ANCIENT ANALOGUES OF CHEMICAL EQUATIONS

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Abstract

The symbolizing of chemical reactions with chemical equations goes back to Lavoisier and Berzelius. In Plato's Timaeus, his only dialogue devoted to science which was for many centuries the most influential of his works, we find analogues of chemical reactions which, when written as quantitative constitutive chemical equations, show very clearly that reactants and products are the analogues of molecules. Heisenberg and Bertrand Russell wrote about Plato's reactions, but they interpreted the reactants and products as atoms, and they did not write them as chemical equations. The writing of Plato's reactions in the form of chemical equations shows the power of this modern symbolism even when applied to Plato's analogues of chemical reactions, immediately allowing the modern chemist to see an analogue of the concept of molecule in Plato's geometrical atomism. His theory becomes then the first mathematical theory of the structure of matter at the three levels molecular, atomic and, as will be shown in the text, even sub-atomic, an unbelievable feat 2200 years before John Dalton and Amedeo Avogadro. His theory is also here compared with the atomic theory of Leucippus and Democritus.

The Birth of Chemical Equations

The modern way of symbolizing a chemical reaction with a chemical equation begins with Lavoisier and Berzelius. In William H. Brock's book *The Norton History of Chemistry* (1) we read that in one of his essays Lavoisier wrote:

> In order to show at a glance the results of what happens in the solution of metals, I have constituted formulae of a kind that could at first be taken for algebraic formulae, but which do not have the same object and which do not derive from the same principles.

Brock comments:

> The important point here was that Lavoisier used symbols to denote both constitution and quantity. Although he did not use an equals sign, he had effectively hit upon the idea of a chemical equation. … once Berzelius' symbols became firmly established in the 1830s, chemists began almost immediately to use equations to represent chemical reactions.

We are today accustomed to the happy marriage between algebra and chemistry that allows us to represent chemical reactions with chemical equations.

Plato's Geometrical Atomism and His Reactions

The Greek philosopher Empedocles (ca. 440 BCE) of Akragas, today Agrigento in Sicily, as Bertrand Russell writes in his *History of Western Philosophy* (2)

> established earth, air, fire and water as the four elements…Each of these was everlasting, but they could be mixed in different proportions and thus

> produce the changing complex substances that we find in the world.

In Plato's Timaeus (3), his only dialogue devoted to science, Plato associated the shapes of four of the five platonic solids to the four elements of Empedocles: tetrahedron for fire, octahedron for air, icosahedron for water and cube for earth. Benfey and Fikes briefly discuss the reason for this choice (4). In Timaeus (Ref. 3, 55d, 55e and 56a, on pp 51 and 52), Plato writes:

> We should allocate the figures…to fire, earth, water and air. Let's begin by assigning the cube to earth, because, of the four bodies, earth is the most inert—the hardest to move…we assign the most inert of the remaining figures to water, the most mobile to fire, and the figure that is intermediate in terms of mobility to air; the smallest to fire, the largest to water, and the one in between to air; and the most angular to fire, the second most angular to air and the least angular to water. Of them all, then, the one with the fewest faces is bound to be the most mobile, since it is altogether the sharpest and the most angular of the three figures; and is also to be the lightest, since it consists of the smallest number of identical parts.

Note that Plato had obviously the concept of weight but didn't have that of mass.

Why did he choose the regular polyhedra to represent the four elements? His was an esthetic criterion. We read (Ref. 3, 53a, p 47) that the four substances are "each of outstanding beauty." We also read (54e, p 47) that "there's an infinite number of right-angled scalene triangles" and that the scalene elementary triangle of Figure 1, two of which combine to form an equilateral triangle, is "the most beautiful of this infinite plurality of scalene triangles." Plato then writes four reactions between fire, air and water in which these elements can transform into each other (Ref. 3, 56d and e, p 51), which I write here in Plato's words just adding a numbering in square brackets:

> [1] When water is broken up in its parts…the result might be one bit of fire and two bits of air; and [2] the fragments of air produced by the disintegration of a single bit of air could become two bits of fire. Conversely…[3] two bits of fire combine to make one air-figure. And [4] two-and-a-half bits of air join together into a simple complete water-figure.

Schematically the four reactions are the following:

[1] Water = Fire + 2 Air

[2] Air = 2 Fire

[3] 2 Fire = Air

[4] 2.5 Air = Water

For the modern chemist all Plato's reactions are single-reactant reactions when read from left to right; two of them, the third and the fourth, also involve a single reactant when read from right to left; the second and the third are opposite reactions. If we now consider that the fire is represented by a tetrahedron, which is made up by four equilateral triangles, we can represent it as T_4 where T is the symbol of an equilateral triangle. Likewise we can represent air and water with T_8 and T_{20}. Using these symbols we can write the above four reactions as

[1] $T_{20} = T_4 + 2\ T_8$

[2] $T_8 = 2\ T_4$

[3] $2\ T_4 = T_8$

[4] $2.5\ T_8 = T_{20}$

As reported elsewhere (5), the reaction

$T_{20} = 2\ T_8 + T_4 = 5\ T_4$

is a simple combination of reactions [1] and [2], deduced from Plato's above reactions.

Two earlier attempts at writing Plato's reactions in symbolic terms are described in detail on pp 22 and 23 of Ref. 5. Neither conforms to chemists' conventions for formulae and reaction equations—another demonstration of the power of the correct chemical equations symbolism.

The above equations are impressive: we are looking at the first analogues of chemical reactions in the history of science. They are the analogues of chemical reactions such as

$2\ I_2 = I_4$

$I_4 = 2\ I_2$

$I^- + I_2 = I_3^-$

$3\ O_2 = 2\ O_3$

Notice that while in chemical reactions masses are conserved, here the areas are conserved; see also p 24 of Ref. 5. There is an isomorphism between masses and areas. Of course these are deductions allowed us by our writing the reactions as modern chemical equations, and Plato didn't know the concept of mass. In these reactions the polyhedra play the role of molecules and the equilateral triangles out of which they are made play the role of atoms. But the analogies with modern science may be carried further. Plato considers his atoms, the equilateral triangles making up tetrahedra, octahedra and icosahedra, and the square making up the cube, made up, in their turn, by two kinds of elementary triangles, the equilateral triangle made up by two right-angled scalene triangles and the square made up by two isosceles triangles (Figure 1).

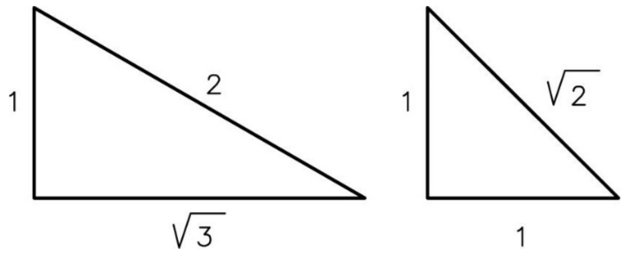

Figure 1*. Plato's elementary triangles, from which the faces of his elements are composed.*

Can we use the term "chemical" equations for the above "reactions"? I believe we are justified to do so because in Plato's reactions the "atoms" are reshuffled but their nature and their numbers remain the same on both sides of the equations, the nature and the number being here the constitution and the quantity considered by Lavoisier.

In so doing Plato is describing matter at three levels, which, in modern terms are analogous to those of molecules, atoms and sub-atomic particles. Plato considers also "atoms" of different sizes (Figure 2). These atoms of different size have been aptly called "isotopes" by Friedländer (6) because isotopes are atoms of the same nature and different mass while here the "isotopes" are made up by atoms of the same form and different areas. By the way, it is not possible to transform tetrahedra, octahedra and icosahedra into cubes because the cubes are made up by a different atom than the other three polyhedral, but it is possible to transform cubes of one size into cubes of a different size (5).

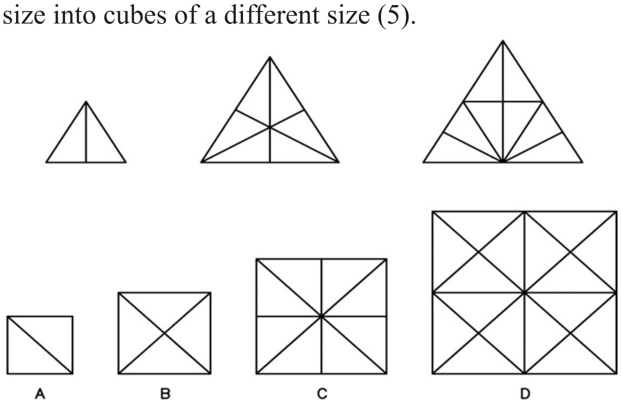

Figure 2*. Graded sizes of equilateral triangles and squares.*

Leucippus's and Democritus's Atomism Compared to Plato's Geometrical Atomism

Probably every student of physics or of chemistry knows that the concept of atom was created by the ancient Greeks Leucippus and Democritus and maybe some also know that they created the concept of void. Russell writes that Leucippus and Democritus "believed that everything is composed of atoms which are physically, but not geometrically, indivisible" and that there was an infinite number of atoms of all possible shapes and size (Ref. 2, Ch. 9). Another character of atoms of the ancient atomists is that they are always in motion, a very modern idea. There were impacts among the atoms

> The only thing that atoms do is to move and hit each other, and sometimes to combine when they happen to have shapes that are capable of interlocking.

We see then that Leucippus and Democritus were the first to create the concept of combination of atoms. The above description of Leucippus's and Democritus's theory is just a brief résumé of the beautiful chapter dedicated to the atomists by Russell with a couple of Russell's quotations. In his opinion "The theory of the atomists, in fact, was more nearly that of modern science than any other theory propounded in antiquity."

Plato didn't have or he didn't accept the concept of void (Ref. 3, 79bc and 80c on pp 81-82). This is not surprising because, as Russell writes (Ref. 2, p. 72),

> Plato never mentions Democritus in the Dialogues, but is said by Diogenes Laertius to have disliked him so much that he wished all his books burnt.

Nevertheless, Plato's geometrical atomism with its limited number of atoms of a well specified nature is closer to our idea of atoms. Moreover Plato introduces the new idea of intertransformability of elementary corpuscles and with that the first chemical reactions of history. His theory is also the first mathematical description of the structure of matter in history and we have seen that mapping his theory in modern terms it appears also as describing the matter at the molecular, atomic and subatomic levels. Of course one may ask why Plato after having introduced his two atoms, the equilateral triangle and the square, considered the elementary triangles described above. This point is discussed in Ref. 7.

Heisenberg compared Democritean and Platonic atomisms (8):

> In the philosophy of Democritus the atoms are eternal and indestructible units of matter, they can never be transformed into each other. With regard to this question modern physics takes a definite stand against the materialism of Democritus and for Plato and the Pythagoreans. The elementary particles are certainly not eternal and indestructible units of matter, they can actually be transformed into each other… . But the resemblance of the modern view to those of

> Plato and the Pythagoreans can be carried somewhat further. The elementary particles of Plato's Timaeus are finally not substance but mathematical forms. "All things are numbers" is a sentence attributed to Pythagoras. The only mathematical forms available at that time were such geometrical forms as the regular solids or the triangles which form their surface. In modern quantum theory there can be no doubt that the elementary particles will finally also be mathematical forms, but of a much more complicated nature. The Greek philosophers thought of static forms and found them in the regular solids. Modern science, however, has from its beginning in the sixteenth and seventeenth centuries started from the dynamic problem. The constant element in physics since Newton is not a configuration or a geometrical form, but a dynamical law.

Moreover, Heisenberg highly valued the introduction of symmetry in Platonic atomism because Plato's atoms are symmetrical objects (9): "In the beginning was symmetry! This sounded like Plato's Timaeus." More recently, physics Nobel laureate Frank Wilczek (2004) wrote about the relation between modern physics and Plato's ideas (10):

> In its symmetry-based standard model, it would appear, fundamental physics comes closest to achieving the vision of Pythagoras and Plato, a perfect correspondence between what is real and what is mathematically ideal.

Heisenberg, Russell and Wilczek Write about Plato's Reactions

The importance of writing down the reactions using chemical equations, that is of using the modern standard chemical symbolism, can be seen if one considers how Heisenberg describes in words the above reactions. In *Physics and Philosophy* he writes (8, pp 68-69):

> If the regular solids, which represent the four elements, can be compared with the atoms at all, it is made clear by Plato that they are not indivisible. Plato constructs the regular solids from two basic triangles, the equilateral and the isosceles triangles, which are put together to form the surface of the solids. Therefore, the elements can (at least partly) be transformed into each other. The regular solids can be taken apart into their triangles and new regular solids can be formed from them. For instance, one tetrahedron and two octahedra can be taken apart into twenty equilateral triangles, which can be recombined to give an icosahedron. That means: one atom of fire and two atoms of air can be combined to give one atom of water.

Heisenberg calls here atoms objects which, as we have seen from the above reactions, correspond more closely to our concept of molecule. Moreover the equilateral triangle, as we have seen from the above reactions, is an atom and not an elementary triangle. For Plato the molecules, not considered by Heisenberg, are made up by atoms represented—we remind the reader—by equilateral triangles which are divisible in their elementary triangles, as modern atoms are divisible in more elementary particles. Thus the two triangles mentioned in the passage above come from different structural levels: the equilateral is a face of some polyhedra, whereas the isosceles is more elementary, from which the faces of cubes are comprised.

Russell writes (2, p 145):

> The true elements of the material world, Timaeus says, are not earth, air, fire and water, but two sorts of right-angled triangles, the one which is half a square and the one which is half an equilateral triangle … By means of these two triangles, it is possible to construct four of the five regular solids, and each atom of one of the of the four elements is a regular solid.

Contrary to Heisenberg, Russell rightly describes the two elementary triangles but like Heisenberg he considers as atoms the objects we consider as more analogous to molecules.

Wilczek follows in their steps titling a section of his book *A Beautiful Question* "Platonic Solids as Atoms." Then, coherently with his considering atoms the polyhedra, he interprets the triangles, which we have seen as Plato's analogues to sub-atomic particles, as the equivalents of "quarks and gluons" (11).

Conclusions

We have here a clear demonstration of the fundamental importance of chemical equations that show constitution and quantity. Heisenberg and Russell would have developed a closer analogy to current chemical theory if they had written Plato's reactions as chemical equations. Wilczek perceptively interpreted Plato's model as having three structural levels, but his analogies are more appropriate to particle physics than to chemistry: atoms, sub-atomic particles, and sub-sub-atomic particles.

References and Notes

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10. F. Wilczek, "Physics in 100 Years," *Physics Today*, **2016**, *69*(4), 32-39; doi: 10.1063/PT.3.3137 . See also Ref. 7.
11. F. Wilczek, *A Beautiful Question*, Allen Lane, London, 2015, pp 46-49.

About the Author

Francesco Di Giacomo is a retired chemistry professor of the engineering faculty of Sapienza University of Rome. He has published articles of experimental electrochemistry, theoretical chemistry, educational chemistry and history of chemistry. In 2020 he published two books on the Marcus theory of electron transfer reactions.

HIST Elections

The following HIST members were elected in the 2022 divisional elections:

Chair-Elect (term 2023-2024)	Joe S. Jeffers
Secretary/Treasurer (term 2023-2024)	Vera Mainz
Councilor (term 2023-2025)	Roger Egolf
Alternate Councilor (term 2023-2025)	David Lewis
Councilor (term 2024-2026)	Mary Virginia Orna
Alternate Councilor (term 2024-2026)	Christopher Heth

As arranged in previous elections, Arthur Greenberg will begin a two-year term as Chair in 2023 as Seth Rasmussen begins a term as immediate past chair. Daniel Rabinovich's term as immediate past chair ends at the end of 2022.

Congratulations to those elected and thanks to those who are and were willing to serve the division.