful, definition suggests that an element is 'a substance composed of identical atoms'. This definition was one of the cornerstones of John Dalton's atomic theory, published in 1808 (see **Box 4**). The observation that 'elements' always combined in whole number ratios to form new substances convinced Dalton that they were made up of singular building blocks. He reasoned that if atoms did not really exist, the ratios in which elements combined would be random.

Both these definitions were made obsolete by the discovery of isotopes. This discovery showed that some substances that had been previously classified as 'elements' (because they were believed to be non-decomposable) could decompose (naturally or on bombardment with charged particles in a nuclear reactor) into isotopes. The isotopes of an element differ from each other in their physical properties and can be recombined to produce the original sample. If we were to accept the first definition, such elements would be classified as compounds. Again, contrary to Dalton's definition, the atoms of isotopes are not identical—they differ in their mass (due to differences in the number of neutrons) and often in the physical properties of the substances they form (see **Box 5**). Thus, if we were to accept Dalton's definition, each isotope of an element would be classified as a separate element.

The modern era of chemistry started around 1789, when the 'father of chemistry', Antoine-Laurent de Lavoisier (1743-1794), attempted to classify elements. Lavoisier defined an element as a substance that could not be further divided by any known method of chemical analysis (see **Box 6**). This very precise definition is remarkable because by restricting it to substances that were indivisible by 'known methods of chemical analysis', it seems as if Lavoisier was acknowledging the possibility that other methods (which would come to be known only about 150 years later!) could succeed in further decomposition. It may also be interesting (and amusing) to note that Lavoisier included all those entities that he could not split using chemical means in his list of elements. This included light, heat, and metal oxides. It was only with the widespread use of the electric current in the 19th century that metal oxides were found to be decomposable. Since light and heat are not substances, they are no longer classified as elements.

Advances in many fields of science, including nuclear physics and astrophysics, in the 19th and 20th centuries, have provided clear evidence that all known elements are made up of atoms. We also know that atoms are made up of three stable particles—positively charged protons, neutrons with no net charge, and negatively charged electrons. And that protons and neutrons are bound together in

Box 5. Ordinary water and heavy water:

Ordinary water has the common isotope of hydrogen, with one proton in its nucleus; while heavy water has Deuterium, an isotope of hydrogen with one extra neutron. A mole of heavy water is significantly heavier (2 g) than ordinary water, its freezing point changes to 3.8°C, and it is about 11% denser than ordinary water. Isn't it amazing that the presence of a single extra neutron causes such a difference in properties? Due to its unusual properties, heavy water is extensively used in nuclear reactors to absorb neutrons (or as a neutron moderator).

the dense inner core (or nucleus) of the atom, which is surrounded by orbiting electrons that fill most of the volume of an atom. With this knowledge in mind, we arrive at what may be a more accurate definition of an element: 'An element is composed of atoms of one kind, all of which have the same number of protons (called its atomic number)'.

Box 6. How do we know if a substance is likely to be an element, a compound or a mixture?

If you were to put two graphite rods or thick pencil leads into a glass of tap water and connect these rods to an 18V battery, you would see bubbles (of gas) arising at both electrodes. The two gases can be easily collected in separate test tubes. We know from textbooks and other reference materials that these gases are the elements hydrogen and oxygen, but how do we prove this experimentally?

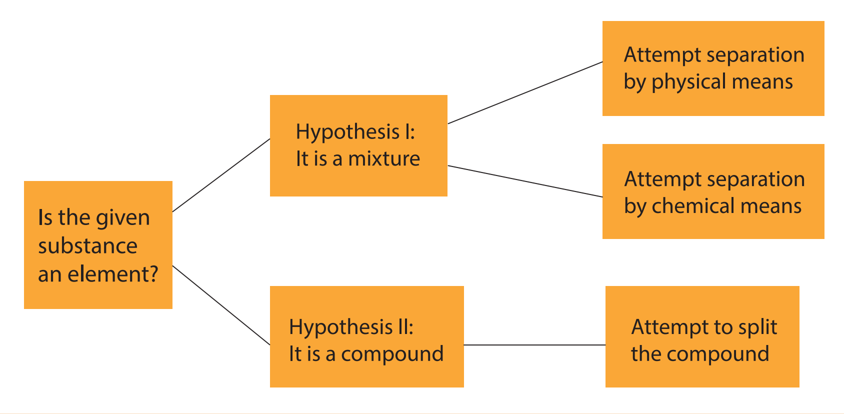


Fig. 3. A flow chart showing a possible scheme of investigation when you encounter a substance that is new to you.

Take oxygen for example. Let us start with the hypothesis that it is a mixture of two or more gases. Assuming that we can use all known gas separation techniques, there is a high chance that we would be able to separate it into these gaseous components by at least one of these techniques. This would provide experimental evidence that oxygen is not really an element but a mixture of gases. In reality, however, we would have only managed to separate the different isotopes of oxygen, all of which are very similar to each other in their physical and chemical properties. This does not eliminate the possibility that our inability to separate oxygen into other gaseous components may be due to the absence of sufficiently advanced technology.

Our inability to separate oxygen into other gaseous components by current separation techniques may also be because these gaseous components may have similar physical properties, like weight. This leads us to the possibility that they may differ in their chemical properties. If so, one way to separate the oxygen mixture would be to set up reactions between oxygen and specific quantities of pure alkali metals, like sodium and potassium. If even one of these reactions yields two or more compounds that we can clearly distinguish by their physical (like sight, smell, or touch) or chemical properties, it would prove our hypothesis. It would be best to avoid using transition metals for such reactions—due to their different oxidation states, even if oxygen were an element, such reactions would result in the formation of more than one compound.

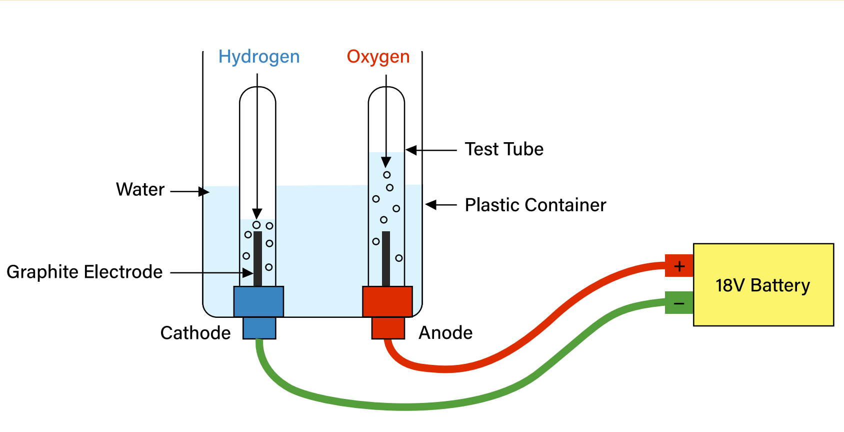


Fig. 2. The electrolysis of water: oxygen and hydrogen gases collect in the test tubes.

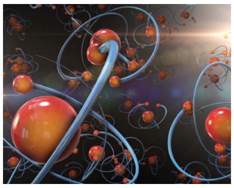
Another way to test this hypothesis would be to obtain oxygen from other sources, like by heating mercury oxide or some nitrates. If this reacted with the hydrogen obtained from our initial experiment (with the graphite rods) to produce water (and this is what really happens), then the simplest explanation would be that oxygen is not a mixture of gases. Whew! That is a lot of work just to show that a given substance is not a mixture!

This does not, however, eliminate the possibility that oxygen is a compound. Testing this possibility is a lot more complicated because we do not, at present, have the tools to split this compound chemically. Till such tools are developed and oxygen is decomposed, the possibility that oxygen is a compound cannot be eliminated. Also, once oxygen is decomposed, its components will be regarded as elements till we find an appropriate method to split them further. Since neither of these has occurred yet, we continue to believe that oxygen is an element.

Parting thoughts

While the concepts of atoms and elements are fundamental to our understanding of chemistry, they do not have clear unambiguous definitions. Instead, many textbook definitions represent stages in our understanding of each of these concepts and their relation to each other. Teachers often assume that students are familiar with the limitations and uncertainty of these definitions or will figure these out by themselves with time. However, what is likely to be less confusing is for teachers to trace the history of these evolving definitions, communicate the conditional nature of their validity, and encourage an exploration of the kind of developments that could make our best definitions in the present seem inadequate or flawed in the future.

Key takeaways



- Our ability to make more complex substances and systems with ‘desired’ properties depends on our understanding of elements and atoms.
- Our evidence for the material reality of atoms and our understanding of their subatomic structure has evolved with new advancements in technology.
- Our definitions of elements evolve with the techniques of separation available to us and the methods we use to test the purity of a sample.
- Teachers and textbooks rarely communicate the uncertain nature of common definitions of elements.
- Tracing the history of evolving definitions of elements could be useful in communicating the conditional nature of their validity to students.

◆

Notes:

1. This article is derived from a longer article first published in i wonder..., Feb 2017, pg. 84-94.
   URL: https://publications.azimpremjiuniversity.edu.in/1267/1/16_THE%20ORIGINS%20OF%20ELEMENTS.pdf.
   This version has some additions (by the editors) to update it and to make its connections to middle school science more explicit.
2. Source of the image used in the background of the article title: Chemistry. Credits: tommyvideo, Pixabay.
   URL: https://pixabay.com/illustrations/atoms-molecule-chemistry-science-5064796/. License: CC0.

References:

1. See ‘The Atom in the History of Human Thought’ authored by Bernard Pulman and published by Oxford University Press (1998) for a more comprehensive account.
2. See an accurate motion picture of Brownian motion here: https://en.wikipedia.org/wiki/Brownian_motion.
3. Watch Sam Kean take us through the nearly 2,400-year quest to see the atom in this episode of Reactions' "Legends of Chemistry" series: https://www.youtube.com/watch?v=ipzFnGRfsfE.
4. Watch Olivia Gordon, from SciShow, explain how the Scanning Tunnelling Microscope allows us to see individual atoms in a sheet of metal: https://www.youtube.com/watch?v=S-M7JjYCITY.
5. See David Nadlinger’s award-winning photo of a strontium atom and read about how he took it: https://www.ox.ac.uk/news/science-blog/image-strontium-atom-wins-national-science-photography-prize.
6. See David Muller’s image of an atom and read more about it here: https://dug.com/behold-the-highest-resolution-image-of-atoms-ever-taken/.

Srinivasan Krishnan has a PhD from The Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune in the field of semi-classical quantum gravity. He has taught science at the Centre for Learning (CFL), Bangalore. His other interests include design and technology, electronics, and reading. He can be reached at: ksrini69@gmail.com.