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The Theory of Four Elements Through History and Its Influence on the Development of Chemistry

Roberto Barbosa de Castilho
Federal Rural University of Rio de Janeiro (UFRRJ), Seropédica, RJ, Brazil

The theory of four elements (or roots) was the first plural attempt to explain life and change and was based on the combination of four different roots that give rise to life and matter. The four elements (fire, air, water and earth) were thought to be the building blocks of all substances. This theory was derived from observation and reason and it might be viewed as a material or substancialist theory. Its development brought important concepts such as equilibrium, proportion and combination to chemistry and medicine. The aim of the present paper is to describe the theory of four elements, its origin and development from Empedocles and Aristotle to Roulle and Beeckman. Although the conception of the chemical elementsin modern chemistry is different from the theory of four elements, that theory was valuable as an intellectual effort to understand nature and transmutation and to conciliate reason and senses, besides being the first theory postulating the pluralism of matter's composition, in opposition to monism. I argue that chemistry has a past and it is important to know the theory of the four elements for its historical value because it can be considered an introductory chapter of chemistry, introducing the concepts of indestructible elements and the proportional combination of them in Western thought.

Keywords: four elements, chemical element, pre-Socratic philosophers, transmutations, Bachelard

The theory of four elements (or roots) was used through the centuries to explain the transformations of substances as well as their changes of physical state. Its history harks back to pre-Socratic philosophers and their cosmologies aimed at explaining the origin of the world and living things. Those philosophers broke with the mythical explanations reigning at the time and formulated concepts based on rationality and observation. Some of them, such as Parmenides (530-460 BC) and Heraclitus (535-475 BC), sought to explain reality based on constructs that ran contrary to the common sense at the time, almost exclusively resting on the senses. These philosophers tried to describe a principle invisible to the eyes, only accessible through thought, that was able to perceive totality. Reality was understood as a unity that could be encompassed by a principle that was not detectable by the senses, but was intelligible. Hence, there was a rupture between reason and the senses. Besides this, the pre-Socratic thinkers postulated that the answers to the great questions of existence could be found by carefully observing nature. For the monists, reality was singular and everything derived from a fundamental principle or material (primitive material). Among them, the philosopher Thales of Miletus (624-546 BC) stands out, for proposing that water is the primordial and fundamental element from which everything else originates. In contrast, for the pluralists, reality is plural and derives from a combination of various fundamental elements.

Roberto Barbosa de Castilho, Ph.D., Associate Professor, Department of Fundamental Chemistry, Institute of Chemistry, Federal Rural University of Rio de Janeiro (UFRRJ), Seropédica, RJ, Brazil.

One of the first pluralists known to history is Empedocles of Acagras (490-430 BC), who formulated the theory of the four elements to explain the generation and corruption of matter: fire, earth, water and air. According to this framework, these four elements are the fundamental roots of all things. They are natural, but innate, immutable, irreducible and imperishable, and are not transformed qualitatively: the transmutation of the elements is not possible in the theory of Empedocles. The material world is the result of mixtures of these four elements in different proportions – like a painter who can generate an infinity of shades by combining the four basic colors. The elements are combined not in the sense of completely mixing two primary colors to obtain a new color different from the originals, but are juxtaposed to produce all substances, like placing stones and bricks beside each other to build a wall, or mixing powders made from different metals.

The elements join to form matter (generation) and separate upon degradation (corruption) by the action of two antagonistic forces, love and hate. The force of attraction (love) is responsible for aggregation of the elements in different proportions and generating the substances, while the force of repulsion (hate) leads to the separation of the elements and degradation of the substances. The continuity of life depends on the equilibrium between these two forces. There is no birth and death, only the union and separation of the primordial elements. The force of love is like a type of glue that keeps the elements harmoniously united. However, the elements do not join randomly, but instead according to mathematical proportions, so as to give stability to the object formed. For example, bones consist of four parts fire (4F), two of earth(2E), and two of water (2W) and no air (0A), while the tendons derive from fire and earth mixed in twice the quantity as water. The "chemical" formula or proportion of the four elements for the formation of the bones might be: $E_2W_2A_0F_4$ (Ierodiakonou, 2005).

Empedocles considered fire to be white and hot, while water was dark and cold. Therefore, the bones are white due to the excess of the element fire. The different colors of objects are a product of the combination of particles of fire with particles of water in different proportions, like a spectrum that goes from white (only the element fire) to black (only the element water). For example, at noon the sun appears to be white, but at dawn and dusk it variously appears to be yellow, orange, pink and red. These colors are produced by the combination of the igneous particles of fire in different proportions with particles of water present in the atmosphere as moisture. The increase of the quantity of water produces all types of colors, until little or no fire remains, leading to dark blue and then black. Yellow is caused by more fire than water, while blue is the result of more water than fire. Blood and flesh are red and contain the same proportion of fire and water, meaning that red is located in the middle of the color spectrum. Eye color can also be explained by the proportion of the elements: brown eyes result from more water than fire, while gray-blue eyes result from more fire than water. The mechanism of vision works similarly: white objects emit small particles of fire that enter the pores that are commensurate with them (regions of the eyes with abundance of fire), and black objects emit a large quantity of particles of the element water, which enter in pores of the membrane that surrounds the eyes – aqueous pores. In the places of the eye containing a high proportion of water, the color is black. The eye pores receive particles of fire and water with certain size, which is different from the particles that other organs receive in their pores. For example, the tongue's pores receive particles of water with different size than received by the eye pores. The eye lens is composed of fire, surrounded by the aqueous part and protected by membranes and tissues. More specifically, the iris is composed of fire and tears are formed of water. The eye functions like a lantern: it issues igneous particles to illuminate the object for observation. We see by similarity of the object being observed (constituted of the four elements) with the different parts of the eyes, also composed of the four elements: "With earth we see earth, with water water, with aether divine aether, with fire destructive fire, love with love, and strife with baneful strife" (Ierodiakonou, 2005).

Empedocles correctly noted that something was preserved in the transformations of matter, which he called primordial elements, postulating the existence of four indivisible ones. For example, water passes from the liquid to the vapor state without alteration of its nature. When moist or green wood is burned, water and smoke (air) are released from the surface, with deposition of ashes (earth) and release of heat (fire) – the most subtle of the elements, which dissipates in the ethereal regions (Renouard, 2018). Curiously, the fire phenomenon depends on air and fuel, i.e., it is not only the fundamental element fire. Therefore, the elements are the fundamental particles that compose living beings and objects. After nearly two thousand years, the idea arrived of the chemical elements (atoms), which are conserved in chemical reactions. Since then, the number of fundamental elements discovered exceeds a hundred, far more than the initial four posited by the ancient thinkers.

Therefore, the principle of all things is not unique, but multiple. Unlike his predecessors, who postulated that reality depended either on an intelligible principle – accessible only via thought – or a sensible one – accessible through the senses, Empedocles sought to integrate the senses in the knowledge of nature, making the operations of thinking and physical exertion compatible, linked to the notions of distance, size and weight. Empedocles can be considered the first "chemist" or the father of a proto-chemistry, because he was the first philosopher to reduce the complexity of the processes of nature and life to a manifestation of basic principles. The alteration of processes and transformation of substances, i.e., the changes perceived by the senses, could be explained by permanent and immutable basic entities (Wright, 1997). The theory of the four elements probably originated before Empedocles, and is often attributed to the Persian prophet and philosopher Zarathustra (or Zoroaster), who lived two centuries before Aristotle. Zoroaster considered the four elements to be sacred, i.e., essential to the survival of all living beings: humans and animals need air to breathe, water to drink, fire to cook food and earth for plants to grow (Habashi, 2000). Empedocles can be seen as a distant precursor of the recent advances in the studies of genomes, combining physics, chemistry and biology to unravel the secrets of life, i.e., to map the DNA sequences and their unfolding. The genetic code is based on variations of a basic alphabet of four letters, corresponding to four nitrogenous bases of the DNA molecule: A (adenine), C (cytosine), G (guanine) and T (thymine), which compose the basic instructions (codification) for the synthesis of proteins – in principle something similar to the four roots of Empedocles (Wright, 1997, p. 163).

The theory of four elements underwent modifications with the passage of time, but still influenced the scientific conceptions for nearly two thousand years. Aristotle (384-322 BC) believed in the theory, but added two important modifications: transmutation of the elements to explain the changes of physical state of matter, and the presence of two qualities in each element, acting as the agents of the transformations. Each of the elements was formed by the union of an amorphous substrate material (the substance) with two of four essential qualities. Today it is known that the formation of liquid water (H_2O) occurs from a chemical reaction between the gases hydrogen (H_2) and oxygen (O_2). During the long era when the theory of four elements was in vogue, the formation of water was explained by the transmutation of one element into another: air was transformed into water. A transmutation was measured by the qualities of the element, which were characterized by different degrees of heat and moisture. Fire is hot and dry, air is hot and wet, water is cold and wet, and earth is cold and dry. While water and air are fluids because they are wet, cold causes water to be liquid and heat makes air gaseous (Weisberg et al., 2016). Dry combined with cold makes earth solid, but dry with hot produces fire. Each element has two qualities, with one predominating over the other: dry in earth, cold in water, wet in air and hot in fire. The transmutation of one element into another occurs by the alteration of one quality by the opposite quality, but while maintaining both common qualities. For example, air can become water by means of moisture and by alteration of the heat: hot → cold. Fire can turn into air when moisture exceeds dryness, maintaining the quality of hot. In principle, any element can be transformed into another, although some transmutations are slower than others. The transmutation of water into fire, although possible, is the most difficult, since it requires the change of two qualities: cold and wet must be overcome by hot and dry. This is slower because it requires consecutive (not simultaneous) alteration of two contrary qualities: first, the dryness of fire must be overcome to form a wet intermediate substance, and then hot is supplanted by cold to form water. Likewise, the heat of fire can be overcome to form a cold intermediate substance, and then dry can be supplanted by wet to form water (Neddham, 2006). Figure 1 depicts the four elements and their respective qualities.

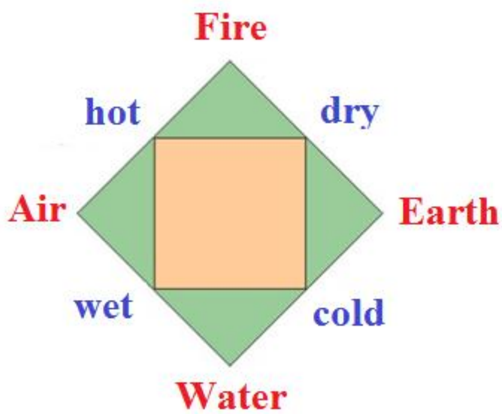

Figure 1. Aristotle’s four elements and their features.

The green figure is a rhombus (or square rotated 45°) and contains the four elements at its vertices (fire, earth, water and air), while the qualities (dry, cold, wet and hot) are placed at the midpoints of the sides, also forming the vertices of an inscribed square (beige). Each element at the vertex of the external square (green) has two qualities arranged along the sides that emanate from it. For example, fire has the qualities: hot and dry. Between two adjacent vertices, the elements share a common quality (on the side that connects the two vertices), which make a transmutation feasible. For example, fire and air. For the transmutation to occur, the quality of the diametrically opposed element must prevail over the other one. For instance, for fire to become air, the wet quality must prevail over the dry and, and the change is possible because both fire and air share the same quality, hot.

The transmutations were macroscopically related to the changes of physical state. However, there was not yet any differentiation between a chemical transformation (alteration of the structure and composition) and a physical transformation (alteration of the physical state). As already discussed, the combustion of water was an incontestable example that matter is formed by four elements: water + fire → air (vapor) + earth (residue). Fire was the subtlest of the elements and tended to diffuse to the ether (upward movement), while earth, being the heaviest of elements, tended to sink to the center of the Earth (downward movement). The four elements theory did not provide the necessary framework to understand that combustion is a chemical transformation, i.e., a chemical reaction of the material with the oxygen in the air (O_2), producing carbon gas (CO_2) and liquid water (H_2O). Since combustion is an exothermal event, there is release of energy (fire). The visualization of the changes perceived by the senses was not sufficient for the establishment of chemistry as a science. A long time passed until the abstraction of the qualities of the senses occurred so as to reach the modern notion of the atom and chemical elements. Nevertheless, as early as the eighteenth century, various chemists tried to revisit the theory of four elements dressed in more mechanistic clothing after the advances in physics of Isaac Newton (1643-1727) and the proposals of Robert Boyle (1627-1691). Even though the theory of four elements had fallen into disuse, the chemists used analogy of contraries to explain the transformation of substances: acids react with bases, electropositive with electronegative, and so on. Qualitative explanations played an important role in the development of chemistry. Besides this, it was shown that the transmutation of a chemical element (atom) is possible through radioactive decay, but that fact demanded the substantial experimental evolution (spectroscopy) and theoretical progress (atomic models) of particle physics.

An important contribution of Aristotle to chemistry is the difference between transmutation (change in physical state) and mixture (chemical combination). Another important contribution is the differentiation between substance (characterized by properties) and element (component of substances). Pure or simple substances are composed of the four elements, which are partially present. This means to say that when one prepares a mixture, the elements cease to exist in the state of true elements, but continue to exist (potentially) while the mixture lasts. For example, when dissolving a small amount of sugar in water and mixing it with a spoon to dissolve the sugar, a homogenous solution is obtained that is no longer water or sugar, or does not have the properties of pure water or pure sugar, although the two pure elements are present and can be recovered by an analysis or chemical transformation, which apparently approaches the concept of chemical element of Lavoisier: the last possible step of a chemical analysis (Bensaude-Vincent & Simon, 2008). On the other hand, the potential existence of the elements can be understood as a metaphysical construct, in which the elements are the basic constituents of matter, but inaccessible to the senses.

Still another contribution of Aristotle is the difference between formation of a mixture, or *synthesis* (agglomeration of parts), and the formation of a compound, or *mixis* (a new substance). When elements form a *mixis* they are transformed into something entirely new, yet those elements still exist, potentially (Leroi, 2017). For Aristotle, hard uniform parts (bone, nails, hooves, horns, etc.) had lots of earth but little water; soft uniform parts (fat, semen, menstrual fluid, etc.) had little earth but lots of water, and flesh is something in between.

Plato (428-347 BC) considered the four elements to be composed of geometric structures and formed a correspondence between each element and a Platonic solid (or regular convex polyhedron): air–octahedron; earth–cube; fire–tetrahedron; water–icosahedron. Therefore, the elements were composed of geometric solids. Polyhedrons with different sizes could generate elements with different properties. For example, depending on the size of the tetrahedron, one can have conventional fire, visible light of various colors, or a type of radiation emitted by the eye as part of the process of vision. Likewise, water and gold are considered elements of water and associated with an octahedron; various forms of "air" are associated with different sizes of octahedrons. These three polyhedrons are formed by equilateral triangles – these in turn are formed by the truly fundamental units: the scalene triangles with angles of 30 º, 60 º and 90 º. For being formed by the same fundamental units, the elements water, air and fire can be transformed into each other. The element earth was associated with the cube, this formed by the junction of squares, in turn formed by isosceles right triangles. Hence, the element earth could not be transformed into any other element (Lloyd, 2007; Restrepo & Villaveces, 2012). Fire, air and water are formed by the same type of triangles, so these elements can interconvert: fire: $2 \times 3 \times 4$ scalene, air: $2 \times 3 \times 8$ scalene, water: $2 \times 3 \times 20$. The sub-elemental particles (triangles) can split up and recombine into other kinds of elements. For instance, an element in liquid form, consisting of 120 triangles, can be broken up into five elements of fire (5×4), or into two of air (2×8) and one of fire (1×4). The earth element is made up of rightangled 4×6 isosceles triangles forming squares. Since the basic triangles making up "earth" (cubes) are dissimilar to those of the other forms of substances, these triangles cannot be combined into any of the other shapes. If a particle of earth happened to be broken up into its constituent triangles, they will drift about – until these parts meet again somewhere, refit themselves together and become earth again.

The association of the four Platonic solids is illustrated in Figure 2. For example, the association of fire with the tetrahedron was explained because it is the polyhedron with the sharpest angles, fewest faces and greatest mobility.

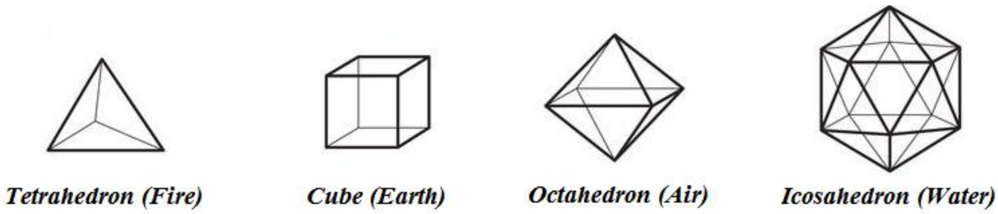

Figure 2. The Platonic solids.

In the eighteenth century, particularly in Germany and France, some chemists revisited the four elements theory with a more operational than metaphysical vision, in the sense of chemical analysis. The German chemist Herman Boerhaave (1668-1738) had a physical view with more emphasis on the agents of changes than the nature of the transformations, and added two instrumental elements to the four Aristotelian ones: *menstrua and vessels*, i.e., the solvents and mortars and pestles, which are the experimental agents of the chemical transformations. In the middle of the eighteenth century, the French chemist Guilleaume-François Rouelle (1703-1770), based on the ideas of Boerhaave, proposed the existence of the four natural elements (fire, earth, water and air) and two more artificial elements (solvents and laboratory glassware used to carry out chemical reactions). Rouelle attributed a dual function to the elements: they were the constituent units of a mixture responsible for conserving and transmitting individual properties through chemical changes, and the instruments of chemical reactions. The elements of Rouelle were individual, indestructible and radically invisible – never isolable. They were only accessible through the laboratory operations – circulating from one mixture to another through displacement reactions. They were defined by operations (reactions and manipulations) of nature and in nature (Bensaude-Vincet & Lehman, 2007).

The theory of Rouelle, which became known as the element/instrument concept, proposed the existence of an elemental function (the four elements occurred either fixed in a chemical combination or were free in an uncombined state, in an aggregate of parts), and an instrumental function (physical operations). This distinction was fundamental for chemistry to start to have an internal coherence (fundaments of chemical composition) and to set it apart from the mechanical philosophies of the era. Rouelle differentiated the chemical from the physical behavior of matter, i.e., he believed that the properties of bodies in an aggregated state were different than the properties of the individual particles that formed the aggregate. The distinction between the singular and aggregated states was based on the concept that each element could be present in two forms: free of combination, i.e., in an aggregated state where only similar particles were gathered, or in a fixed state in which particles of different types were combined. The definition of element followed the Aristotelian tradition in which it was not possible to isolate an element in a material reality. The only way to decompose a mixture containing only two principles was to offer another mixture that could exchange patterns with those of the first mixture. Although following the metaphysical tradition of the elements, Rouelle's theory incorporated materialities of composition, and thus materialized the chemical element. He even coined the expression. "crystallization of water" to differentiate the chemical role from the physical role of water. Rouelle distinguished the chemical element (that in combination) from the physical instrument (elements in the free state), and also the "chemical fire" (phlogiston), that which increased the weight of calcinated metals, from the "physical" fire – the sensation of heat (Siegfried, 2002).

The four elements theory also influenced ancient medicine since the time of the famous Greek physician Hippocrates (460-370 BC). According to this thinking, the human body contains four basic humors: blood, yellow bile, black bile and phlegm. Disease results from an imbalance of the humors, while health depends on their proper balance. In the second century, the physician Galen (130-201 AC) believed that foods consisted of basic elements, which after the digestive process turned into the four humors. According to this framework, each humor corresponds to an element and also to two qualities. Blood is hot and wet and corresponds to air; yellow bile is hot and dry and corresponds to fire; black bile is cold and dry and is related to earth; and phlegm is cold and wet, so it is associated with water. When there is too much or too little of one humor in comparison with the other three, diseases occur. The treatment then involves ingesting certain foods and beverages, or through bloodletting and emetics, aiming to correct the imbalance of the humors.

Thus, the theory of four elements had an important influence on the diagnosis and treatment of diseases in ancient times (Applebaum, 2000; Renouard, 2018). Health was thought to depend on the proper balance among the humors and was maintained by a fire in the left ventricle of the heart. The heat generated by this fire was dissipated by respiration. The theory of four humors persevered until the sixteenth century, when it yielded to the discoveries achieved by the microscope and other advances in physiology. In particular, Marcelo Malpighi (1628-1694) discovered that blood is not a mixture of the four humors, and instead consists of plasma and a countless number of particles and red cells (Ling, 1984, pp. 3-4).

Isaac Beeckman (1588-1637) argued that the four elements (earth, water, air and fire) constitute four types of atoms which can combine to form an aggregate (*homogenea physica*) or molecule. Each molecule is composed of specific numbers of each atomic species, arranged in an equally specific spatial structure. The atoms of an element are not identical to each other and can vary geometrically in form and magnitude – each property has values varying from a minimum to a maximum. The atoms of Beeckman are the building blocks of matter and the ultimate causes of the observable properties of all substances (color, taste, smell, etc.), not unlike the modern concept of atoms. The variability of each substance is caused by the small differences of form and magnitude of atoms of the same element. The molecules are composed by the four types of atoms (elements), which are bonded and characterized by specific numbers of atoms and specific spatial arrangements. As the structure of the molecule changes, a new type of substance is produced, which clearly points to a property called spatial isomerism. Beeckman compared the atoms with equilateral triangles and the regular polyhedrons that can be constructed with them: tetrahedron (four), octahedron (eight) and icosahedron (twenty). In the same way, atoms are unable to give rise to anything since they can only constitute discrete kinds of molecules, representing discrete substances. A mixture is formed by two or more pure substances (Kubbinga, 1988).

Gaston Bachelard (1884-1962) did not consider the theory of four elements to be scientifically viable, because it did not lead to refinement, questioning and formulation of experiments: "the first impression is what remains." For him, to undertake scientific investigation it is necessary to continually reformulate the first experiment, and each new finding should be the result of another experiment (Bachelard, 1953). According to Bachelard, there is no continuity between the four elements theory and modern chemistry, but rather an epistemological break. With respect to the present concept of chemical element, there is a duality of meaning, recognized by renowned specialists and the IUPAC (International Union of Pure and Applied Chemistry): empirical and abstract (metaphysical). The chemical element can be understood as a simple substance, characterized by an empirically verifiable macroscopic property (atomic weight), or as a fundamental building block, characterized by an atomic number(an abstraction). The modern chemical element was defined, after the works of Boyle, Lavoisier and Proust, as the limit of the chemical analysis, where it is no longer possible to find more fundamental blocks. On the other hand, the periodic table of Mendeleev contains abstract chemical elements, which can be characterized when combined with other elements, but not as fundamental blocks. They are thus metaphysical elements in the sense that they cannot be readily verified by experiment.

Conclusion

The theory of four elements influenced chemistry and medicine over the centuries. It constituted the first plural proposition to explain the very structure of matter, i.e., the four elements are the building blocks of everything.

The failure to criticize facts and inferences that underpin the theory and then propose new or innovative experiments are the main problems with this theory. Ideas like equilibrium and proportion of combination are the main contributions of the theory of four elements. It was not the precursor of modern chemistry, but a wrong theory is better than no theory at all. Today, we know more than a hundred chemical elements, so the roots of Empedocles are very different from the present chemical elements. Psychologically, it is quite unreasonable to postulate that matter is composed of more than a hundred elements. The easiest way to speculate about the composition of matter is to begin with one or four elements. Our perception is not prepared to deal with hundreds of elements at once – therefore, we need mathematics. The concept of the chemical element has evolved from the simplest (one, four...) to the more complex (more than a hundred) by combining new experiments with new theories. Even considering the epistemological rupture of the four elements with the modern chemical element, we might say that the theory of four elements was important to ancient chemistry and gave us fundamental concepts like combination, proportion and balance.

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