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Foreword

This book aims to observe the evolution of chemistry as a science. Its main goal, however, is not to give the reader a regular popular science account of the history of chemistry. The history of chemistry is only intended to serve as a background material for the analysis of problems which emerge at the intersection of the history, methodology and philosophy of science, presented in the format of popular science. These questions concern the nature of science, the preconditions for the emergence of science, its timeline, the rules and regularities of the development of science.

The goal of popular science literature is to interpret the advances of a particular scientific discipline for the general audience in a language that is more accessible and captivating to a wider readership. This book does not belong to this genre. Indeed, what we have at hand is actually not a clearly defined scientific discipline with advances recognised by specialists. Yet, the questions which we intend to tackle should be of interest to a truly wide readership, anyone and everyone who is curious about the history and development of human cognition. It is the intention of the author of this book to demonstrate that the traditional view of the history of science and many of the related commonly held perceptions, such as the birth of the scientific way of thinking already in the antiquity, application of the standards of modern science and culture to alchemy, discarding of the phlogiston theory as unscientific, etc., are unfounded.

Why the choice of chemistry as an illustration of the general problems in the evolution of science? One of the reasons is certainly the author's familiarity with the field. However, it is not the only reason. Chemistry holds a special place among the branches of natural science: on the one hand, it is an exact science like physics, but on the other hand, it is rooted in natural history, much like biology. Therefore, chemistry is a perfect example of a science in which to observe the preconditions and development of an exact science. From the history of physics, in that sense, we can learn less, since the material of "inexact" sciences offers almost no "resistance", whereas in the case of biology it is too substantial.

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Tartu
18 April 1981

Introduction. Which bias should we want to proceed from?

It is a strange question, one should think, that has been posed in the title of introduction. Why should it be desirable to be biased at all? It is the hard facts and the history of science that we should trust, not any preconceived ideas. But is there such a thing as a truly "hard" fact? How to be certain that what we know accurately represents the historical reality? We must have a certain premise, a basis, a spotlight to help us find, see and understand the events of the past. This, in a sense, is already what implies the necessity of a bias. That is why we have asked *which* bias (read: assumption, preconception, premise) should we want to proceed from.

If it is our goal to examine the mechanism by which science emerges and evolves, specifically in the case of chemistry, we must already have at least some kind of an idea what science is. This preconceived idea determines what we consider as relevant to science in the humanity's past, what we regard as the necessary conditions leading to the emergence of science, including the moment of its inception and the periods of revolution in its evolution. If we take the science of chemistry simply to mean the body of knowledge regarding the phenomena what we today call chemical reactions, we will be able to trace its beginnings to the moment of the first use of fire by the early hominins of the Lower Paleolithic. Making fire and cooking food are most certainly chemical processes! In that case, science would appear and develop concurrently with the human consciousness.

Most accounts of the history of chemistry indeed begin with the Paleolithic and show that practical chemistry is at least as old as humanity. What we identify as the birth of chemistry as *a science*, and the circumstances leading to such a development, however, depend directly on our preconceived notion of science. What is paradoxical here is that it is a rather common preconception that it is possible to have an unbiased perspective! That is indeed a rather biased view in the negative sense of the word, by which we mean an unobjective and unreasonable approach, the one that simply looks past the important facts that concern the phenomena that interest us, let alone allows us to notice the important relationships.

The thing is, such an "unbiased" perspective will probably have assumed some unquestioned commonplace truth as its premise. It is only to be expected that we have no chance of noticing any new events or facts if we lack altogether any kind of prior knowledge, a certain kind of thinking, a logic of thinking. We only see something if we know how to look. And we can only look through whatever perspective we can find in our prior experience. If we look into the past, we should not forget to adjust our perspective accordingly, otherwise what we will see is only present in the past, although in an unfamiliar context, appearing distorted and increasingly unrecognisable as we delve deeper.

Such an "unbiased" approach to the history of science can be encountered in quite a few publications dedicated specifically to the history of science. This is especially common in the popular science literature and school textbooks, where the introductory chapter is certain to include a few colourful stories about the sensationally weird notions espoused by people in those dark ages and yet how, regardless, some genius was already then clever enough to realise or discover the truth, proving these notions false, etc., etc. Unfortunately, they were so much ahead of their time that they were not taken seriously and their revolutionary ideas were also hidden in some sort of weird context... Still, certain things are found to be already discovered and proven in the distant past and those things are then held as the earliest established foundation of the modern edifice of science.

In this book, when we talk of the history of science, we will try to pick a more appropriate bias instead, one that is conducive to a better understanding of history. To be precise, that will indeed be one of our goals, to discuss what should be the proper "apparatus" for observing the progress of science in time and how to interpret its readings, in order to avoid a biased, distorted understanding. Obviously, we will specifically need to articulate and posit our bias first, otherwise its critical assessment will not be possible. Our premise should be such as to illuminate the actual main highway of the real history and keep us from veering off to unimportant side tracks and, most importantly, stop us from building any new roads which would take us farthest from the reality. At the same time, that premise should also include a built-in mechanism to correct its direction on the main highway of history, i.e., it must be self-critical.

Our bias or preconception is the following. Science is not built of single concrete elements, like a building is made of bricks. Science is part of human culture and may emerge only within a certain type of culture, i.e., in the system of material and intellectual human activity. The type of culture is ultimately decided by the mode of production, i.e., the manner in which people earn their livelihood. Depending on the nature of material production, people also produce social relations and the corresponding forms of thinking (Marx & Engels, 2010, p. 98). The way of seeing the world and the logic of thinking develop in the process of sociohistorical practice, correspond to it, are justified, natural, necessary in the light of the practices of the age, etc. Scientific thought and world picture can only arise if the reality of the world that exists for the people can give rise to it. Social consciousness, hence also science as a form of social consciousness, is a reflection of the social being of people, their real lifestyle, their sociohistorical practice.

The reader might feel a bit confused at this point: is the nature whose existence is independent of humans then not this real world, the reality which human beings reflect in their scientific world picture? After all, it is not the nature that changes as the human practice develops, but the human understanding of nature! The history of science reveals to us how the humanity has progressed from the most primitive notions to increasingly accurate and precise pictures of reality. It is only the human consciousness, human thought that develops, not the objective world which it reflects.

If the readers happen to reason along similar lines, they will share the bias which Karl Marx criticised as the position of metaphysical or contemplative materialism (Marx, 1888, p. 533). The world does not appear to people as nature untouched by human practice, but as "humanised" nature, nature that has been inserted into the humanity's historical activity, nature that is "given" and "seen" through practice. The way of thinking emerges and develops not through passive observation of nature, but through the process of practical restructuring. The immediate reflection in thinking is that of practice, not nature. Nature reflects through practice. It has been said, "Nature is earlier than man, but man is earlier than natural science."[1] This observation becomes especially poignant if we consider that Marxist philosophy observes a human being not as an abstract individual, but as a sociohistorical being, the subject of practice.

Before natural science can emerge, the human world must have at first a place for it (necessity and opportunity), type of activity, and the material and intellectual resources necessary for the scientific inquiry of nature. Although nature itself is not a handiwork of humans, its appearance in natural science is nevertheless a human creation: nature makes no science of itself, science must be invented by humans. And science is by far not the only form through which nature is inserted into the human world. The human world can be such that the forms of activity

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[1] This oft-quoted aphorism is credited to our contemporary philosopher and physicist Carl Friedrich von Weizsäcker whose wisdom has been emphasised by Werner Karl Heisenberg in his book *Physics and Philosophy* (Heisenberg, 1959, p. 39).

existing in it are adequately "serviced" by such conceptions of nature which take shape in mythology, religion, art, the so-called common sense, philosophy of nature, or in some other still developing type of cognition.

For instance, it would be entirely wrong to think that a myth is simply pure fantasy or a convenient analogy for understanding the real world, which is derived from the primitive lifestyle of humans because human consciousness and human ability to think were at a rather rudimentary level in their development and therefore humans could not explain the world in any other way. On the contrary, the human world was dominated by mythological thinking because the real world itself existed for people objectively only through their primitive lifestyle that the mythology accurately reflected. Only if we do not know and do not want to know what was the real "mechanism" of a mythologically thinking culture, its type of practical activity, how it made the world appear to the people living in it—only then we can accept as natural the explanation that mythological interpretation is an attempt through analogy to understand the same world which the modern human inhabits and which we now understand as it is thanks to our developed intellect and advanced science. In truth, we must admit that between the human consciousness and the world which exists outside of it, that is nature, lies the human sociohistorical activity. And only through this activity, by virtue of its mediation, the nature becomes a real object of cognition. In other words, the nature becomes the object of cognition in such a manner and to such an extent as it becomes the object of the activity.

Thus, it would have been impossible to create an abstract logical conception of the world in the setting of a tribal society. Namely, the means by which the humans produce the necessities of life, consisting then of hunting, fishing and gathering, were such that the individual's survival was completely dependent on the entire tribe acting as a whole. Of course, the human society as such is always a whole; the human being is a social being and cannot conceivably exist outside of it anyway. However, at first, the early human society was an undifferentiated whole where individual tribe members did not even possess any relative independence. In a tribal society, an individual human being was not yet a productive force on its own. The social relationships that formed the basis of the society in the process of producing the necessities of life—the relations of production—coincided with those of kinship. The division of labour developed naturally according to person's gender and age.

What has been said above, however, indeed means that the tribal way of life renders impossible and baseless such conceptions of things and phenomena, as well as of human beings, which regard them as separate entities, and of such relations between things and phenomena, or of their properties, which would not be the relations or properties of the functioning of the entire tribe. The concrete activity of the tribe, in a sense, replaces the abstract logic, and is a peculiar logic of its own—the logic of real life. To the uninitiated, however, such a logic naturally appears quite unusual and mystical, since things and phenomena, even human beings themselves, are being attributed such qualities and properties, are connected in such a manner, which from the perspective of their own properties and relations appear completely random and illogical. Yet, if we really knew the situation we are dealing with, we would see that it would be mystical instead if an unlikely coincidence happened and, by acting in the manner described above, the tribe stumbled upon the discovery of the objective properties of things and their logical relations. The world of a human being who lives and thinks tribally is as logical as any other real world. The clash with logic occurs only if we do not consider what the real world in that particular case actually was. In other words, what is logical will become illogical only if, instead of the real situation, we see things as we think they should be. And vice versa, what is illogical will become logical if we relinquish our "natural" position and reconstruct the historical reality. Logic which bears no relation to life, which has no practical foundation, has no use—it does not even emerge. For instance, from the perspective of things and phenomena, their properties and relations, it indeed defies logic that Zeus can be at the same time heaven and earth, air, sea and underworld, an ox, wolf, ram, eagle, human, sometimes a bug or even a certain geometrical body. Mythological thinking, however, follows the principle "everything is in everything". The logic (or absurdity) of mythological thinking extends back to the tribal way of life where things and phenomena acquired their meaning only according to the function they happened to fulfil in one or the other specific situation. In myths, the world is seen through tribal traditions. In order to understand the real foundation and logic of a myth through the perspective of a modern person, we would need to understand the corresponding tradition. The myth itself and abstract logic alone are not sufficient. Knowledge of the general type of the activity is also not enough for the reconstruction of a particular myth, its foundation and development, since tribal traditions include numerous purely coincidental relations and random events which have acquired symbolic meanings, which usually cannot be figured out or reconstructed in their particularity anyway. What we can reconstruct, however, is the principle of "everything is in everything", the principle that is indeed founded on kinship as the force that binds the tribe together. The actuality and power of the force are apparent in the living conditions which show that only through the tribe can an individual obtain its means of livelihood and ensure its survival. A phenomenon or object by itself, just as an individual human being, is nothing, with no meaning and of no significance. It only acquires meaning as a manifestation of the tribe's force. Therefore, all phenomena and all objects which are inserted into the life activities of the tribe are expressed as the force of the tribe and are related. Such is the logic of the mythological account of the world.

Thus, the way of thinking, the way of seeing the world of an era is always logical, but the logic is only revealed if we observe it in connection with the historical reality, not the modern world or nature whose logic we assume to know on the basis of our current knowledge. Reality is a historical category which is founded on the sociohistorical practice. If the era's way of thinking appears illogical to us, then it points to the fact that the imagined context of the era, the reconstruction of the reality on whose background we observe that way of thinking is incorrect and does not match the historical reality. Science is also a historical phenomenon. It has not developed from those few pieces of knowledge that are true from the modern point of view and of the research methods which resemble those we use today and which can be found in the mostly weird and illogical world picture of the past. The emergence of science presupposes, first of all, the existence of a specific way of seeing the world and the type of the practical activity that has shaped it.

The way of seeing the world is based on a certain structure of thinking, a system of general concepts or categories, the logic of such a system. Among the prerequisites for the emergence of science are the formation of the categories of thinking characteristic of the sociohistorical practice of a specific era, the development of the logic of the scientific way of seeing the world.

The scientific world picture is founded on the principle of seeing the world independently of the human being, the subject. A scientific world picture leaves no room for mysterious and supernatural forces, no room for the transposition of relations, qualities, factors and behaviour originating in the human consciousness and activity. The world is observed as a world of things and processes and their properties which do not depend on the human will and consciousness (or some kind of overarching will and consciousness, such as God's) and which are governed by objective laws. The laws manifest in the objective forces that can be experimentally verified. The force of a law does not depend on the human component or supernatural factors, does not depend on whether one knows the law's content or not, whether one likes it or not. The laws show what is objectively possible and what is impossible. A law is an objective, important, general, inevitable and permanent relation between phenomena. If we know under which conditions the occurrence of a phenomenon is determined by a law—which can be found out experimentally, there is no mystery about that whatsoever—then we can be certain that whenever these conditions are met, the phenomenon will occur. A law of nature can never be evaded, enforced or repealed; however, it can be used for the benefit of the people. One can, by creating the corresponding conditions, call forth a phenomenon or sometimes also prevent its occurrence. In the eyes of science, the world is an immense testing ground for any conceivable experiment. Experiment is the method by which we coax secrets from nature and make discoveries.

Our contemporary culture is dominated by the scientific way of seeing the world, creating the illusion that it is the only real and natural way, universally applying everywhere and everytime. The past appears different from the present only because the people simply knew less at the time, were burdened by all kinds of unreasonable bias and prejudice, suffered from the paucity of specific data and therefore drew highly erroneous generalisations, and could not obtain accurate experimental facts and make mathematically rigorous deductions. It will never cross our mind that in the past the people's way of thinking might have been entirely different from ours, that their "mistakes" and "bias" might have been what they had been aspiring towards all along. Accurate facts and rigorous deductions might not have been anything they had interest in at all, since these were not consistent with their living conditions, sociohistorical practice and were alien to their culture type.

Thus, the emergence of science and the occurrence of scientific revolutions are, first and foremost, a problem of logic, but not in its abstract form, but as a specific inquiry into the reflection of the humanity's historical practice in our mode of thinking, in the meaning and structure of our general concepts, i.e., the categories of thinking.

I Was science (of chemistry) born in antiquity?

Ancient Greece has often been referred to as the cradle of modern science. Some have even gone as far as to claim that science is conceptualising the world in a Greek way (this is a rather often quoted view of John Burnet, a scholar of ancient philosophy). Indeed, the teachings of ancient philosophers reveal ideas and lines of argumentation which can be easily interpreted as rudimentary approaches to physics, mathematics, astronomy, chemistry, biology, psychology and other disciplines. The most readily available example here would be the atomism of Leucippus (5th century BCE) and Democritus (*c.* 460–370 BCE), which is juxtaposed with the atomic theory of modern chemistry and physics. Erwin Schrödinger (1887–1961), one of the founders of quantum mechanics, has suggested that modern atomic theory merely reprises the ideas of Leucippus and Democritus (of course, referring to the broad concept). A question posed in *The Feynman Lectures on Physics* is: “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?” And the answer Feynman gives is that would be the hypothesis of atomism 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.” (Feynman, Leighton & Sands, 1963, ch. 1–2) If we disregard the notion of the forces of attraction and repulsion that is absent in ancient atomism, this phrase could well have been taken from the teachings of Leucippus and Democritus.

Then again, is it possible to claim that the teachings of nature by ancient philosophers had the same purpose as our modern-day natural science? Did nature represent the same cognitive object for ancient thinkers as it does for us? We will take a closer look at these questions below.

1. What are the origins of the way of thinking in antiquity?

To answer that question (let us recall the notion of "bias" that was explained in the Introduction) we need to explore the way of life in ancient times because the way of thinking is moulded in the course of social-practical activity. In ancient Greece, people lived in city-states—*poleis*. What is a *polis* and what are its implications for understanding the issue that intrigues us?

First, let us take a look at the evolution of the way of thinking in societies without polis. The historically earliest type of social order—the socioeconomic formation, since Karl Marx named the stages of development in the society after geological formations—was primitive tribal society and it was built upon relations of kinship: clan, tribe, family. A primitive tribal society was characteristically permeated by mythological thinking (which was briefly discussed in the Introduction).The primitive social order developed in two directions. One was the development of polis in ancient Greece and its colonies and in ancient Italy, while the other, through the merging of communities, led to the formation of large despotic states of China, India, Egypt, Babylon and others. In these states the former rural communities were essentially preserved, to a varying extent, but they were added a state apparatus, the upkeep of which required collecting various taxes from the communities (for example, in grain). The state justified its existence and exploitation of the communities with the need to organise and manage communal work, which had become indispensable. For instance, in China one of such works that required centralised administration was regulating the flow of rivers to avoid floods and build irrigation systems. Similarly to the period of primitive social order, the entire way of life in such states was oriented to stability, maintaining the present situation, and balancing. The way of thinking also had a corresponding "homeostatic" nature. The ways of living and thinking were traditional and followed the principle of doing and thinking as always had been done and thought; nothing could be changed in the established tradition and independent choices were unthinkable. What happened naturally, what had always been, could not be changed through one's unexpected action. A peasant must farm the land the way he has always done and once he has done all the expected work, all he has to do is wait for the harvest. He cannot accelerate plant growth with unexpected activity, for example, pulling the plants longer, otherwise he might lose the harvest altogether.

Of course, new experiences, observations, and knowledge also accumulated over time. Yet, when observing the traditional ways of life, experiences and knowledge have the nature of nothing other than practical instructions, or prescriptions, if you will. Such prescriptive knowledge-how demonstrated how to practically achieve a goal in a specific field: material production, military activities, politics, etc. It was formed and established on the basis of purely practical profitability, success, and purely practical justification. A typical example of prescriptive knowledge-how is ancient chemistry. (The prescriptive era in the history of chemistry stretched over an extraordinarily long period as chemistry was considered to belong to the "kitchen domain" as late as in the 18th century.)

The centre of ancient chemistry was prehistoric Egypt. According to one version, chemistry was even named after Egypt since the country was referred to by the ancient Egyptian word *chemi*. The reference would entail, for example, the secret "sacred art" of Egyptian priests which enabled them to extract or transmute "noble metals" from compounds, embalm the dead, etc. Also Babylonian mathematics, their precise calendars, forecasting the flooding of rivers, etc. were prescriptive in nature. Prescriptive were also Chinese inventions which later spread to Europe: gunpowder, compass, paper and printing, mechanical clock, porcelain, etc. Prescriptive skill requires precise following of instructions for the very reason that the desired result may not be achieved if anything, even rather insignificant, is done differently. Then again, this very fact—that it is not known what's significant and what's not in the prescription, a slightly different step may lead to a new result, but it is quite difficult to follow the prescription to every single detail, and this inevitably leads to doing things slightly differently—is coincidentally a random source of new prescriptions, a well of some improvement and updating of knowledge and experience, despite the fact that the entire manner of thinking and acting is convulsively against doing differently.

Similarly to the primitive social order, the world picture of traditional and prescriptive way of living and thinking is of mythological type, i.e., all traditions and prescriptions are associated with all-explanatory fantastic factors in a way that questioning this "explanation" or demanding justification of the "explanation" is rendered completely inappropriate and out of question. In terms of the mythological approach, knowledge is as if memory of the world which stores everything that is considered to have happened, that which is the origin of everything. This, however, means that there is no right or reason, no point to think, speculate or conjecture differently because the real world is still characterised only by the narrative of the beginning of things, the memory of the world, in which nothing can be left out, revised or invented. For example, the famous Chinese philosopher Confucius (6th–5th century BCE), founder of the Chinese state religion and philosophy Confucianism, emphasised that he was not inventing anything new and rather conveyed with his teachings the things that had been created in a distant past.

A different way of life and thinking, however, evolved in ancient Greek poleis in the 7th–5th century BCE. With manual work separated from agriculture, navigation, the expansion of trade and financial relations, polis evolved into a centre of manufacture and trading, which had rather active contacts with quite faraway states in the East. Polis was a typical form of slave state. While under the conditions of tribal social order an individual had no active power in the society but assimilated into the clan, the human society and way of living in a polis was already a far more complex organism.

Slaves were the immediate producers of tools for living. A slave was a chattel in possession of a free citizen, as if an object or a pet, “a walking tool”. At the same time, the slave played an important role in the life of a free citizen, serving as a continuance and enhancement of the citizen’s actions. A slave owner was the programmer of the slave’s actions and the slave was the executor of the program. Of course, in the period of antiquity, “invention of slavery” was a great step in the evolution of an individual (and humankind) because in primitive society human activity represented the activity of the clan as a whole. While in the primitive social order the population was governed by the power of the clan as a whole and people were as if “slaves” of this whole, from then on human slaves were governed by human citizens, who formed a new type of a governing whole—the state. The clan as a whole, which subordinated individuals that constituted it, was replaced by polis, in which a slave owner with his slaves had independent power even though he acquired the power only through the mediation of the polis, i.e., he could exist as a slave owner only by being a citizen who followed the laws and regulations of the city-state.

Thus, polis ruled over a citizen and the citizen ruled over his slaves. An ancient Greek conceptualised and perceived the world specifically to the extent to which he ruled over the slave and shaped the slave, the latter’s work and the products of this work. For his master, the slave was a tool, a natural body that the master could exploit to the extent of its physical capacity. Thus the world that an ancient Greek understood or knew, the world that actually existed for him, was on the one hand limited by the slave’s physical capacities—that which could be reshaped with slave labour. In this sphere, the word was the immediate tool of a free citizen himself: one had to know how to verbalise the instructions that the slave was supposed to follow. The prescribed instructions could not be formulated arbitrarily but the slave's physical capacities had to be considered. The prescription had to be as simple and unambiguous as possible, so that it could be followed blindly, so to speak, mechanically, precisely and quickly. On the other hand, the contents and limits of the world of an ancient Greek were defined by the polis. A free citizen could be the master of slaves and household only by virtue of the polis. The polis functioned as the binder of all free citizens. Each citizen felt himself to be subject to a certain independent and inevitable force of reason that appeared to be the basis of the harmony of the entire universe, entire cosmos. This force of reason—*logos*—has had various names and definitions in ancient philosophy. Heraclitus, for example, spoke of logos as cosmic fate or justice (*dikē*), Anaxagoras about the mind of the world (*nous*), Democritus about necessity (*anankē*). Harmony and necessity are expressed through opposites, they are enforced through chaos. Opposites and the conflict of opposites have also been approached from various perspectives in ancient philosophy. So what is the actual content of logos that is manifested in this war of opposites?

The social and political life in polis was arranged in a way that all affairs of the state were solved in a public assembly of citizens. Each free-born Greek was in one way or another closely connected with the state affairs, i.e., life in the polis—he was either elected to a state position or was one of the electors, he took actively part in the discussion of all issues and everything that happened in the polis also concerned him personally. The political climate at the time was very unstable, with different groups involved in constant hostile conflicts. Winners were those who were able to better defend their arguments, refute all counterarguments, disperse doubts, and convince everyone with the clarity of their discussions. The main conflicting forces were aristocrats and democrats. Aristocrats claimed they deserved power on the grounds of heritage, i.e., they were bound by ancestral traditions, whereas democrats did not recognise ancestral privileges and stood by the equality of all citizens, rule of majority over minority, and considered only those worthy of leadership who could prove their suitability, superiority to the majority. In early polis, aristocrats were the majority, which is only logical because polis evolved from ancestral relationships. The heyday of democracy was the 5th century BCE in Athens.

After reading this brief description of polis it is not difficult to see where the teaching of cosmos, ruled by logos which is manifested through the war of opposites, is derived from. Also, the reason why logic—both the logic analysing the content and relations of concepts and categories and also formal logic, the main principles of which were formulated by Aristotle (384–322 BCE)—became so vitally important in ancient Greece has now become self-evident. Indeed, Aristotle's only task was to formulate the rules and principles which had essentially evolved and which had been in constant use throughout previous centuries in discussions typical of poleis, held at crowded agoras. Alongside formal logic also mathematics could emerge, no longer as a prescriptive calculating ability but as a logical deductive proof system. Ancient mathematics, however, was not science in its modern sense, i.e., an exact science inseparably related to natural sciences, a language of other sciences, primarily physics. The logic and mathematics which emerged in ancient Greece had a completely different meaning for the Greeks than the disciplines of formal logic and mathematics have in modern day. For example, in the religious-philosophical community (6th–4th century BCE) established by Pythagoras (*c.* 580 – *c.* 500 BCE), mathematics was first and foremost a device for "purifying soul" and identifying mystical relations. Of course, all the above does not mean that the ancient logic and mathematics could not appear completely modern in our culture today. Aristotelean syllogism "All men are mortal. Socrates is a man. Therefore, Socrates in mortal" and Pythagorean theorem "The square of the hypotenuse is equal to the sum of the squares of the other two sides" are still valid, be it the period of antiquity or modern times.

The point lies elsewhere: thinking about the world the way ancient Greeks did is not scientific (even though this is exactly how science has been attempted to define!). In the period of antiquity, the world, nature, was not the object of science and man was not the subject perceiving that. What is meant by the world as the object of science will be clarified on several occasions below, but first it is important to understand that it is the world independent of human, subject-free, so to speak, that is the object of science. In science, the search is for objective truth, for knowledge that would not be dependent on human or humankind as a perceiving subject. According to the scientific world picture, an object under research is independent of the researcher's peculiarities; anything that is said about the object must be essential of the object itself, not the researcher; the subject perceiving the object cannot be reflected in the object. A researcher, of course, could take a picture of himself or herself, but then he or she must become the object for the moment that the picture is taken, and will by no means be the same as the person who took the picture but is an object like any other. Quite characteristic here is the term 'world picture', so natural and taken for granted in our modern science-centred culture. Speaking about world picture in the period of antiquity is a nonsense. An ancient Greek did not know a picture of the world or the world according to a picture. A Greek knew and understood the world according to his polis. For a Greek, the world was not an object that one could place in front of oneself, it was not an object that could be studied or experimented with, etc. A Greek lived in the world, was a part of this world and the world manifested in him—it was cosmos as a macro-organism. It was a Greek's vital responsibility to identify the harmony of cosmos and live in accordance to this.

From the perspective of an ancient Greek's actual sociopractical activity, a scientific study of nature based on experimental approach would be completely pointless; it would have been regarded as unfathomably eccentric and disparaged, much like the way free-born citizens disparaged physical labour, an activity so natural for slaves. For an ancient Greek, a scientific approach would have been dealing with random, insignificant details, overlooking the nature of the thing, observation of special and exceptional situations that would elude general attention, and distancing from the truth. Theories about nature in antiquity could be based only on commonplace views, traditional knowledge, largely borrowed from the prescriptive Oriental experiences. An ancient Greek's own experience in the so-called natural sciences came from the work of slaves, where, of course, no exact devices were used and which did not require any special knowledge. The most typical technological tool of the ancient times was a lever. And the law of the lever was indeed formulated. As mentioned above, the immediate universal "tool" of an ancient Greek, however, was the word. A right word at a right moment guaranteed success in material production (if said to the slaves) and in life in general. Therefore, the main cognitive task was finding the right words, the right way of saying things. Of course, this also applied to finding the exact words to convey the Greeks' world, the way of life in the polis.

Ancient philosophies of nature are widely different, presenting completely conflicting views. Next to the views that seem ingenious assumptions from the modern perspective (often pointed out to illustrate the farsightedness of the Greeks), some ideas that were expressed now appear incredibly foolish, childish and naive (and are shamefully kept quiet about or downplayed as random curiosities). Certainly, bringing these different original conceptions to the trial of reason, and the relentless criticism of these (which would be unthinkable in a society based on traditions but was completely natural for the ancient Greeks), was one of the important prerequisites for a scientific understanding of the world. However, this prerequisite alone is not enough for scientific truth to emerge from such discussions. Ancient study of nature simply lacks aspiration to scientific endeavour. We may even venture further: ancient teachings of nature, natural philosophy of the period of antiquity was not even interested in the physical content of the studied object (in the sense we know it), there were no attempts to anticipate the physical, chemical, and other mechanisms of nature. Perhaps we are too eager to attribute to ancient philosophers the various ingenious or foolish assumptions about physics, chemistry, etc.? It certainly appears to be so. But let us take a closer look at the issue.

2. Did ancient philosophy entail ideas of chemistry?

There exists no general historical approach to chemistry that would not name the elements of ancient authors or philosophers of nature—water, fire, earth and air—as the distant predecessors of chemical elements. Ancient atomism is everywhere referred to as the source of chemical atomism as a self-evident fact. Evaluations given to these teachings often diverge because opinions of the degree of proximity between natural-philosophical theories and scientific theories of chemistry vary. But no one seems to doubt that ancient scholars also aspired to understand the composition of substance as the object of research in natural sciences, only they did it within the limited range of their understanding, skills and possibilities.The first philosophers of science—Thales, Anaximander and Anaximenes, philosophers of nature who lived in the 6th century BCE—belonged to the so-called Milesian school as they all came from the city of Miletus. Traces of mythology are still clearly visible in their teachings. Similarly to Greek mythology which explained the emergence of cosmos from the primal chaos with the activity of Olympian gods, the first philosophers searched for the source from which the world had emerged but they set themselves a task to understand this source of the world through logic, through reason; the gods themselves were expected to come up with the rational explanation (no ancient Greek thinker would deny the existence of gods). Thales was convinced that the unified universal principle or element (arche) of a changing world was water. Anaximander proposed it was apeiron (an indefinite substance), and Anaximenes posited air as the arche. Heraclitus of Ephesus, who lived in the 6th–5th century BCE, considered fire as the arche of the world. For Pythagoras, philosopher of the same era, the number represented the origin of all things. Parmenides of Elea, who also lived in the 6th–5th century BCE, taught that it is reasonable to talk about being ("what is") as the only and unchanging principle. Anything that can be spoken about must exist because non-being cannot be expressed in words or thought about. Being cannot come from something because this assumed something would be being itself. Being cannot also change into something because, again, this something would be being as well. Zeno of Elea (*c.*490–430 BCE), a pupil of Parmenides, formulated his famous paradoxes, logical problems which emerge in understanding motion as in that what is, cannot change. But in addition to the logical analysis of the category of being ("what is"), Parmenides also discussed the issue of ontological principles, speaking, for example, that fire functions as an efficient principle of being and earth functions as a material principle and in the centre of being is goddess of love Aphrodite leading it all. Anaxagoras of Clazomenae (5th century BCE) proceeded from the principle that everything is in everything; the unified world is based on the primeval mixture of imperishable "seeds", each of which is comprised of the rest of these (aggregations of *homoiomeria*). In the 4th century BCE, Empedocles claimed that everything is based on four elements (arche)—fire, air, water and earth—and two forces—love and strife—making them to blend together or carry them apart.

The love and strife in the teachings of Empedocles are characteristic enough to demonstrate that considering an ancient scholar a researcher who was posing hypotheses on the physical or chemical composition of a substance would be a clear case of modernisation. Let me present here an analogous "non-natural-scientific" idea by Anaximander, which is indeed viewed as the only surviving sentence definitely attributed to him. It reads like this: "The things that are perish into the things from which they come to be, according to necessity, for they pay penalty and retribution to each other for their injustice in accordance with the ordering of time."

Analogous is Heraclitus's train of thought when he speaks of cosmic justice and judgement executed through fire.

The given arguments for the divergence from science in the ancient scholars' approaches to nature may be seen as primitive criticism, a wish to debate over the words. One may argue that the ancient authors simply thought by means of analogies with human activity while trying to convey the physical content. We so desperately wish to prove to ourselves that Empedocles, Anaximander, Heraclitus and other ancient Greek minds were thinking like our contemporary scientists of nature and we cannot wrap our heads around the fact that they spoke about the reciprocal love and strife, crime, sentence and condemnation, cosmic justice and judgement of natural phenomena in all seriousness, not metaphorically. It is also worth noting that the natural sciences of modern times also employ human concepts such as 'force' or even a property such as 'oddity'.

Still, the point lies not so much in words but the fact that there are no grounds to argue as if ancient authors only used analogies derived from human activity because understanding relationships between humans were their ultimate goal. Nature was not studied separately; traditional knowledge, perceptions borrowed from various sources and everyday experiences were given different interpretations which were easily changed, which never coincided in the works of different authors and which were often highly contradictory. All this was not important and was used only as exemplification. In the minds of Greeks, nature was not situated outside the world of humans or the human world outside nature. But the focus of studying was the human world, which was attempted to be understood as the consequence or manifestation of natural, cosmic processes. In a Pythagorean society, for example, which tried to explain everything by mathematics, the approach to the world characteristic of the antiquity in general was represented by the following equation:

$$\frac{\text{cosmos}}{\text{human}} = \frac{\text{human}}{\text{art (technē)}}$$

In this equation art does not represent artistic creation in the narrow sense but stands for anything created through human activity (the art of construction, gardening, cooking, medicine, governing, warfare, etc.). Logical analysis of concepts was the applied research method, and concepts were observed as manifestations of reality itself, which were even imagined as physical manifestations! This is how Socrates (470–399 BCE) formulated the general cognitive method of the classical antiquity; he considered the attempt to directly study nature completely pointless, even wrong and profane in principle. He taught that wisdom lies in prudence and it means knowing what is just, beautiful and good, useful for the man and the foundation of human happiness. Socrates proceeded from the principle “I know that I know nothing” and posed the axiom “Know thyself”. He considered knowing oneself the path to objective knowledge. The Socratic method is based on systematic asking of questions until it leads to contradictions, which means identifying false claims to knowledge (using ‘irony’). This is followed by midwifery (‘maieutics’), which entails inductive reasoning and definition—the process of arriving at generalisations through a logical analysis of specific phenomena and concrete examples, in which ‘irony’ plays its constant role.

Now let us take a look at ancient atomism and then proceed to Aristotle’s teachings. There is no doubt that both atomism and Aristotle’s teachings have had an impact on the emergence of natural sciences. But we try to understand

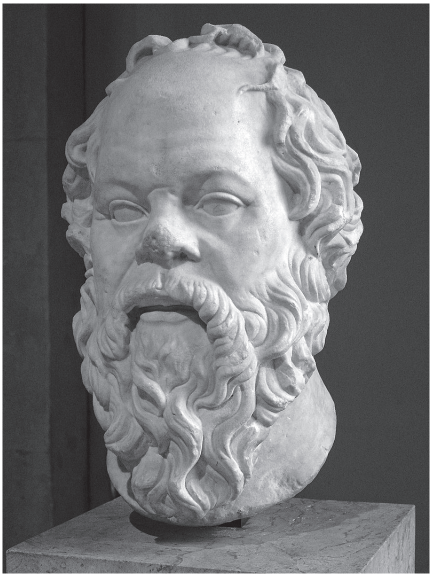

Figure 1. Socrates (470–399 BCE). Roman artwork (1st century), perhaps a copy of a lost bronze statue made by Lysippos (*Wikimedia Commons*, 2019a).

what in these teachings was important for natural sciences and which, as we will see below, has significance in understanding the development perspectives of modern science.

Socrates formulated the purpose of cognition—to provide general logical definitions to concepts. But like ancient authors themselves note, clear definitions were already given by Democritus (5th–4th century BCE). Relying on the general cognitive method of ancient authors—the idea of the distinction of microcosm and macrocosm—Democritus emphasised that for achieving the truth one must understand a human and his activity because these are directly accessible to us, since all else is intuitively perceived. On the logical plane, the atomism of Democritus is perhaps the closest to the teachings of Parmenides. Democritus (since virtually nothing is known about the views of his teacher Leucippus) divided Parmenides' concept of "Being" into an infinite number of material Beings—atoms, which all retained the properties of the concept of Being, such as indivisibility, indestructability, internal immobility, qualitative change, but acquired also external motion because by "destroying" Parmenides' indivisible Being emerged the void, empty space, which made the moving of atoms possible and even inevitable.

For Democritus, the atoms' lack of qualities represented the impossibility of concrete sensory perception but at the same time a combination of atoms formed the basis for the emergence of objects of any qualitative property. Atoms were like letters of the alphabet, which, in combinations, can produce texts of any content, be it a comedy or a tragedy. Atoms have a specific shape or structure. The differences stem from the shape of the letters, as A differs from N; from their positional orientation, as N differs from Z; and from their arrangement, as AN differs from NA. Democritus' atoms did not represent the limit of the divisibility of *substance* but the limit of the *qualitative* divisibility of all things; what remained indivisible was the form (structure) of atoms. Cosmos is the ultimate extent of the self-initiated motion of these moving atoms, the unified whole within which this motion takes place. In this sense, all atoms are inevitably connected and the world is governed by necessity, chance. Even though the motion of each atom is determined by the main properties of this atom, the free movement of atoms is inevitably such that no potential combination in terms of the main properties can be avoided and no combination is eternal.

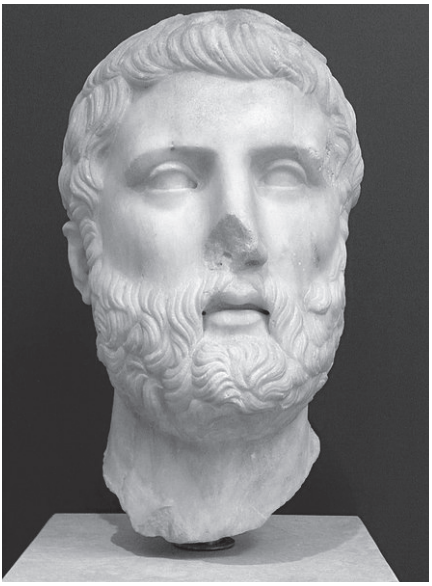

Figure 2. Democritus (460–370 BCE). Hadrianic (2nd century AD) copy of a fourth-century BCE Greek prototype (*Wikimedia Commons*, 2019b).

It is interesting to juxtapose Democritus' atomism with that of Epicurus (341–270 BCE). Epicurus lived in Athens during the crisis of the polis, which was marked by the spread of snitch accusations, bribery, fraud and slander, and the outbreak of wars over supremacy between the poleis, all of which created a favourable situation for barbarians (foreigners) to occupy these later. The polis no longer served as fosterer of the intellectual abilities of a "cosmic personality" or uniter of such personalities. Moods of avoidance and withdrawal from socio-political life started to prevail. Epicurus conveyed the new atmosphere of the era in his atomism by criticising the theory of Democritus: he did not agree with the reasoning of necessity, being subject to predestined fate. Epicurus discovered a weak link in Democritus' argumentation—if one claims that everything arises from necessity or determinism, then it also means that anything that happens randomly also arises from necessity. Epicurus showed that this statement by Democritus does not apply to human activity because this would mean that a human being lacks freedom of the will and would not be morally responsible for his actions. To justify the possibility of free will in human activity, Epicurus introduced an important amendment in atomic theory by formulating the so-called principle of indeterminism in ancient atomism: he explains that the movement of atoms is not absolutely predetermined but when moving through the void they may swerve a little from their course.

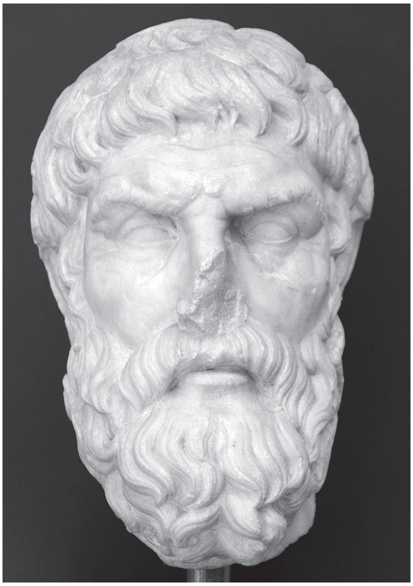

Figure 3. Epicurus (341–270 BCE). Roman copy (1st century) after Greek original (3rd century) (*Wikimedia Commons*, 2016).

Thus it is plainly evident that Epicurus' atomism is not a natural scientific speculation about the structure of substance but a logical argument, a logical analysis of concepts, the direct content of which are human activity, human relationships, and issues of justice and morality. Epicurus made a clear distinction between the method used for explaining celestial phenomena and the method for explaining human activity. The former relies on analogies and this allows explaining the same phenomenon in different ways (the explanations themselves are required only for helping people overcome the fear of the unknown). In the latter case, however, only one explanation is possible because logical conclusions are made on the basis of what is directly observed rather than on the basis of analogy.

So we must agree that ancient atomism approaches atom primarily as a concept of logic, and studies the so-called logical and moral qualities of atoms rather than their physical or chemical properties. Physics can be viewed merely as an interpretation of logic. Ancient atomism is an attempt to study being through the categories of thought, to identify the most generalised, "ultimate" definitions from which specific definitions to understand the rest of the world can be derived. According to atomism, a phenomenon, if it can be reduced to a combination of atoms, becomes cognitive, understood, after the atoms forming it are identified. Nothing else is needed for understanding the world but atoms and the void. Atomism essentially analyses the interrelation of unity and variability, randomness and necessity, consistence, structure and quality, part and whole of the world, and relations of other categories. But ancient atomism is not purely an analysis of categories. The concept of atom itself proves to be "illegitimate" from the perspective of the logic of categories. This is a so-called model of a category assigned through a material object, whereas a clear distinction is not made between the material properties and the logical qualities.

Democritus did not explain the basis or nature of qualitative determination of the phenomenon from the perspective of logic (it is namely qualitative determination that makes a thing what it is). The essence of all things is the same—atoms and the void. The methodology of Democritus is based on reductionism—explaining a complex phenomenon through the simple, or the whole through its components or parts, even though Democritus himself did not recognise such complete reductionism because he did not claim that a whole is a simple sum of parts, that the quality of the whole is no different than the quality of the parts. On the contrary: as we can see, Democritus particularly emphasised that atoms, in a sense, lack qualities but qualities of some sort or another emerge in their compounds. But this is exactly the point—he does not propose a logical reasoning for the emergence of quality. For Democritus, quality is something that is yielded through cognition. Therefore, also the question of when will we get to atoms when analysing something and how these atoms form into a whole, which is of specific qualitative determination, also proves to be a cognitive one, solved only empirically, something that cannot be deduced from category relations. Atom itself, as something that has specific qualities or properties (specific "form", as it was referred to in the ancient times), is indivisible only from the perspective of logic. The essence of the concept of atom in the sense of the category of thought is that a thing is indivisible as a specific wholesome quality, nature (form). As long as we can "divide" a thing we have not arrived to its essential nature, to that which makes it what it is. Using logic, Democritus only proved that every single phenomenon has a limit of divisibility and when this limit is exceeded, the phenomenon stops being this specific phenomenon. However, he did not demonstrate how the atoms determine the quality of the specific thing or why the whole is not simply a sum of its parts. Democritus' atomism does not give instructions on what can be considered an atom, i.e., which determination, which whole can be considered indivisible.

From the atomism of Democritus follows a clear methodological programme, which was, of course, not formulated by ancient atomism due to its non-experimental nature. Firstly, the atomic composition of something, for example a substance, has to be determined *empirically*, relying on some empirical criteria and (still empirically) determine the composition's relation to the quality or properties of the substance. Secondly, the relation between the quality or property of the substance and the way how the atoms of the substance have combined, the relation between the structure and qualities of the substance have to be explained, again empirically. Later, as we will see, the evolution of the scientific world picture in chemistry began on the basis of such reductionist programme.

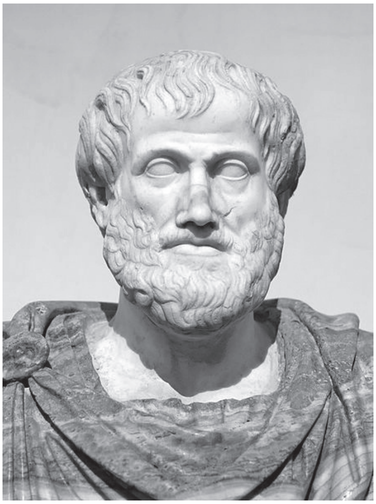

Figure 4. Aristotle (384–322 BCE). Roman copy after a Greek bronze original by Lysippos from 330 BCE. (*Wikimedia Commons*, 2018a).

Let us now move on to charting the Aristotelian conceptualisation of the world. Aristotle (384–322 BCE) became responsible for summarising, systematising and developing the ancient world of thought. The medieval way of thinking was also based on his teachings. Compared to modern times, it was characteristic of both prehistoric and medieval culture that social production had relatively little impact on nature, procuring subsistence was based on exploiting natural processes (in agriculture) and manufacture, rather than on applying the forces of nature in machine technology.

These kinds of production activity and daily practices, unmediated by machine technology, do not require or demand special apparatuses, precise measurement, or measuring devices, which is why human activity and knowledge used in this have a qualitative nature. Here it is important and pragmatic to characterise phenomena based on the qualities attributed through sensory perception, and to describe the processes according to the qualitative properties that are most available for humans. Man knows and governs nature to the extent that is his immediate living environment, to the extent that he himself is capable of shaping into products that he needs with his physical labour (or the labour of his slave, serf or manufacturer) rather than using technology, and therefore to the extent that he governs and knows his own activity rather than the applications of natural sciences in technology. Nature, human activity and all the products of this activity form an entity, all components of which are the same; there is no component that would be clearly different from others and would subject other components to itself. In prehistoric and medieval times, man's rule over nature did not only entail ruling over the external nature (man rather had to adapt to it) but ruling over that part of nature that is man itself. Prehistoric and medieval views of nature were inevitably connected with human activity, were mediated by human activity, and definitely included human activity as a factor of nature. The way people lived during these eras does not provide us a completely independent picture of human activity, or of human characteristics. At the same time, this human activity is not an individual's arbitrary, subjective way of doing things, and is rather an activity that has to comply with very many social restrictions, cultural norms, prescriptions and regulations, ranging, for example, from rules of casual speech and common behaviour or logic of thinking and methods in some field to legal and ethical standards. It must be separately emphasised that understanding the recurrence of natural phenomena, for example, the knowledge that a peasant has to consider for sowing or harvesting, etc. in time, is acquired through the communal experience of previous generations, cultural norms and social prescriptions, similar to the rules of handicraft, rather than through personal experience.

Next to what was characteristic specifically of antiquity, Aristotelian philosophy represents the general nature of the era in ancient and medieval times alike. In his atomism, Democritus described the individual life of a human being in the democratic polis. Indeed, the abstract, theoretical manifestation of ancient democracy is the idea that the structure and quality of polis as an entity (whereas the polis represented the whole society at the time) inevitably, and spontaneously, i.e., unpredictably, derives from peoples' own capacities, their inherent "structure" (the atomic form). The crisis of the polis inevitably brought along a criticism of the concept of atoms "automatically" combining into a natural, the only possible and best whole. Like his teacher Plato, Aristotle theoretically tried to save the polis. This also meant "saving" the rational reasoning of the world, a logical development of the categories of thinking. Aristotle emphasised the independent and determining, regulative importance of the general, whole, or form in relation to the parts constituting the whole as material. He demonstrated that it is important to understand the process in which material is given the form, the evolution of qualitative determinism of a thing, to locate the source of the process. In terms of this, he placed much emphasis on analysing things from the perspective of their purpose, to understand their position in the more general whole. Aristotle argued that earlier thinkers have entertained a far too casual attitude towards experience, sense perception, considering it simply an opinion and not bothering to show how to gain truthful knowledge about the way in which the rationally captured general and constant is related to the particular and mutating perceived by the senses. Aristotle emphasised that namely understanding change, or motion, constitutes physics—the study of nature, natural phenomena, the nature of things (*physis*).To learn about and understand nature, Aristotle gives examples of human activity—art (in the broad sense), proceeding from the abovementioned parallelism of micro- and macrocosm which was so characteristic of the ancient times, i.e., he took it for granted that human activity only imitates the activity of the universe as a whole. In order to understand the universe, it is practical to rely specifically on art because we are more familiar with our own activity. The difference between the activity of nature and the activity of humans manifests in the different level of perfection but in both cases the rational principles are the same. Aristotle explained that, for example, a doctor or a house builder proceeds from thinking and sense knowledge and needs to realise and consider the principles and causes for doing in this particular way and no other. In nature, phenomena occur naturally in a more rational and reasoned manner than what a human can imitate in his activity. Nature does nothing without cause, without reason, and always acts as if with deliberate intention, always chooses the best variant, acts in the most economical way, etc. even though mistakes are possible in the operations of nature as well. In cognition, one must be able to differentiate what is really inherently characteristic of the phenomenon, what corresponds to it in the natural whole and what is unnatural, achieved by force, disrupting rational harmony.

According to Aristotle's teachings, there are four source principles, explanations or causes of motion (the nature of things): (1) matter, which Aristotle understands as material, substratum, out of which an object is composed, or created, "that out of which" only as a potentiality; (2) form, the particular nature of an object or a phenomenon, that which determines what a thing is, the structure of a thing "what-it-is-to-be"; (3) efficient cause, the active agent that makes a potentiality into a reality; and (4) the end purpose or final cause, that "for the sake of which a thing is done" and is developed and is necessary as such.

The primary cause in the universe, according to Aristotle, is God as the unmoved mover, which in its existence is the highest end and good. It is a pure form, the most perfect and pure actuality which is not born out of potentiality; it is a form that lacks matter, it is pure reason, the most perfect thinking, which is thinking of thinking. Man is the supreme being of the material universe. The material cause of a human is his physical body and the form is its soul. The highest form of soul, in turn, is intellect. According to Aristotle, the universe has a hierarchical structure, in which everything has a form particularly suited to it and a particular position which corresponds to the dignity, function, or end cause as the best of the potential causes. The universe is harmonious in its essence, a perfect organism, a unified whole.

The four causes formulated by Aristotle explain the essence of both human activity (art) and a natural thing (*physis*). In terms of art, we first have a skilled maker with its intentions and tools (= efficient cause). The maker must have matter, the material that he needs to produce the intended object. Then, the maker must have knowledge of what he is going to make, i.e., he must have an idea of the object, a plan, project and structure (form) of the intended object. In addition (and this is already necessary for understanding the structure of the object better), the maker must know what the created object is for, he must know the function and place of the intended object in the more wider whole, the more general system. The activity of nature differs from human activity (art) only in that the function of the created natural phenomenon, a natural thing is not external of this thing, it is not determined by human but is internal in nature as an organic whole, the organism itself. The activity of human and the activity of nature are identical, Aristotle explains, when human activity is directed at himself, for example, a doctor healing himself.

Earlier philosophers proceeded only from a few causes (for example, the first philosophers recognised only the material causes, etc.) and prior to Aristotle no one studied all the causes together. According to Aristotle, it is impossible to understand the emergence of any real thing without considering all the causes. At the same time, Aristotle believes that this explains the relation between a single thing perceived by senses and a general concept in thinking: the concept represents the nature of a thing, and the thing intrinsically entails its concept—a thing is a concept realised in material. At the same time, a thing does not necessarily always correspond to its concept; that which is most natural to a thing may not always be what is inherent to it and some other potentiality may be actualised in the thing (the same material may yield different things, even those that are not suited for the nature of the material); a thing may come to be completely by accident, other than as a result of its cause. Demonstrative general knowledge (*epistēmē*) is possible only for these things that completely correspond to its name, its nature, its primary principles (i.e., the four causes). From this also follows Aristotle's (syllogistic) logic: *if* a thing comes into being out of its name, it has all the qualities, all the attributes that the name has assigned to it.

Aristotle also relies on the four primary principles (causes) when interpreting the traditional, more specific notions and common experiences of natural phenomena; among other things he has presented arguments that could be regarded as Aristotle's contribution to the evolution of chemistry. This is first and foremost Aristotle's teaching of elements (arche). Let us take a brief look at it below.

What is interesting here is Aristotle's operation with terms, his analysis on the level of categories of thought rather than actual knowledge of nature. Aristotle did not study the composition and qualities of substance from the perspective of physics or chemistry, which is why there is no point of searching for "ingenious" or "ignorant" thoughts on that from his teachings.

Aristotle argues that distinguishing between matter and form is relative in the sense that matter and form are inherent to every individually existing thing, substance, and every substance has its own substratum and structure (form). Matter which exists potentially is at the same time a kind of actuality. For example, in a case of a brazen sphere, brass is only potentiality of the brazen sphere, its matter. But brass itself is also actuality if we do not observe brass in the form of a sphere or a sculpture, etc. This means that it is necessary to identify the matter of brass, to identify the potentiality of brass. For that purpose, Aristotle relied on the four elements in Empedocles' philosophy—fire, air, water and earth. Brass is a composite of these elements. But these elements, in turn, are also something specific, something determined, not just material for brass. This means that they, in turn, must have matter and form. Aristotle argues that the matter from which the primary elements have come into being is completely indeterminate. There may be some analogues to these but a specific term (and one that is not perceived by the senses as this too would be a certain kind of determinism) cannot be applied to this. Matter of this kind is therefore only a potentiality that lacks its specific (determined) actuality and that can become any random actuality. Aristotle refers to such matter which is only potentiality without specific actuality as "prime matter", distinguishing it from the "last matter", in which case matter has a specific actuality (for example, brass is matter in relation to the brazen sphere but is itself an actuality in relation to its "last matter"—the four elements).

Aristotle introduces also the fifth element into his teaching, which in later scholastic tradition came to be called "quintessence", i.e., the "fifth being". He derives the existence of the fifth element from the main categories of movement. There are two of these—the circular and the linear movement. To each type of movement corresponds an element to which this type of movement is the most natural. Moving in a circle is movement corresponding to the fifth element. Aristotle called this element "aether". Aether is the lightest element. Heavenly bodies, which are much more perfect than earthly bodies and move in a circle, consist of aether. Aether also fills the space of universe in which these heavenly bodies move.

Linear movement takes place in two directions—it may be upward or downward. The upward and downward direction exists because the universe is spherical but

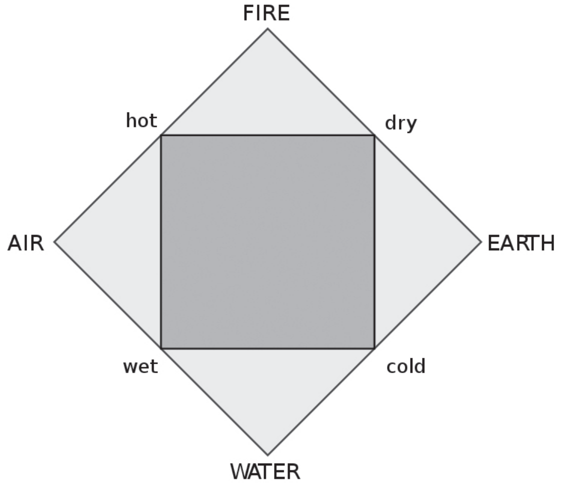

Figure 5. The four classical elements, after Aristotle (*Wikimedia Commons*, 2018b)

the sphere has a centre, which is why motion must be either towards the centre or away from it. Downward motion is moving towards the centre, whereas upward motion is moving away from it. As is natural to the most imperfect element, the earth, it moves towards the middle of the universe and in this centre lies planet Earth. There is its natural place. Experience shows that any portion of the Earth thrown upward falls back down, i.e., returns to its natural place. The most perfect of the earthly elements—air—moves upward (towards the perfect heavenly bodies!). This is also easy to confirm from experience. Water and air are the intermediate elements. Water moves towards the centre but only in case the centre has not already been occupied by a denser body. The same applies to air, which moves away from the centre, but must make space for fire, which is lighter and more close to aether. A similar nature of water and fire can also be confirmed from experience.

All natural things are composed of elements. The elements themselves never exist in entirely pure form. They always contain each other to a greater or lesser extent. If one of the elements occurs in greater extent, it is either fire, air, water or earth. But if there is a greater proportion of some element relative to another, then it is a natural object that is different from fire, air, water or earth.

Aristotle introduced the properties of the elements by means of combinations of perceptible main qualities—warm, dry, cold, moist. Out of the "prime matter", the main qualities shape the element, giving the matter form. The qualities of each

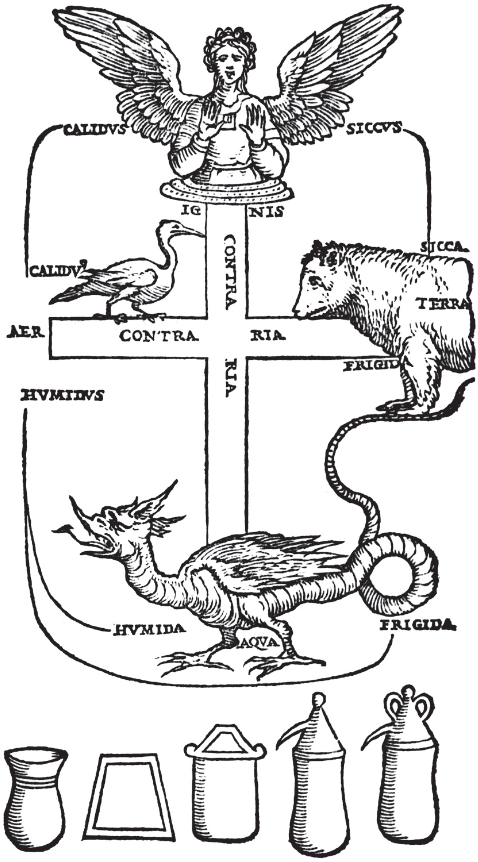

Figure 6. An alchemical rendering of Aristotelian four primary qualities and elements. Attributed to Petrus Bonus of Ferrera, early 14th century (Lacinius, 1546).

element come from combining a pair of properties, whereas only one property is characteristic of each element. (At the same time, an element cannot come into being as a result of a combination of contraries.) The qualities of fire are hot and dry, its specific quality is hot; air is hot and moist, specific quality—moist; water is cold and moist, its specific quality being cold; earth is cold and dry, its specific quality is dry (see Fig. 5)

Aristotle then differentiated between active and passive qualities. Active qualities are cold and hot, passive qualities are dry and moist. As we notice, each element has an active quality and a passive quality, suggesting that each element, with its active quality, may influence another element with a passive quality but, because of its passive quality, it may also be susceptible to some other element's active quality. In the end, it means that elements may transform into one another. (Only the fifth, the most perfect element—aether—is unchangeable).

Aristotle's categories always prove necessary for studying the qualitative aspect of changes but there is no need to determine precise quantitative relations or it is not possible ("a hot body heats", i.e., heat is transferred from a hot body to a cold one; "a moist body dries", i.e., moistness transfers from a hot body to cold, etc.) This is the very thing that was characteristic of ancient (and medieval) practices. Aristotle himself applied his conceptual apparatus to analyse the most common phenomena in the ancients' everyday practices, often making references to the art of cooking or gardening. The impact of hot and cold as active qualities on passive qualities like moist and dry became especially evident in the kitchen and the garden. After all, the main operations of preparing food involve boiling, baking, heating and cooling, which are done either with moistness or with dryness. Also, in the garden (as in nature in general) "the sun is baking" and "the moon (night) is cooling". Indeed, the qualities of hot, cold, moist and dry (among which hot and cold as active qualities accede to others) are those from which the qualities of end products—sweet, sour, soft, hard, green, red, etc.—are achieved.

For medieval alchemy and later iatrochemistry, Aristotle's "qualitative physics" became a source for most of their categories. Alchemy and iatrochemistry will be the topic of the following chapter. Below we will see that, in terms of categories. Aristotle's teaching of the four causes will prove useful also in identifying the stages of evolution of scientific chemistry and conceptualising the newest tendencies.

II Mysterious alchemy

That alchemy is indeed mysterious the readers have probably already had the chance to become convinced of. The readers must certainly know that alchemists, said to be capable of turning base metals into gold and of doing all sorts of other wondrous stuff on their quest of finding the "philosopher's stone", had a penchant for secrecy and mystery, which is evident in their peculiar symbols and highly allegorical language. So let us take a closer look at the enigma that is alchemy.

1. What is the mystery we want to solve?

Let us consider, for instance, the following alchemical recipe:

> To make the Elixir of the Wise, also known as the Philosopher's Stone, take, my son, the philosopher's mercury and burn it until it turns into a green lion. Then, make the heat even stronger and the lion will become red. Boil the red lion in the sour spirit of wine on a sand bath, let the fluid evaporate and the mercury changes to a resinous substance that can be cut with a knife. Place the resinous substance in a retort that is coated in clay and distill it slowly on a flame. You will obtain a tasteless liquid, a spirit and red drops. The shadows of Erebos[2] enshroud the retort and from the inside you will find a true serpent, since it eats its own tail. Take this black serpent, reduce it to powder by rubbing it on a stone and touch it with a hot ember. The serpent bursts into flame and, taking on a magnificent lemon hue, gives birth to the green lion once again. Make it to eat its tail once again, and then distill the product. Finally, my son, after careful purification, you will witness the appearance of a corrosive liquid and human blood. That is the Elixir. (George Ripley in Dumas, 1837, p. 30)

It may look like complete nonsense at a first glance, all of it just the gobbledygook of a medieval witch or charlatan. However, this is not quite so. We chose this particular text, since it has been translated by historians of chemistry into the

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[2] Ancient Greeks believed Erebos to be the land of eternal darkness on the other side of Oceanus, the mighty world stream, beyond which lies the entrance to Hades, the underworld.

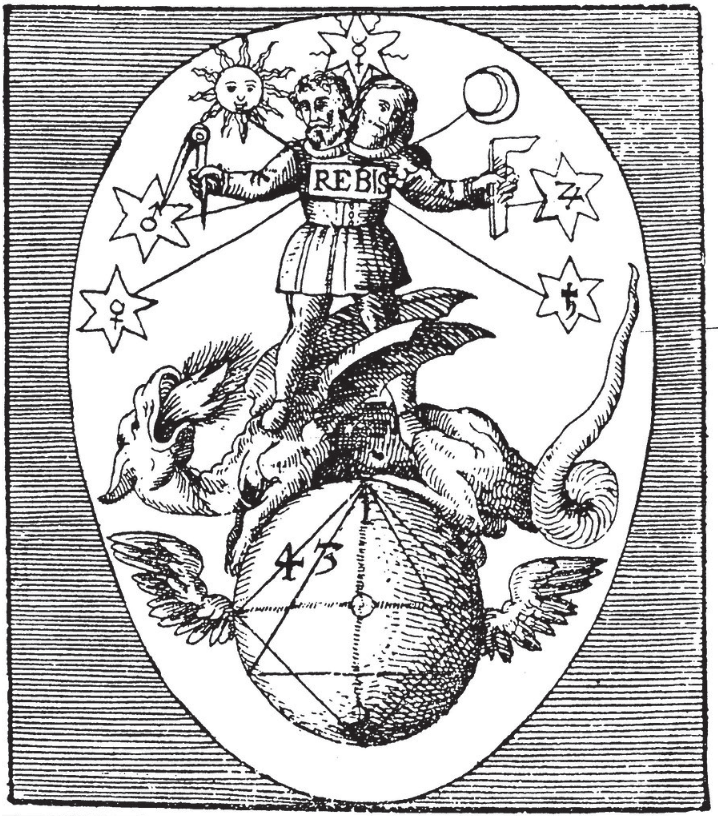

Figure 7. ‘Rebis’. Alchemical symbols. The two-headed man-woman (Rebis) depicts the union of both male and female essences (sulfur and mercury). Around the creature’s head, seven alchemical glyphs are placed, standing for the seven metals (and their companion seven celestial bodies). *From left to right:* copper (Venus), iron (Mars), gold (Sun), mercury (Mercury), silver (Moon), tin (Jupiter) and lead (Saturn). The serpent represents primal matter and the winged sphere is the symbol of the four elements. (Nollius, 1617)

language of modern chemistry. The “philosopher’s mercury”, in this case, is lead. The “green lion” and “red lion” are the oxidation products of lead: the first being the greenish-yellow lead(II) oxide (PbO) and the second being the ‘red lead’ (Pb_3O_4). The sour spirit of the wine is the acetic acid that dissolves the ‘red lead’. After the evaporation of the solution, the resinous substance that remains is the plumbic acetate. Upon heating, it first releases the water of hydration (the tasteless liquid), then the acetone (the spirit) and finally a reddish oily liquid which has a mixed composition. The “black dragon” left in the retort is fine-

Figure 8. 'The Alchemist'. A sixteenth-century caricature which mocks alchemy for being a futile and pointless labour which only leads to poverty (seen from the window). Engraving after Pieter Bruegel the Elder (after 1558).

grained lead which, in powdered form, ignites when coming into contact with hot embers. Upon the oxidation (burning) of lead, we once again obtain lead(II) oxide, which is responsible for the "magnificent lemon hue". This process is described by the alchemist as the "black dragon" (lead powder) eating its own tail and becoming a "green lion" again. Further heating also produces red lead again, and all the following steps will be repeated. In this recipe, the Elixir of the Wise is the reddish oily liquid, described as "human blood", which can be used to precipitate gold from the solutions of its salts. Thus, the historians of chemistry have demonstrated that the recipes of alchemists can also be rendered intelligible to chemists. Yet, by possessing the ability to decipher alchemical texts as shown above, can we claim to have solved the mystery of the alchemical process?

In different times, the attitudes towards alchemy have swung from one end to the other and so have the views and assessments historians of chemistry. The chemists have seen it as a completely absurd phenomenon of the "dark Middle Ages". The seventeenth-century French chemist Nicolas Lémery (1646–1715) gave the

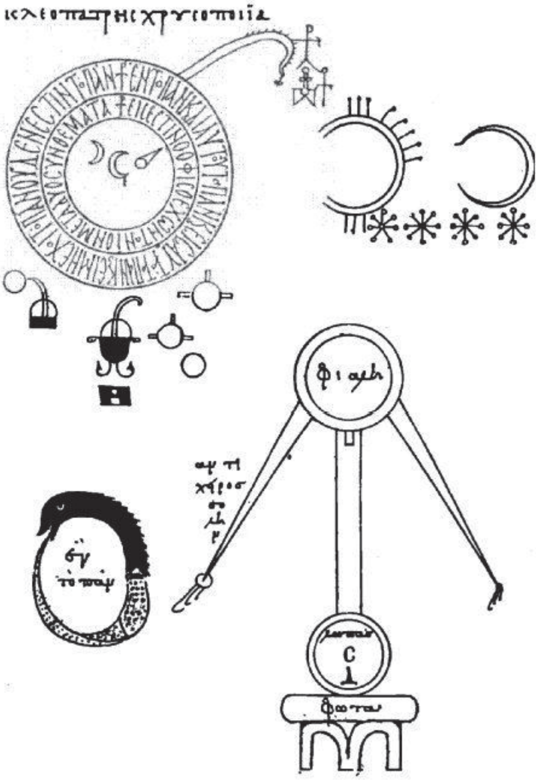

Figure 9. Chrysopoeia of Cleopatra. The magical symbols and drawings of a Greek-Egyptian female alchemist. On the right below, one finds a depiction of an alchemical distillation apparatus—alembic with two (*dibikos*) receivers. (These images are found in a third- to seventh-century manuscript.) (Berthelot & Ruelle, 1887, p. 132)

following laconic appraisal of alchemy: “An artless art, of which the beginning is to lie, the middle is to labour, and the end is to beg” (Lémery, 1757). Yet, at the beginning of the 20th century, numerous occultists saw alchemy in a completely opposite light: it was the “superscience” which held the key to making contact and communicating with supernatural powers. Between these extremes, one can find a number of “reasonable” views, such as that alchemy is the mother of chemistry, or its infancy, or perhaps even chemistry proper, merely dressed in a dreadfully quaint outfit completely out of place in the modern era—yet none of them captures the true essence of alchemy either.

The illustrious nineteenth-century chemist Justus Liebig (1803–1873) once asked: indeed, what would modern age chemistry be without sulfuric, muriatic and nitric acids, without phosphorus and ammonia, without spirit, acetone and ether, all of which had been discovered by alchemists? What would modern age chemistry be without the laboratory glass and equipment of the alchemists— flasks, retorts, alembics, water and sand baths? (Liebig, 1878, p. 38) Is that not the bedrock of chemistry? And why only bedrock? Is there not a ring of truth to the words of Wilhelm Ostwald (1853–1932), the Chemistry Nobel Prize laureate of 1909:

> We have become accustomed to looking derisively down upon medieval experimental efforts to call forth this change [i.e., trying to change base metals into gold by considering that any piece of matter can be endowed with any property] as some unimaginative folly. Yet, we have as little right to do that as, for example, when considering the modern attempts to synthesise artificial proteins. […] artificial production of gold was merely a technical matter for science at the time, much like the artificial production of diamonds is in our time. (Translated from Ostwald, 1908, p. 21)

All of this indeed is true, but only if our perspective is that of a modern-age chemist who assumes that alchemists were simply chemists who only lived in a different era and studied, according to the best knowledge and methods available in their age, the same phenomena as do the chemists of today, only according to the best knowledge and methods available in our current age. However, this perspective often disregards much of what lies at alchemy's core as mere unnecessary flourishes, just the external trappings of the age. So many questions remain without answers. Why, throughout the long Middle Ages and even later—roughly for fifteen hundred years!—did the alchemists never abandon their quest for chrysopoeia, turning base metals into gold, and for the philosopher's stone, regardless of the fact that the most they ever achieved in their actual recipes was the precipitation of elemental gold from its salts or making the surface of other metals appear like gold? Were all those alchemists really struck with blindness? What for did they have all this language of poetic symbols, carefully drawn dragons who eat their own tails, lions of many colours, and so on? If in actual reality they worked no miracles, never found the philosopher's stone, never produced genuine gold, then what was the justification of all these grand claims of being close to solving great mysteries and exaggerated emphasis on the need to keep their art in utmost secrecy? For instance, doctor *universalis* Albertus Magnus (1193–1280) has included the following warning in the foreword to his alchemy tome:

> I beg and I adjure you by the Creator of the world to hide this book from all the foolish. For to you I shall reveal the secret, but from the others I shall conceal the secret of secrets because of envy of this noble knowledge. Fools look down upon it because they cannot attain it; for this reason they consider it odious and believe it impossible; they are, therefore, envious of those who work in it and say that they are forgers. Beware, then of revealing to anyone our secrets in this work. A second time, I warn you to be cautious. (Heines, 1958, p. 3)

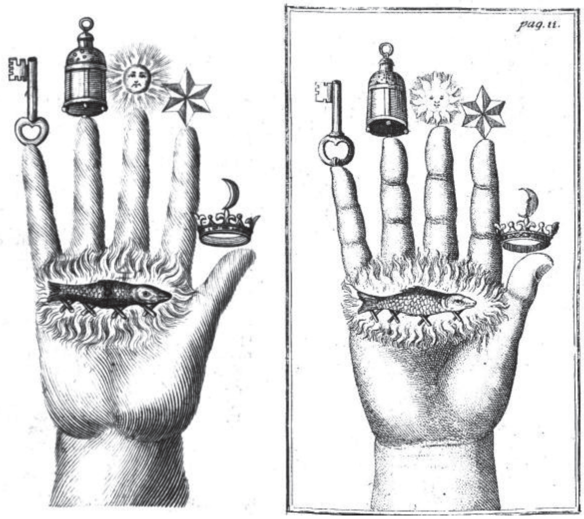

Figure 10. 'Hand of the Philosophers'. Chemical meanings of the symbols from the little finger to the thumb: common salt, alum, sal ammoniac, Roman vitriol, saltpetre. The fish aflame in the centre of the palm symbolises mercury joining with sulfur—the male joining the female—which begins the transmutation of matter. (Image found in a treatise attributed to Johan Isaac Hollandus, a fifteenth-century alchemist (Holland, 1667 (left) and 1746 (right)).

The uninitiated have always been misled by the matter of making gold. Very often, in public perception, recognising or refuting alchemists' work (and also our understanding of alchemy's nature later and even in these days) has been reduced to whether the transmutation of metals into gold was considered possible or not. When an alchemist failed to produce gold, he was seen as either a bungler or a fraud. Alchemists had rightly a very good reason to be twice as cautious, since they could very easily end up before the inquisition tribunal and lose their lives. Alchemists were only tolerated (or flattered, as Albertus Magnus put it) because of their promise to make gold, while no one thought of it as a fool's errand. As a matter of fact, in the context of Aristotelian philosophy, the transmutation of metals was an entirely plausible concept. However, as the alchemists always kept on asking for more time to complete their work and no one could actually understand what they were doing, they were naturally regarded with mistrust and more often than not their gold-hungry patrons lost their patience.

But what, then, was the true meaning of chrysopoeia for an alchemist? What did the alchemists really strive for?

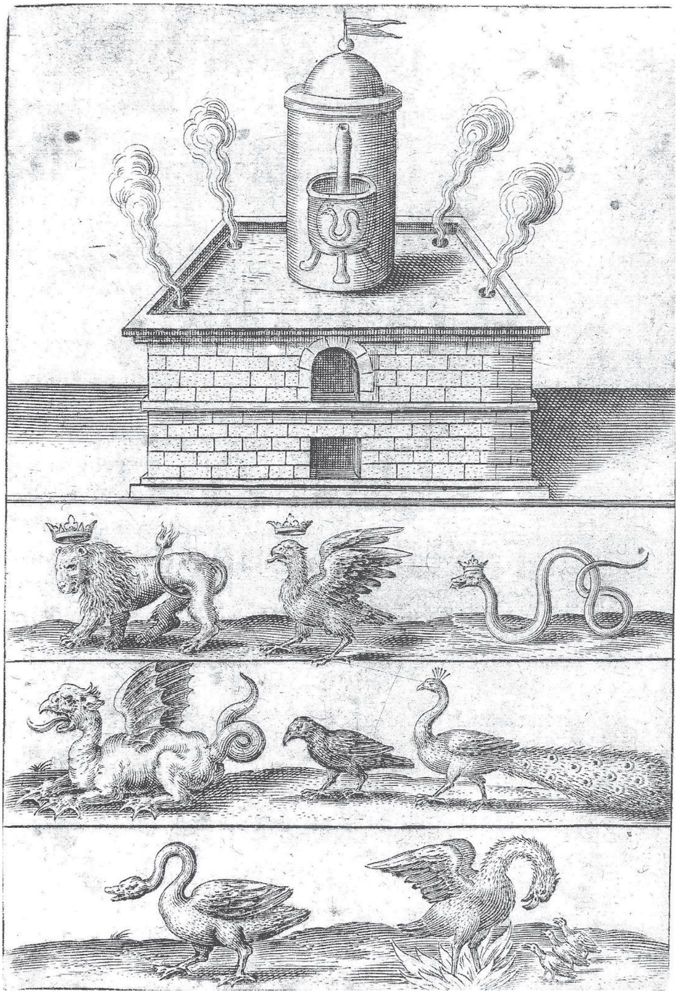

Figure 11. Alchemical symbols.
Above: The Athanor, an alchemical furnace; the domed cylinder (the "philosopher's egg"), bearing the symbol of the matter, is a hermetically sealed vessel. *Below*: The lion is the symbol of the fixed, the eagle is the symbol of the volatile. The serpent stands for the female principle in transmutation (female substances include, for example, silver and mercury, female processes are silver/white); the dragon stands for the male principle in transmutation (male substances include, for example, gold and sulfur, male processes are yellow/green); the crow, the peacock, the swan and the phoenix represent different stages in the transmutation of matter in the progressive order of perfection, also reflected by the colour sequence: black, rainbow colours, white, red. (Maier, 1618a, p.76)

2. Is alchemy even chemistry?

We must set it straight at once that the preceding title is not to be understood as an analogy to the question “Is a sea-lion even a lion?” It would serve our purpose to ask such a question about alchemy only if we wanted to stress the completely different and unrelated character of alchemy as a cultural phenomenon as compared to modern-age chemistry. And yet, this is exactly what we must stress—that alchemy is a thing unto itself, a distinct medieval cultural phenomenon and not primitive chemistry or weird chemistry. That part of alchemy which coincides with chemistry, such as the identification of various chemical substances and their properties, study of their reactions, basic laboratory glassware and equipment, etc., was not a separate goal in itself for alchemy. As a painter cannot make a painting without a palette, brushes and canvas, so an alchemist cannot strive to obtain its goal without chemistry. As the painter’s goal is not to make the palette, brushes and canvas, although he can certainly increase the number and quality of tools at his disposal, so the alchemy’s *raison d’être* was not to develop chemistry, although it cannot do without it. From the perspective of the principal goal of alchemy, any progress it made in chemistry was merely a byproduct. Of course, that also does not change the fact that the history of chemistry still remains intertwined with alchemy. In a sense, this is the way of the history of culture in general, where everything remains related, the future, one way or another, always relies on the past, new grows out of the old, borrows from the old, combines with parts of the old, and so on. Yet it is crucial to understand that, just as the ancient philosophers’ theories of nature are not simply naive forms of natural science, but accounts of the world conceived in an era radically different from that of science (while historical connections between science and ancient philosophy certainly exist), so is alchemy not merely a naive and fantastic form of chemistry, but a peculiar medieval account of the world.

Alchemy is distinctly different from the ancient theories of nature. First of all, already the eras in which they emerged are different. This also implies different ways of thinking and different purposes of cognition. True, as we already saw in the previous chapter, the ancient and the medieval world held much in common. For instance, the Aristotelian philosophy—primarily its doctrine of the hierarchical structure of the world, based on the principle of an unmoved mover, or God—was very appealing to medieval sensibilities, so it was adopted, but not without significant modifications. The principal new development was the irreconcilable nature of the medieval dualisms of flesh and spirit, or body and soul. Moreover,

DE ALCHIMIA
OPVSCVLA
COMPLVRA VETERVM PHI-
loſophorum, quorum catalogum ſe-
quens pagella indicabit.

Cum gratia & Priuilegio Cæſareo.

Figure 12. Title page of *De alchimia opuscula complura veterum philosophorum, quorum catalogum sequens pagella indicabit* (1550). The engraving depicts Rebis, a being of both male and female qualities (a compound of sulfur and mercury—cinnabar), wearing a crown of alchemical gold and trampling underfoot the three-headed fire-breathing dragon (symbolising the three elements and the solid, liquid and gaseous states of matter—earth, water, air—and their union in all-consuming fire). The same dragon heads also appear as three small serpents in the chalice of all-powerful red elixir held in Rebis' right hand, while the fourth serpent—fire—is gripped by Rebis' left hand. The green lion behind Rebis symbolises the transmutation potential in the matter. On the left, an alchemical tree of life has been depicted. Its fruits are metals, products of the union of male and female. On the right, a pelican feeds its young, representing the distillation process which multiplies the strength of the wondrous elixir.

the only true reality was to be found in the spiritual realm, while the material world was considered worthless. In the classical period, however, no such disregard of the body had existed, not even in Platonic and Aristotelian idealism; the ideal world was not understood as a mystical antithesis to the material world. The world, cosmos, was for ancient Greeks an immortal living organism, one immeasurably huge body. Platonic and Aristotelian philosophies were idealistic, because the essence of things, their original shape or idea/εἶδος was immaterial, while matter was merely passive material in relation to the ideal. However, the ideal was still seen as manifested in matter, found in nature, built into the cosmos.

As we know, polis, the slave-holding ancient Greek city-state, a unique phenomenon in the human history, became the early model of the ancient world, or the cosmos. In the days of Aristotle and Plato, polis had already entered its decline period, although the philosophers still attempted its "theoretical salvation". A few centuries further on and the medieval thinkers, theoreticians of Christianity, were all instead busy with the salvation of the human soul, its delivery from the sins of the earthly world, all their attention focused on a human being, a person, individual self-consciousness, one's intellectual self. The polis-cosmos entirely disappeared from the collective consciousness. In a polis, especially in the golden days of the ancient democracy, all urgent matters were brought to be judged before the tribunal of reason. In open and public discussions, the irrefutable authority of the logos governing the elements of the world and the objective harmony of the cosmos would become clear. In a medieval feudal society, however, one's path in life was entirely prescribed by a set of strict rules whose universal validity required no proof or empirical evidence. The thinker's attention therefore turned from the human as a cosmic being, the nature's elements made flesh, manifestation of the living cosmos, to one's inner spiritual world, which is something else entirely than the world of natural, bodily things. In ancient Greek society, personal spiritual inner world did not exist in the sense it later emerged in the feudal society. Why?

We observed that in the ancient world which was directly founded on forced labour or slavery, human status was reserved to free-born citizens whose personality, ego, was expressed in how they exerted their influence in the ecclesia, the popular assembly of the polis, and what their "talking tools", or slaves, as a certain type of natural objects, could produce. Feudal society, however, was no longer founded directly on forced labour. Here, direct labourers could not be treated simply as mere material property, their master's "talking tools", and the master's own role did not develop spontaneously either, as a direct consequence of his political skills and abilities. Direct labourers already performed independently whole sequences of work tasks and, just as their master, they were human beings with a will and a mind of their own. Although they were dependent on their master, they also enjoyed a few rights and had a spiritual self that was theirs only, had their own personal emotions and will. While the ancient Greek society appeared and behaved like a force of nature and the people therein could feel as part of the cosmic harmony emerging in that maelstrom, the feudal society was built of interpersonal, individual relations and patterns, which did not seem natural or stemming from elemental chaos, and the entire world became individual-centered. That hierarchical system of individual relations, which determined everyone's place in either the higher or lower social order and everyone's duties to each other, was indeed regarded as God-ordained, yet in the medieval perception, God acquired the image of a spirit opposed to nature. While the ancient deities were seen as governed by cosmic harmony, the medieval personified God was the creator of the entire world and ruled it however He saw fit. The Christian God is bound by no harmony, fate or law that is external to him, but is believed to be omnipotent and able to work miracles, which, in fact, is an important concept of this religion.

Such a conception of the almighty God, the transcendent creator and sovereign leader of the entire world, could only emerge, of course, if the inner world of an individual acquired a certain independence through human activity, allowing it to distance itself from the society and nature which was the material world. The medieval men and women often perceived their existence in material world as a shackling experience—everywhere, everything was governed by a particular order which demanded your submission and which could not be influenced or changed. At the same time, that world was the world of human activity and not a playground for the raging forces of nature. In a feudal society, no world picture could emerge without the human activity component, since social practices, or the real life, which shaped the world picture, were such where connections and relations that were divorced of human qualities (or "superhuman", divine qualities), the world of things, had no significance on their own. Like in an ancient society, life in a medieval society was not based on direct identification of the objective relations of the external world, on the authority of the things themselves and the objective relations between them. In the Middle Ages, authority was vested in tradition, rules, regulations and laws established by the people (society), although the people (society) had become an "absolute being"—God. The farmers or craftsmen of the feudal society, as well as members of any other trades, had to learn and strictly observe the traditional rules governing the activities in their particular field. However, the degree of perfection with which one learns and understands the rules and acts on their basis depends solely on the person himself. For example, a craftsman, having acquired traditional working methods and making traditional things, makes any of such things himself and can do it either better or worse than other craftsmen, his predecessors and contemporaries. Every such thing, every result of an activity possesses the individuality of the maker, something that arises neither from the thing itself nor from the rules governing its making.

So it transpires that in addition to the external world, the world of things and laws external to people, there also exists an inner world, which can be accessed only by its owner, or directly by God. That inner world is the site of the person's will, skills and abilities—the person's soul which controls the body and which bows to no rules and answers to no worldly lords. In the medieval world of things, social hierarchy and rules, there was nothing new to discover, no mysteries to solve, nothing to question—everything was as per tradition. Only one's soul could be explored, studied, improved and developed. Through the soul one could access God. The world was believed to be God's creation. The practices of the age and the real structure of the society gave rise to the view that God has created the world and rules over it rather in the same way as we create things through work and rule over them and over our bodies. However, being the opposite of humans, God is so perfect that His creation and His reign over His creation are not bound by any rules or anything at all. God's powers and options are limitless, all being His creation, all rules of His own making, all consequences the result of his own will, no need to have any prior assumptions—God has created the world from nothing. Therefore, the goal and higher purpose of a medieval cognition was to seek divine perfection, deliverance from everything mundane and mortal, train self-discipline and self-control in the ascetic spirit. A medieval scholar never took a purely abstract approach to the issue of cognition, but always tied it to a theological or ethical problem which he also (or in truth, primarily) hoped to solve, while also seeking the meaning of life, working on the perfection of his soul, trying to capture the essence of the divine or speak the language of God, to earn His love, to find a way to be as close to Him as possible. What was important was not the end result of the activity (no soul was left in the activity when finished), but the fact that the result had been achieved by someone, the activity itself, the efforts that had been made to attain perfection, the presence of soul. Perfection was to be sought in the pure spiritual pursuit itself, in the act of creation and not in the thing to be created. The thing was but a sign or symbol to remind us of the always unique, personal, animated process, the lesser or greater degree of perfection achieved in that inner process whose workings largely remain a mystery. The limit of perfection is God, to whom no limit can be applied and who cannot be identified with anything created, but who is the creator, reason, foundation, idea and the truth of everything that exists and of all the possibilities that may exist.

The most immediate reality of one's creative intellectual power is word. In words, all deeds begin. It is precisely the word that makes the most direct contact between God and a human being possible. To really know a thing, understand it, to reach its truth means to discover the divine design behind its creation, to find the word of creation, to understand the unique meaning of that word

Figure 13. God (under the sign of fire) reveals the secret of making the philosopher's stone to an alchemist. (Barchusen, 1718, fragment of Table 1, pp. 502–503)

in its unique context which describes the divine creation situation. Therefore, the principal work of medieval scholastic scholars was the increasingly detailed and precise analysis of the Scriptures. Of course, given such a goal, no objective criteria exist whereupon we can rely when deciding which interpretation is the closest to the divine creation situation. Consequently, what eventually counts is the opinion of the authorities. The work of a scholastic scholar would only find recognition if he could defend his conclusions before other scholars by careful referencing to authoritative sources.

One's scholarly erudition determined the rank of the position attainable in the clerical hierarchy. The erudites were higher up, i.e., closer to God, than any lay persons of any trade, as the erudition of clerics lent them the authority to speak in the name of God or even claim the position of God's representatives on Earth. The scholars' focus in their study of God's creation drifted increasingly towards finding more and more evidence in support of the hierarchical structure of the world, so as to demonstrate their growing closeness to divine wisdom and eventually obtain again and again new confirmation of the clerics' entitlement to high positions in society. Initially, their studies were limited to the "divinely inspired Scriptures", to which the Greek wisdom was added in the 11th–13th

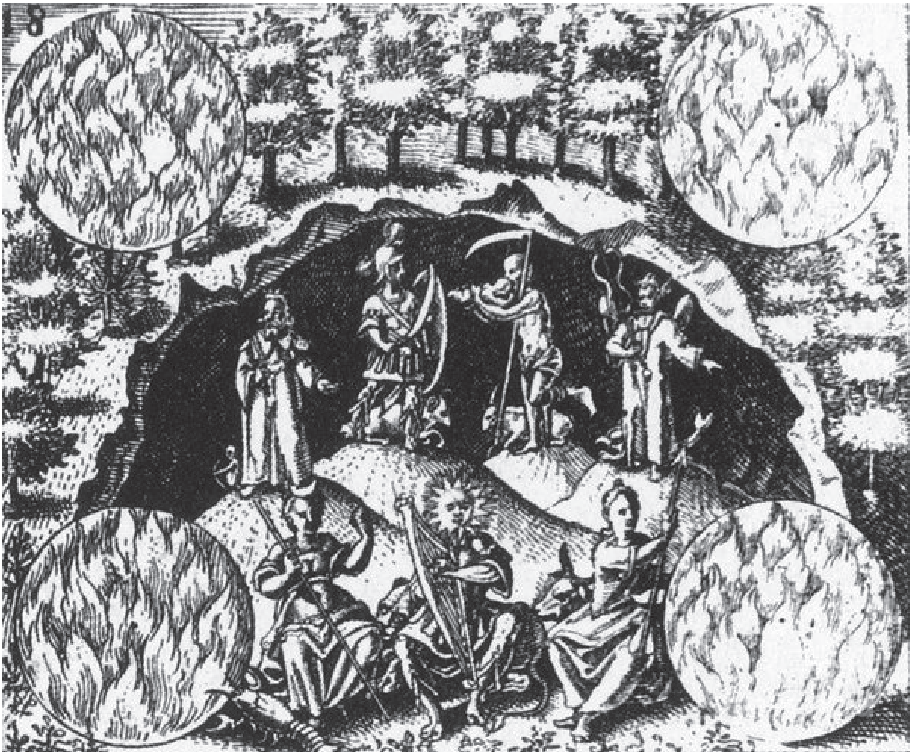

Figure 14. 'The Seven Metals.' *Front row*: silver (Moon–Diana), gold (Sun–Apollo), copper (Venus). *Back row*: tin (Jupiter), iron (Mars), lead (Saturn), mercury (Mercury). Here, however, their order is slightly confused. In their proper order of increasing perfection, they would appear as follows: gold, silver, tin, lead, copper, iron, who are born to this world from their mother, mercury, from her union with sulfur. (Stolcius, 1624, Fig. 50)

centuries—primarily the Aristotelian philosophy which, as we already saw, was exactly the right framework in which to serve the hierarchical structure of the world—and, finally, nature, which was called the Book of Nature, in reference to Bible (from Greek *biblion*, which simply means a 'book'). In nature, the medieval scholars did not seek to find evidence for physical laws, as modern scientists do, but confirmation to God's wise creation, the hierarchical structure of the world.

What does such an activity have in common with science? In terms of its goal and method, nothing. But otherwise, a couple of commonalities can still be pointed out. Scholastics and scientists both conduct their activities in a manner which

Figure 15. 'Wolf devouring a dead king.' This image symbolises the purification of gold with antimony (wolf). In the background, we can see the king emerging alive from the flaming pyre. (Maier, 1618b, p. 105)

amounts to a certain discipline that has its own rules, written and unwritten laws, specific instructions as to which kind of research questions to formulate, how to find the answers, which requirements must be complied with and which criteria an acceptable solution to a problem must meet. The obligation to provide references to predecessors, the requirement of original contribution, the tradition of discussions and disputes, thesis defence procedure before a panel of learned academics, academic degrees and titles and, last but not least, without which a discipline cannot survive, academic training of new succeeding generations of scholars at universities (which originally evolved from monastic schools)—all of this science has inherited from the scholastic tradition.

Let us return our focus on alchemy. Its Great Work was certainly a typically medieval conception, but it also had heretic and pagan connotations. It aspired to a greater closeness to God than allowed by the official scholastic tradition.

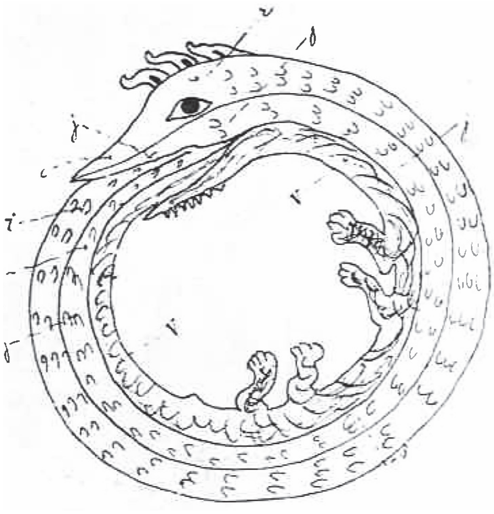

Figure 16. One of the earliest alchemical depictions of a serpent eating its tail. Letters r, j and v denote the colours red, yellow and green which represent different stages of transmutation (green is the initial stage, the raw matter, and red is the final stage, the ripe matter, between them is yellow, the intermediary stage). Ouroboros design based on a 1474 medieval manuscript illustration. (*Wikimedia Commons*, 2015a)

Alchemists used, in a sense, more effective methods, all of their work resembled God's work in a more apparent and direct way. They could regard themselves as creators, equal to God, and not mere observers and interpreters of God's work and divine predestination.

Although the entire alchemical Great Work appears rich in symbolism, the chemical processes it relies on are very real and tangible. Its chemical aspect can sometimes be so "transparent" and requires so little deciphering that we can magnanimously forgive an unnecessary reference to an imaginary serpent or the language that waxes lyrical about the magnificent yellow hue. For alchemy, however, all of that real chemistry is of secondary importance; it is simply a reflection of the primary reality of the world of divine meanings and actions. Set in a biblical context, the tail-eating serpent could signify the divine knowledge to which the humans were tempted by a fallen angel. The same serpent also symbolises the pagan (pre-Christian) ideas of the cycle of life and death, eternal reincarnation and much more. We know that alchemy linked metals to particular celestial bodies and corresponding guardian deities: gold corresponded to the Sun (Apollo), silver to the Moon (Diana), copper to Venus, iron to Mars, lead to Saturn, tin to Jupiter, mercury to Mercury. Fire, naturally, in the Great Work means the fire of purification. Chrysopoeia, the infamous quest of making gold out of lesser metals, however, symbolises the pursuit of perfection. It is the tale of the noble Christ in whom God was made flesh, who took our sins unto Himself and by His sacrifice redeemed us, and then rose from the dead and ascended to heaven, returning to His perfect state. In alchemy, it is the perfect gold who by its sacrifice becomes rusted iron, its base

Figure 17. The descending bird symbolises the condensation of the vapours of mercury (female principle, Moon) and sulfur (male principle, Sun). As we can see, the Sun and the Moon are sealing their union (with the promise of the elixir and the alchemical gold and silver). (*Rosarium philosophorum*, 1550)

self. By the intervention of the philosopher's stone, the iron, however, would be restored to its perfect self and made gold again. So, the alchemical transmutation of metals symbolises in the world of material and palpable things the sacrifice and resurrection of the Christ, as well as the human aspiration for spiritual and moral perfection. Also, the analogy with the work of God is complete. The alchemist's microcosm exists as a replica of the macrocosm in which the God's role has been assumed by the alchemist. God is capable of working miracles. The alchemist's miracle-working powers are represented in the philosopher's stone, otherwise called the Elixir of the Wise, Elixir of Life, universal medicine, etc. The creation of the philosopher's stone is the pinnacle of the sacred art of alchemy, its secret of secrets. This is to be achieved through moral self-improvement or the "purification of the soul" and a stressful creation process following the intentionally obfuscated instructions of an alchemical recipe.

The alchemical Great Work helped the medieval mind to make sense of the world in a way humans could relate to. As we know, in medieval times, the things which humans created were always intended for someone particular, and they represented the process of their creation and the craft of their creators. Alchemy indeed emphasises the creative, animate component of the human's (and God's) work. What is important is not so much the particular objectified result of the activity, but the activity itself, its significance, the emotional experience gained through the process, the opportunity to indulge in internal reflection. The exaggerated mysteriousness of the Great Work, the poetic language, artistic illustrations, the colours, smells and tastes of chemical substances, all of it is in the direct service of alchemy's principal goal, which is to experience the spiritual process of world creation and to attain the human moral perfection.

Figure 18. The green lion devouring the sun (changing the lion's colour to gold), with blood dripping from its mouth, symbolises the elixir-yielding transmutation process which takes place between philosophical mercury (blood) and philosophical sulfur (Sun), the elixir's second component and also precursor to alchemical gold. (*Rosarium philosophorum,* 1550)

In alchemy, on the one hand, all chemical substances are real chemical substances which are used in real chemical processes, but on the other hand, which is more important to alchemy, the real chemical identity of these substances is only a trivial matter. It is not important at all, for example, that gold should be really gold and the red oily liquid really human blood or even "true" philosopher's stone. What is important is for the alchemist to experience the divine moment of creation and to develop the divine qualities in himself.

3. What is iatrochemistry?

We have already stressed that alchemy was a medieval cultural phenomenon which also exhibited a certain heretic streak. In that sense, we could say that the advent of the Renaissance which heralded the end of the Middle Ages did not come as a surprise for alchemy. In the 16th century, "classical" alchemy mutated into "medical" alchemy, known as iatrochemistry (Greek ἰατρός means 'physician'). Most chemistry historians regard iatrochemistry separately from alchemy and consider it an individual stage in the evolution of chemistry, but in our view, it is simply the alchemy of the Renaissance. In this particular case, a peculiar twist of historical irony comes into light. Namely, the Renaissance, the word which in French literally means 'rebirth', was so called because of the revival of the culture and ideas of ancient Greece and Rome, all the while the Middle Ages were transitioning into Early Modernity. Paracelsus, one of the founders of iatrochemistry, an essentially Renaissance phenomenon, however, dared to come forward with fundamental ideas of medicine that directly contradicted those of Hippocrates (*c.* 460 – *c.* 370 BCE) and Galen (*c.* 130 – *c.* 200), the foremost ancient medical authorities. (Of course, Renaissance did not necessarily mean simply a return to the creators of the culture of ancient Europe, rather, it encouraged to overcome the medieval bias towards certain thinkers of antiquity and embrace all of the intellectual legacy of the ancient world, so that part which had been neglected and forgotten could be used to justify, validate and corroborate recent contemporary developments. Medieval world, for instance, had held the Aristotelian philosophy and Ptolemy's geocentric model of the universe in very high regard, and in that respect, the Renaissance could, at least at a first glance, mean the rejection of the authorities of the ancient world. The Renaissance-era scholar Nicolaus Copernicus built his defence of the heliocentric system, which refuted the geocentric doctrine of Ptolemy, an ancient philosopher, on the works of other ancient philosophers, such as the Pythagoreans and Aristarchos, whose existence had been largely forgotten, and also on the overlooked arguments of the well-known authorities, including even Aristotle.)

Hippocrates and Galen recommended natural medicine for the treatment of diseases and maladies, whereas Paracelsus preferred the fruits of the alchemists' labour—that is, the artificially created chemicals. Paracelsus (whose full name ran Philippus Aureolus Theophrastus Bombastus von Hohenheim) very much stressed the independence of both himself and his theories (also asserted in the choice of his name, whereby he claims to "surpass Celsus", the famous Roman medical scholar.)

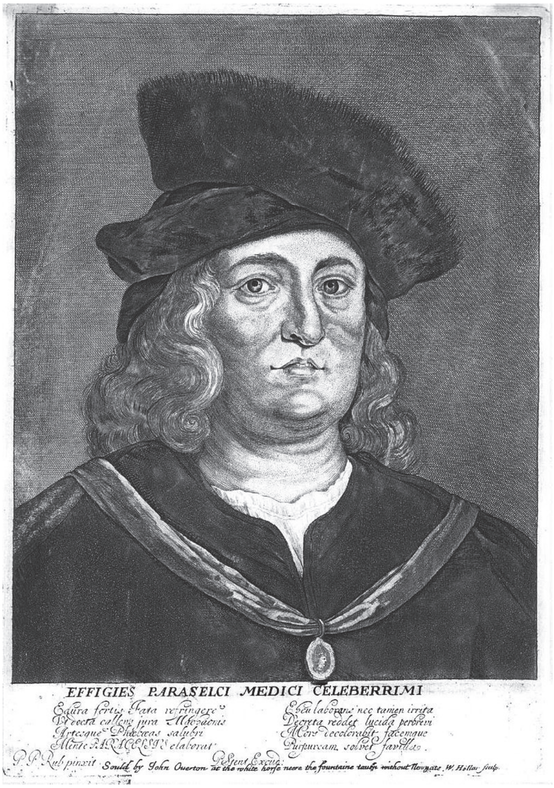

Figure 19. Paracelsus (1493–1541) by Wenceslaus Hollar (17th century) after Peter Paul Rubens. (*Wikimedia Commons*, 2019d)

For the improvement of medical knowledge, he also turned to folk medicine and the experience of various medical practitioners, such as barbers, faith healers, witch doctors and soothsayers. As a theoretical doctrine, however, Paracelsian iatrochemistry was nothing more than medicine-oriented alchemy. It was built on the fundamental concept of *tria prima*, the principles of sulfur as the prime of flammability, mercury as the prime of volatility, and salt as the prime of solidity, which in alchemy are the constituent elements of metals. According to Paracelsus, the human body is also defined by *tria prima*—mercury is the spirit (*spiritus*), sulfur is the soul (*anima*) and the salt is the body (*corpus*). Another important concept is *archaeus*, the vital force residing in one's stomach and regulating all bodily functions. A failure of the *archaeus* would cause an imbalance in the body, give rise to a disease. The balance can be restored by alchemical, i.e., magical, and by chemical means. An important cure would lie in the alchemically obtained "quintessence" (*quinta essentia*) which has wondrous powers.

How then was medicine brought to the attention of alchemists (or medical alchemists)? That alchemy would assume a medical form was, of course, not an outcome dictated by the alchemy's own internal logic of development or general development logic of human cognition. (According to one view, however, iatrochemistry emerged, because by the 16th century, based on their experience, the alchemists had come to realise the futility of their efforts to make gold and saw much better potential in the creation of new medicines.) The 16th century was the time when medieval artisans' workshops were turning into manufacturing enterprises and new developments in commodity production were changing the economic structure of Europe. The cities were growing fast. The developing dense population concentrations were extremely vulnerable for epidemic spread of infectious diseases, not in the least because of the non-existent sanitation (sewerage was an unheard concept) in the suddenly overcrowded cities or villages turned into cities. Through its flourishing trade with Oriental countries, Europe imported not only exotic goods, but also pandemics of plague, smallpox and cholera. No knowledge existed about how to deal with such diseases, how to contain epidemics, as the traditional treatments and medicines were utterly useless. It seemed that only miracle-workers with access to arcane secrets and God-like powers, defying the God's will, could be of any help here. And alchemists were exactly such people who would claim equality with God.

In that context, it was only natural for the alchemy to assume a medical character. The original core of alchemy, the belief in the unity of the microcosm (a human being, human activity) and the macrocosm (all of the outside world), favoured by the ancient (and Oriental) philosophers, was preserved intact in iatrochemistry, with the antiquity's notion of cosmic fate and the medieval Christian doctrine of divine predestination now being supplanted with the Renaissance vision of human sovereignty over the microcosm, equal to God's sovereignty over the macrocosm.

Suffice to say, in the war against diseases, iatrochemistry fared neither better nor worse than the traditional medicine of the time, epidemics remained the "scourge of God" and survival never depended on anything else than God's mercy alone. Only by chance and luck could an alchemist/iatrochemist stumble upon an effective (or seemingly effective) cure. Several new medicines (such as mercury treatments for syphilis) and principles (the concept of disease being a chemical imbalance in the body and its treatment being a restoration of that balance, the dose of a medicine determining its beneficial or harmful effect, etc.) which were brought into medical practice still remained only byproducts of iatrochemistry as an alchemical operation. Iatrochemistry, however, did exert a certain ideological influence on the medical practice. It encouraged practitioners not to be afraid to explore new ways of treatment, to seek out alternatives for traditional medicines. Of course, the specifics—what is effective against which disease and in which dose—required all separate investigation. Iatrochemistry, that medical variety of alchemy, provided no solutions as to how to obtain these answers.

III Phlogiston theory put chemistry on a stable basis as a science

The question of when chemistry became a scientific discipline, in truth, still remains without a definite answer by historians of chemistry. That does not mean, of course, that it has not been attempted or that no answers exist. On the contrary, many answers have been suggested, one as good as another, and since no one's argument has been convincing enough, no consensus exists among historians of chemistry. Perhaps the most common view is that the foundation for chemistry as science was laid by Robert Boyle[3] (1627–1691), yet it grew into a science proper only through the efforts of Antoine Laurent de Lavoisier (1743–1794), whose revolution in chemistry toppled the incredible phlogiston theory from its position of power. In this chapter, as suggested by its title, we will argue for the hypothesis that the moment when chemistry became a science coincides precisely with the formulation of this seemingly preposterous phlogiston theory. Lavoisier's revolution, of which we speak in the next chapter, was already a revolution within the evolution of chemistry as a science. We start the history of chemistry section of this chapter with the Honourable Robert Boyle, founding member of the Royal Society of London for Improving Natural Knowledge, and his take on chemistry, but before that, we speak of science in general.

1. How does the world look in the eyes of science?

In the 17th century, in the days of Robert Boyle, science had already been born. By convention, we regard Galileo Galilei (1564–1642) as the first true scientist. He was not only a scientist—a physicist, a mathematician and an astronomer—but also one of the first philosophers of the new age, the so-called Age of Science. Whether Galileo really was the "first true scientist" is still being debated by historians of science and philosophers, but it is the indisputable fact that Galileo was *a* scientist, his method of research was a scientific method and the knowledge

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[3] Friedrich Engels also notes in his *Dialectics of Nature* (which, as we know, is an unfinished work from 1883, the published book was compiled from manuscripts after his death), "Boyle put chemistry on a stable basis as a science." (Engels, 2010, p. 466) Admitted, elsewhere in the same book we can also find a contradicting claim—that it was the phlogistic theory which allowed chemistry for the first time to emancipate itself from alchemy.

Figure 20. Galileo Galilei (1564–1642) by Ottavio Leoni (1624). (*Wikimedia Commons*, 2017a)

he obtained by the application of that method was scientific knowledge. For the purpose of our following discussion, this will suffice. For example, we do not have to argue whether, before Galileo, at least Copernicus (1473–1543) was already a "proper" scientist or not. Still, it is worth noting that Copernicus, a Renaissance scholar, while his ideas were heretical, remained essentially scholastic in his method—regardless of the revolutionary nature of his theory, he could only rely on scholastic traditions for support, rather than on the arguments of science, since the scientific world picture had not yet been formed in the first half of the 16th century. However, for the benefit of the reader, we must briefly explain the nature of Galileo's method, i.e., the scientific method. First of all, we need to understand (again referring to the "bias" mentioned in the Introduction) the type of culture that had emerged by the 17th century and was based on the capitalist mode of production. We are interested in the particular social relations and corresponding forms of thought this mode of production gives rise to, the human world born of capitalism, the capitalist era world picturing and the structure of thinking in terms of categories.

We have already mentioned that at the core of a scientific world picture lies the ability to see the world independently of the subject, the human being (and of the God who is also human, the omnipotent "absolute" human, modeled after human shape). In ancient and medieval periods, no such world picture could emerge, since in the human activity, the connections and relations that did not reflect that activity and belonged to the objective world of things did not have any significance in themselves; social relations and human activity always manifested themselves as relations between human beings and as the activity of humans (although that human activity was not unbound by the cosmic harmony or fate, or God's will). This seeming nonsense may perplex the attentive reader: what could the author possibly mean by emphasising that human activity manifested itself as the activity of humans? What kind of human activity can it be that is not manifested as the activity of humans anyway? There is no mistake, however. The paradox indeed lies in that the human activity of the modern era (including our most recent contemporary era) is defined by the world of things, the interobjective relations, the 'objectness'. And it is the task of the philosopher (the first thinker to come to this realisation was Karl Marx) to specifically demonstrate that our contemporary world is also a human world, that the interobjective relations and the independent world of things, such as "nature as such", do not exist outside and separately of the human activity, yet are themselves a manifestation of a particular kind of human activity.[4] That "particular kind of human activity" indeed began with capitalism and will remain principally the same until the full establishment of communism, i.e., including also under socialism. How, then, does human activity give rise to an independent world of things, a world of relations between things themselves and of their qualities and properties, on which our way of life depends and which we therefore take as our object of inquiry?

We saw that in the feudal Middle Ages every product of an activity spoke of its maker and its consumer. Every manufacturer, for example, performed a complete set of work procedures, followed traditional instructions and applied his personal skills to craft a particular object, a made-to-order artifact tailored to specific needs (of someone particular, very often, whose identity was known). In general, any activity was also a personal activity and any social relation was an interpersonal relationship, while the hierarchy of activities and persons was topped by and flowed from God. The basic relationship structure in medieval production was 'human–object'. With the development of capitalism, the situation changed, things lost their individual makers and consumers; the 'object–object' relationship type gained dominance and began to define human activity.

Already in early manufacturing, the simple workers toiling for their master could not identify themselves as the makers of the final product (and most certainly could not identify the person for whom the product was made), since no worker made the product from start to finish, but only performed a single procedure on it. The object which the worker made was not a complete, specific product, capable of satisfying a human need, but only a tiny piece of it, a component whose parameters and properties had to be such as to make it fit with other components constituting the whole thing. Let us pay heed to the fact that from

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[4] See, for instance, Karl Marx's analysis of commodity fetishism in *Das Kapital* (1867).

such a manufacturing process the personal element, the workmanship that was essential to the craft of a medieval artisan, had been completely removed: an item manufactured in this way had to be entirely devoid of the individuality of the person who made it (of course, in this case, no consideration could also be afforded to the customers' peculiar tastes and personal preferences) and had to conform to interobjective relations alone, without any significant deviation from the standard, to permit its smooth assembly into the whole that it was a part of. We can see that the basic preconditions for the development of machine tools and automated manufacturing had already been put in place by the medieval workshops, which simply cried out for a production process which would be broken down into smaller single standardised procedures whose execution can be handed over to the machines. Manpower was replaced by power from nature and the need for the traditional skills and know-how of artisans and their individual workmanship was replaced by the need for improved ways of harnessing energy from nature and tapping into the laws of nature, its "automatisms", for knowledge which would only express the relations and connections between the things themselves alone, their recurrent, invariant properties under given conditions. The world began to be conceived as an independent mechanism, a soulless automaton, and no longer as the ancient single all-encompassing complex living entity to which humans are inextricably linked, or as the medieval edifice of hierarchy, created by God, which speaks to humans of God. Things, their properties and relations which give rise to the mechanism no longer depended on humans, but the humans could learn how to exploit the mechanism, make it serve their purpose. The single living all-encompassing cosmos (which the humans themselves are a part of) or the divinely preordained system of perpetual hierarchies (which also defines the place and role of the humans therein) could only be described. It was possible to learn the functions of the other body parts in that giant living universe and of oneself, or to figure out the hidden motives and instructions of its Creator. The mechanical world, however, relates to us as the object, to which we relate as the subject. The human being with its purpose, creativity, aesthetic sensibilities and notions of freedom and morality is now placed outside of the world (the object, the mechanism), being a source of unwanted subjectivity which should be eliminated. The human belongs in the world only as an object, thing, as a mechanical detail or function. The society acquires the character of immediate object, social relations become objectified, the relations of the world of things—the impersonal economic relations among the capital and labour power, among commodities. (Such a characterisation applies to capitalism alone, of course; however, as we already mentioned, the type of human activity that began with capitalism is also preserved in socialism in its basic form, since the social relations under socialism inevitably continue to be shaped by the world of things, they are determined by the mechanism of economy and depend on objective conditions: production of commodities remains, the levels of labour and consumption require objective, formal and comprehensive monitoring and control, etc. Generally speaking, in the absence of the material and technical base of communism, in social life, the necessities of improving material production will inevitably prevail and it will not be possible, no matter how much we want it, to develop social relations as immediate and close human relations, to satisfy all the needs that we as humans have and to make those needs truly human.)

While Aristotle, whose philosophy shaped the way nature was viewed both in the antiquity and (regardless of significant differences) in the Middle Ages, gave us the account of four causes, of which he regarded the formal cause (the immaterial form) and the final cause (the purpose) above the others, and taught us that the goal of cognition is to uncover and understand the ultimate, innate form of every object and its natural place in the universe, then in the modern world picture, one no longer finds the purpose and immaterial form as the essential, intrinsic qualities of an object. The object's form, its qualitative delimitation, turned out to arise from the matter (material, substratum) as a result of efficient causes—the forces of nature—and objective laws. In modern times, the word 'cause' has indeed come to mean the efficient cause alone. The final and formal causes only remained as categories that characterise the subjective domain, the conscious human activity. To this day, we continue to claim that the nature itself has neither purpose nor goal, only humans can set goals, which they can also achieve in nature if they know its laws. And within the limits of the laws of nature, a natural object can be given any kind of form, actuality, quality. Objects became products of artificial construction within the confines of the laws of nature, their qualitative delimitations and properties lost their intrinsic nature, priority, superiority, turned out to be derivations, arising from the structure of the object. The purpose of cognition now became to determine the nature and extent of the potentiality of constructs. This, however, implied a change of course towards the discovery of the physical laws and the experimental exploration of nature.

Aristotle's account of causality was a generalisation of human activity in categories of thinking, which was subjected to qualities, forms, purposes and prescriptions defined by society and nature. Humanity was trying to discover its own nature and learn how to govern itself, human activity was aimed at gaining an understanding of the existing world and finding a way to live in harmony with that world. In contrast, the human activity in the modern era is completely different: it is aimed at changing and transforming of the world. Humanity is no longer interested in what is, but what is possible. It is no longer willing or able to govern itself, but wishes to govern the external world, realise its purposes therein, using the incontestable laws of the external world itself, increasingly mediating the human–nature relations and human–human relations with the world of things, objectifying the human world, making it technical, formal, automatically functioning. While in the days of Aristotle, experimenting and technical arts were regarded as unbecoming of a thinker and completely useless for the purpose of exploring nature, then Galileo's time already marks the advent of the era of technology and engineering, radically changing the notion of what is worthy of investigation and what is not, of what is "natural" and what is "distorted".

The central premise of Galileo's world picture was the essential mathematicity of the world. He is famously known to have said that the Book of Nature is written in the language of mathematics and in the characters of geometry. Galileo's atomistic and mechanical world picture is often seen as a revival of Democritus' atomism. However, regardless of the coincidental overlapping of several ideas, we cannot really speak of a true revival. Primarily, since for Galileo, atomism truly was an actual world picture, a particular construct which determines what we see of the real world, while for Democritus (and for the antiquity in general), the world represented itself. The human being was "caught" in the reality and atomism (or ancient philosophy in general) was only an attempt to express and explain that being as a logical system of related concepts. Secondly, as demonstrated by scholars of Galileo's works, Galileo was critical of Democritus' views and borrowed directly from him almost nothing. (How the modern theories actually relate to the ancient atomism of Democritus will be yet discussed in more detail when we come to Robert Boyle and his views.) According to Galileo, the primary properties of bodies of matter or "corporeal substance" are their size and shape, location and time, motion or rest, their number and contact (or the absence of such) with other bodies. The sensory qualities of taste, colour, sound, odour, etc., do not exist in bodies, but only represent their effect on the subject. Unlike Aristotle, who identified matter as the source of imperfection and uncertainty, therefore making the mathematical forms imprecise and rendering the mathematical expression of the physical world impossible, Galileo found that physics and mathematics were always in harmony with each other. Failure to recognise this harmony could only be attributed to the incompetence of the observer who may attempt a mathematical description of the world that is not real, but only as it appears on the surface.

How then can we attain a true undistorted perception of the world? According to the commonly held view, the difference in Aristotle's and Galileo's methods lies in that Aristotle never relied on empirical observations, only on speculative thinking, whereas Galilei worked with empirical data gathered from experiments and avoided abstract theoretical reasoning. That is a simplistic and skewed understanding. Aristotle and Galileo were both theoretical thinkers and both also used empirical observations. Certain Aristotle's claims about nature actually have even better correlation with experimental data (for example, under normal conditions, bodies fall more according to Aristotle and less according to Galileo)! Only in that case we would miss the point of a scientific experiment as Galileo understood it. It all boils down to Aristotle's and Galileo's different ways of thinking, specific to their respective eras and their different goals. It was Galileo's view that the true essence of a phenomenon can only be captured when such aspects which under normal conditions remain hidden are also taken into account, when it is possible to obtain the phenomenon in its "pure form", when it is possible to create its mathematical model and then predict its behaviour under different conditions and explain what causes the "distortions".

A mathematical "undistorted" object, the pure form of a phenomenon means an idealised object, i.e., an object which in reality does not exist. Therefore, it seemed to Aristotle who wanted to understand the true nature of the world that any lines of argument whose premise contradicts the most obvious truths are unworthy of any consideration. For example, it has been discovered that Aristotle has "coincidentally" also asserted Newton's First Law by claiming that in the void a body would remain at rest, or if it already moved, it would continue to move forever at the same unchanging speed (*Phys.* IV.8, 215a19–21). Yet Aristotle would deem it absurd to think that the bodies in nature move according to that law and that an empty airless space exists. If Aristotle had been told that under normal conditions in nature no truly empty space exists, but an almost empty space can be achieved under experimental conditions, then Aristotle would have shown no interest in such a folly, since it would have meant attempting to trick the nature, to find extreme conditions which deviate from the natural state and nature of things. In Galileo's days, however, as we know, technological progress was already starting to gain momentum and consequently, constructive activity was also becoming a more commonplace and acceptable activity, and that changed radically the understanding of what is distorted and what is true representation of nature, what is subjective and what is objective. Although idealised objects do not exist in the normal sense, the physical laws which describe their behaviour form the basis for technology design and engineering, for the creation of the so-called second nature, the one that has been restructured by the humankind.

One cannot trick the nature, rather, it is the nature who tricks the humans, since it only permits a limited view of itself, within the subjective perspective of a particular observer. For a complete picture, it is necessary to give up the single subjective perspective and observe the natural phenomenon from all possible sides, under all conceivable conditions. How can this be accomplished? As it turns out, what leads to the creation of theoretical idealised models are exactly such aspirations. Indeed, to examine a phenomenon under different sets of conditions, eventually under all conceivable conditions, it is necessary to conceive the phenomenon as it is outside of all conditions, in its pure form. What is important is no longer the phenomenon as it occurs under particular observable conditions, but the law of that phenomenon, that something that determines the possibility and observability of the phenomenon irrespective of the subject who perceives it. For such a conception of the phenomenon not to remain completely arbitrary and speculative, but really lead to the discovery of its law, the procedure of whittling away the conditions needs to be grounded in reality, proceed from a situation where the phenomenon itself approximates its idealisation, i.e., behaves as if no "distorting" conditions existed. It is precisely for the enactment of such a situation that we need a scientific experiment.

For instance, let us examine how Galileo discovered his law of falling bodies. Based on diverse observations and experiments which he had conducted and which he interpreted within his scientific world picture, Galileo came to the conclusion that the speed of a freely falling body depends on the resistance of the medium it falls through, not on the body's weight, as had been claimed and also empirically proven by Aristotle who understood free falling as it naturally occurs, i.e., in air. According to Galileo, truly free falling, i.e., the phenomenon in its pure form, only occurs when unimpeded by the resistance of a medium. And Galileo proved that in empty space all bodies would fall the same way. He relied on special experiments which showed that as the resistance of the medium decreases, so does the difference in the falling speeds of different weights. Hence the logical conclusion that without any resistance from the medium, the differences in the falling speeds of different weights would also disappear. As we can see, idealisation implies shifting to the limits of the changes observed in real experiments. The emerging idealised objects are already mathematical objects to which mathematical definitions and operations can be directly and fully applied. Instead of a real physical body, Galileo eventually operated with a point, with the real environment becoming a geometrical space, and the problem of physics being reduced to a problem of geometry. In this way, the creation of a mathematical model is the logical next step following the experimental stage and vice versa. It becomes possible to switch between the two and model the first on the basis of the second and the second on the basis of the first. This was exactly the reason why Galileo could claim that the Book of Nature is written in the language of mathematics.

2. Did Robert Boyle put chemistry on a stable basis as a science?

While in the realm of physics (mechanics, astronomy), Galileo both developed its scientific method and used it as a scientist, in chemistry, the role of Robert Boyle remains limited to that of a philosopher and visionary who was not yet a scientist. Boyle conceived chemistry at the general level of scientific world picture, while the experimental design in chemistry still remained out of his reach (Boyle certainly did conduct experiments, but his chemistry experiments, and the ones conducted by both his predecessors and successors, did not follow the Galileian method). He was incapable of producing the idealisations of real chemical phenomena, formulating laws, let alone developing a scientific theory. Boyle approached chemical phenomena as a natural philosopher. By philosophical speculation, he tried to find answers to both general philosophical problems and specific chemistry problems whose proper solution would require the application of the scientific method. Indeed, Boyle himself did stress that the main motivation behind his chemistry investigations was to make a contribution to philosophy and not so much to chemistry itself, and to achieve agreement between his mechanico-corpuscular philosophy and chemistry. To set such a goal was perfectly reasonable in the 17th century, since, although the scientific world picture had already become established, chemistry remained outside the range of its application. Chemistry was essentially still alchemy, but the latter had lost its meaning in the new era, having been reduced to an obscure art of mystics or medics, or simply to a set of practical skills, prescribed knowledge. Boyle (and several less well-known philosophers before him) wanted to demonstrate by philosophical analysis what problems of chemistry look like when approached from the perspective of the scientific world picture and scientific method, and hurled his merciless criticism at the many unscientific doctrines still dominating in chemistry at the time.

Figure 21. Robert Boyle (1627–1691), line engraving by B. Baron (1722) after J. Kerseboom. (*Wikimedia Commons*, 2018c)

Robert Boyle published his main chemistry-themed treatise anonymously in 1661, under the full title of *The Sceptical Chymist: or Chymico-Physical Doubts & Paradoxes, Touching the Experiments Whereby Vulgar Spagirists Are Wont to Endeavour to Evince Their Salt, Sulfur and Mercury, To Be the True Principles of Things* (Boyle, 1661). It was presented in the form of a dialogue, just as Galileo's *Dialogue Concerning the Two Chief World Systems* (1632) and *Discourses and Mathematical Demonstrations Relating to Two New Sciences* (1638) had been. In these works, Galileo created the fictional characters of two adversaries who clash in dispute: Simplicio, a faithful disciple of Aristotelian thought, and Salviati who represents Galileo's own views and ideas. The third character, Sagredo, serves as their referee. Boyle also employs similar fictional characters in his *Sceptical Chymist* to represent different viewpoints. On a summer day, an august company of four fellows gathers in a cool and shady garden, alongside the unnamed narrator who takes no part in the discussion, but reports to us what he sees and hears. These fellows bear the following dignified names: Themistius (meaning 'just' in Ancient Greek), the Aristotelian who represents the Peripatetics; Philoponus (meaning 'diligent'), who takes the side of Paracelsus and Spagyrists[5]; Carneades (named after the Greek Academic sceptic), the host who speaks Boyle's own mind; and Eleutherius (meaning 'free' or 'impartial') who leads the discussion. However, before we can give the reader an account of the matter and manner of the dispute between these four men, it

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[5] Spagyrists (from Ancient Greek *σπάω*—'to draw out' and *ἀγείρω*—'to gather') was the name by which the followers of Paracelsus identified themselves. The term itself also comes from Paracelsus.

is also necessary to make a mention of the French philosopher René Descartes (1596–1650), since both his and Galileo's ideas are central to Boyle's world picture. Of course, it will be neither necessary nor possible here to indulge in a comprehensive overview of Descartes' works and significance as a philosopher and scientist (active in the fields of mathematics and physics), our intention is only to point out several direct connections between his and Boyle's views.

First, in the case of Boyle, we have a good reason to speak of Descartes in relation to the title of the recently mentioned book. When Boyle called himself a "sceptic", he certainly did so in the Cartesian sense of methodological scepticism. Unlike the "true sceptics" who doubted even the possibility of true knowledge, both Descartes and Boyle emphasised that doubt is only a method for sorting out the claims and beliefs of whose truth we can be certain. This principle condemned the scholastic method and the unquestioning acceptance of authority and dogmas. In Descartes' view, we cannot claim to have a true knowledge of an object, unless that object is a creation of our own, based on the ideas arising in our mind. How something was created by God or nature (what was its innate nature, its natural form, character, purpose, etc.) we do not know and will never be able to know, yet if we ourselves follow God's suit, then we cannot be worse than God. Boyle's credo was also very much in the spirit of the new era:

> For I am wont to judge of Opinions as of Coins: I consider much less in any One, that I am to Receive, whose Inscription it bears, than what Metal 'tis made of. 'Tis indifferent enough to me, whether 'twas Stamp'd many Years or Ages since, or came but Yesterday from the Mint. Nor do I regard through how many, or how few, Hands it has pass'd for Current, provided I know by the Touch-stone, or any such Tryal, purposely made, whether or no it be genuine, and does or does not deserve to have been Currant. For, if upon due proof it appears to be Good, its having been long and by Many receiv'd for such, will not tempt me to refuse It. But, if I find it Counterfeit, neither the Princes image or Inscription, nor its Date (how Ancient soever,) nor the Multitude of Hands, through which it has pass'd unsuspected, will engage me to receive It. And one disfavouring tryal, well made, will much more discredit It with me, than all those specious Things, I have nam'd, can recommend It. (Boyle, 1686, sig. 6v)

Such a principled sceptical attitude did not allow Boyle simply to accept as true neither Galileo's atomism nor Descartes' world picture, but required their critical examination and reworking. Galileo's atomism was seen as the revival of the ideas of Leucippus and Democritus and understood as the denial of the continuous

Figure 22. René Descartes (1596–1650), line engraving by G. Edelinck after F. Hals (1649). (Wellcome Library, no. 2473i)

structure of the matter which was assumed to consist of indivisible and immutable particles *(ἄτομον* indeed means 'indivisible' in Ancient Greek) and of the empty space between them. Descartes' world picture rested on the exactly opposite assumption, i.e., that of the continuous structure of matter (that idea was also nothing new, already existing in the antiquity, espoused, for instance, by Aristotle). According to Descartes, matter consisted not of atoms but of corpuscles. That is, matter does have its elementary building blocks, yet these particles are not necessarily totally indivisible and immutable, but are all modes of universal matter, the essence of which is extension; matter "fills" the space entirely, although it can appear in different degrees of density. Boyle also had corpuscularism as the cornerstone of his world picture, which can perhaps also be described as a "practical atomism". The gist of such an approach lies in that there is no reason, in principle, to rule out any further divisibility and mutability of a body that for all intents and purposes appears irreducible, but there is also no reason to consider that body reducible until practically proven to be so.

Let us now return to *Sceptical Chymist*. Boyle, as most historians of chemistry would, makes Eleutherius the Judge lead the debate and Themistius the Aristotelian and Philoponus the Spagyrist participate in the debate in such a manner that they concern themselves with such matters only which are of interest for Boyle. The main questions which Boyle sought to find an answer to were the following: 1) Is fire really a true"universal analyser"? 2) Are the products of combustion really true elements? 3) Is it really justified to limit the number of elemental substances to three, four or five? 4) Do the elements 'salt', 'sulfur' and 'mercury' really exist? 5) Are any elements actually real?

In his book, Boyle points out that it has never been empirically proven that any of the Peripatetic (or Spagyric) elements truly is an element or that the number of elements is limited to exactly these four or three. It is also completely without grounds to classify two substances as one and the same only on the basis of just a few properties they may share by coincidence, as the Peripatetic and Spagyric camps both have been doing (such as regarding all volatile substances as 'air' or 'mercury'), with no concern for the fact that on the basis of many of their other properties the substances should be different; to be regarded one and the same, no differences whatsoever should be observed in the properties of the two substances. Fire is not the universal analyser of dividing bodies into their elements, or certainly not an analyser alone, since it can also drive the syntheses of substances. In support, Boyle presents evidence that has been gathered from chemistry laboratories, as well as arguments from his corpuscular theory. We already know that Boyle was a "practical atomist". In his view, the primary fundamental corpuscles of universal matter give rise to a multitude of different mixt bodies with wildly varying structures and degrees of firmness. These, in combination with each other, may form other new concretions (we could say that Boyle essentially proposed the abstract idea of such a structure of matter which we today would describe using the modern concepts of 'elementary particles', 'atoms' and 'molecules'). Fire does not necessarily reduce a body down to elements, even when causing its decomposition (i.e., when a single substance is transformed into multiple ones), while it can also cause the separated species of matter (either all or several of them) to become joined again in ways that are new. It is natural that sometimes fire produces not several different substances, only a single one—but a new one at that. The properties or qualities of a substance are indeed determined by the shape and size of its constituent particles, their being in movement or at rest, and the manner of how the particles combine with each other and the structure they form.

In the final chapter, Boyle comes to the conclusion that, strictly speaking, no grounds exist to call any known substance or material an element. Conditionally, all such substances (e.g., gold, silver, mercury, water, etc.) whose further reduction or division so far has not been successful can be regarded as elemental, although none of them is composed of absolute atoms and, as aggregates of primary matter, can be expected in principle to be transformable into one another.[6] However,

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[6] For that reason, Boyle found that the goal of the alchemists, the transmutation of base metals into gold, should in principle be achievable. Several authors who unjustly associate alchemy with that idea alone also extend the same injustice to Boyle whom they see as still under alchemy's undue influence and brand him a faithful believer.

Figure 23. 'The German Alchemist.' Looks like these fellows, as Themistius from Boyle's *Sceptical Chymist* would know, have "… their eyes darken'd, and their Brains troubl'd with the smoke of their own Furnaces". Engraving by H. Weiditz ca 1520 after Holbein. (Lacroix, 1878, p. 185)

Boyle failed at providing clear-cut and unambiguous experimental criteria that would decide whether a substance is simpler or a more complex one and whether the chemical reaction we are observing is a decomposition or a synthesis. For example, by burning sulfur, Boyle obtained an acid which could be converted back (i.e., reduced) into sulfur with turpentine, but which of these two, sulfur or the acid, is a simpler substance, he had no way of telling. The generally held view was that fire causes substances to decompose, yet this was precisely the tenet, the veracity of which Boyle had dared to doubt.

The final chapter also contains Boyle's short definition of the concept of an element, which is often erroneously regarded (probably in every chemistry textbook) as his most important achievement, providing the foundation for chemistry as a scientific discipline. The definition runs as follows: "I now mean by Elements, as those Chymists that speak plainest do by their Principles, certain Primitive and Simple, or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the Ingredients of which all those call'd perfectly mixt Bodies are immediately compounded, and into which they are ultimately resolved." (Boyle, 1661, p. 350) Now, can we find anything truly new in that definition?

Nothing in particular! Boyle's definition of a chemical element is not really an expression of his most revolutionary ideas regarding chemistry. First, he states himself that he only expresses the views of those "chemists who speak more clearly than the others". Second, Aristotle had already given a definition that was essentially the same. Our readers can be assured of this. Aristotle has elaborated on the concept of 'element' and (just as Boyle) has also applied the concept to 'bodies'. The definition can be looked up in Aristotle's *Metaphysics*, where it reads, "'Element' means the primary component immanent in a thing, and indivisible in kind into other kinds" (*Met.* V.3, 1014a26–30). Aristotle provides the example of the elements of speech—parts of speech which cannot be divided any further—and the example of water which can be divided further, but only into parts of the same kind, since water is always water. The elements of bodies, according to Aristotle, mean "the things into which bodies are ultimately divided, while they are no longer divided into other things differing in kind; and whether the things of this sort are one or more, they call these elements" (*Met.* V.3, 1014a33–35).

So the definition of element most certainly was not the bottleneck obstructing the proper progress in chemistry. It would have been naive indeed to pinpoint the birth of a scientific discipline to a simple definition of one of its fundamental concepts. The definition of a concept, after all, is just the briefest verbal description of the activity (both theoretical and practical) in the course of which the corresponding phenomenon has been extracted or constructed from the general relationship between the phenomena. This means that definition only becomes possible when the phenomenon to be defined itself already exists and functions in human activity. In which case, if the phenomenon already functions in human activity, then it won't matter that much any longer whether its definition as a brief verbal description has already been formulated or not (of course, sooner or later the need for a definition will arise, often in relation to teaching and learning, yet it would be wrong to believe that the definition is what creates the concept and encapsulates the correct understanding of the phenomenon).

But now we face the following question: if Aristotle's and Boyle's definitions are essentially the same, then perhaps the activities which these definitions describe are also the same, i.e., Boyle's original contribution actually amounts to zero? In a sense, this is true. Namely, Boyle's concept of an element remained just as general as Aristotle's. Boyle did not define the scientific concept of a chemical element (as we mentioned, he was unable to define the criteria for deciding the elementality of a substance). Boyle criticised the traditional views not because they had been lacking the concept of element, but because, from the perspective of a scientific world picture, those things which had earlier been regarded as elements were revealed to be not what they purported to be according to those very same traditional views. And, ultimately, Boyle demonstrated that, in fact, no true elements had been discovered! Thus, Boyle's only original contribution to our understanding of elements lay in that he transposed the Aristotelian concept into a completely new context. Therefore, we should take a closer look at what kind of a concept Aristotle, in fact, had formulated.

Aristotle formulated the concept of element as a category: he defined the element as a general form of being (and of thinking as well), which, as taken by itself, remains more or less immutable, invariant and acquires a purely logical character. Purely logical character is inherent to such general definitions of being (of something that is) which are the inevitable premises for thinking about the same being (about the same something that is), without which thinking would fail, regardless of the particularities of what currently constitutes that being (that something that is), as it leads to nonsense, destruction of thought by thinking itself, rendering thinking about that being (about that something that is) impossible. This is also true of the concept of element as a category. Regardless of how we interpret the meaning of an element and of which particular elements we speak of—an element must not lose its meaning as a category, since otherwise it would turn into nonsense: we would speak of elements in such a way that what we, in fact, speak of are not elements. The ancient thinkers, and Aristotle in particular, essentially engaged not in the study of nature, but in the analysis of concepts as categories, i.e., they studied the logic of categories. Naturally, this was not how they conceived of their task themselves. This is how it looks to us in hindsight, when we analyse the culture type at the time and the manner of their reasoning. With their analysis, the ancient thinkers themselves aspired to attain the understanding of the world, cosmos, nature, humans—of every conceivable concept; no questions existed which a philosopher would not have anything to say about. Aristotle indeed specially formulated the tasks of the logic of categories (of the First Philosophy) and also pursued the analysis of categories in its "pure form", but that was certainly the limit of his endeavours.

The Aristotelian category of element differs from the concept of atom. Unlike the atomists (Democritus), Aristotle also recognised the concept of qualitative determinism as an independent category of being and showed that it is necessary to consider elements in relation to the whole as a new quality which they give rise to when combined. In reference to atomists' own terminology, Aristotle used the analogy of the letters of alphabet. He emphasised that words are not simply letters or the manner of their combination, but something more. A word as a whole, compared to a combination of letters (that is, the structure of a word), is something new, a new essence, new quality, new determinism. At the same time, the letters (elements) preserve in the word (the whole, new determinism) a certain independence (it means that the manner of their combination is also "visible" and we can discern the word's structure); for example, the word 'house' that is combined of the letters 'e', 'u', 's', 'h' and 'o' is no longer just a set of individual letters and the manner of their combination (a word is a whole, and cannot be reduced to its structure), but, regardless, that word can be (due to the preservation of its structure) broken down again into these letters only. A circle that is drawn on a piece of paper, however, can be divided and cut into any number of parts or pieces of any shape and size (the paper lacks the structure of the circle). Aristotle explains that the letters of a word are parts of the word, a determinism which is different from that of the letters and arises from its form, i.e., they are the elements of the word, but not the parts of the material of the word. The parts of a circle on a piece of paper are, however, parts of paper as parts of the material which serves as the matter in which the form of the circle is realised. For Aristotle, the form in which an object arises, in relation to its matter, is an independent cause, as we know. Democritus' atomism, in Aristotle's view, concerned itself only with the material cause and to some extent also with the efficient cause (emptiness is the cause for the movement of atoms). The essence of an object is ultimately determined by all four causes, and most certainly not by the material cause alone (such as by the atoms of the object). In medieval Aristotelianism, the "substantial form" had mutated into some sort of mystical inner, spiritual power that confers the object its properties. Aristotle had no such view. He simply tried to understand things in their natural determinism, to observe them from the point of view of the world as a single living organism.

The relationship between the categories of quality and property and the categories of element and structure is also problematic in Boyle's corpuscular philosophy. At the same time, the content of the concepts of 'element', 'structure' (that term was not used by neither Democritus nor Aristotle, but they did have the concept), 'quality', 'property', 'part', 'whole', etc., purely in the sense of categories has remained unchanged for the past 2,000 years! What has changed, however, is the general character of human activity and the interpretation of the named concepts, when observed not separately, but from the perspective of the world picture that developed along with the new type of human activity. As we saw, the world picture which corresponded to the character of the 17th century was a mechanistic world picture. The new world picture, first of all, was opposed to the medieval world picture. In relation to the categories of quality and property, it meant the denial of the substantial form: if the properties, quality and nature of an object had earlier been understood as expressions of the substantial form, then the new world picture only permitted the discussion of the properties, quality and nature of an object only by reference to the categories of matter and motion, and element and structure. Boyle did also use ("for the sake of brevity") the word 'form', but he emphasised that by this he does not denote any kind of real substance that would differ from matter, but the matter of a body itself that exists in a certain way. Boyle often compared phenomena to clockwork mechanisms. For instance, he wrote:

> For if we thus consider Things, we shall not much wonder, that a Portion of Matter that is indeed endow'd but with a very few Mechanical Affections, as such a determinate Texture and Motion, but is plac'd among a multitude of other Bodies, that differ in those Attributes from it, and one another, should be capable of having a great Number and Variety of Relations to those other Bodies, and consequently should be thought to have many Distinct Inhærent Qualities, by such as look upon those several Relations or Respects it may have to Bodies without it, as Real and Distinct Entities implanted in the Body itself. When a Curious Watch is going, though the Spring be that which puts all the Parts into Motion, yet we do not Fancie (as an *Indian* or *Chinois* would perchance do) in this Spring one Faculty to move the Index uniformely round the Dial-plate, another to strike the Hour, and perhaps a Third to give an Alarme, or shew the Age of the Moon, or the Tides; all the action of the Spring, (which is but a flexible piece of Steel, forcibly coil'd together) being but an Endeavour to dilate or unbound its self, and the rest being perform'd by the various Respects it hath to the several Bodies (that compose the Watch) among which it is plac'd, and which they have One to another. (Boyle, 1666, pp. 28–29)

The analogy of mechanical systems, such as clockwork mechanisms, is applicable to the structures of all things, be they large or so tiny as to be invisible for the naked eye. To think otherwise, in Boyle's view, would be just as good as to consider the structure of a big tower clock different in principle from that of a watch. The chemist must learn to produce substances just like the clockmaker makes clocks, considering that between the invisible particles of matter, the same relationships hold as between the parts of which a clock is built. The principal tool of a chemist is fire, which can both decompose substances into "details" and cause the "details" to recombine into those substances again.

Boyle needed the last missing component in his scientific world picture and that was God, the “clockmaker” of the universe. The functioning of the universe as an immense mechanism would have been inconceivable for Boyle without its designer and maker. The matter itself could in no way have had assembled itself into such a mechanism, as no clock is formed unassisted by the hand of the clockmaker. God has determined the location of things, their structure and the rules governing their motion, known by us as the laws of nature. Although the seventeenth- and eighteenth-century scientists certainly did need the inclusion of God in their world picture for it to make sense for them, it was already a far cry from the medieval conceptions. God had been mostly relegated to the role of a passive “background force”, He was the last link in the chain of reasoning that allowed the construal of the world as a mechanism, since a mechanism owes its existence to its designer or at least its maker, yet the goal of science was the investigation of that mechanism itself, not its designer or maker. Mostly, God’s role was even smaller than Boyle had attributed to Him (for Newton, God only gave the universe its original impetus).

3. Can the “upside-down” theory be scientific?

We will now speak of the phlogiston theory. The phlogiston theory is often lambasted as a fantasy-ridden pre-scientific conception of the world, since phlogiston, as we know, does not exist. It is called an “upside-down” theory, since it envisions combustion as a decomposition process in which the mythical phlogiston is released from the combustible substances, yet in reality, combustion is a process of synthesis whereby various substances *combine* with oxygen. Indeed, phlogiston does not exist and the theory’s account of combustion is clearly wrong, but does it really entitle us to call it a pre-scientific flight of fancy? Without doubt, science is the “temple of truth”, since its goal is to obtain knowledge that is objectively true, but does it entail that any knowledge that is true is also necessarily scientific and that mistakes, incorrect knowledge, are unscientific? The author of this book finds—and has consistently tried to make it clear since its first pages—that no such conclusion may be drawn. Scientific knowledge should not be construed to include true knowledge only, regardless of the fact that science is essentially a method designed to ensure the objective truth of the knowledge it obtains. The specific character of scientific knowledge, naturally, arises from a certain world picture, from the method that is used to obtain such knowledge—from what is investigated and how it is investigated.

We have already explained that scientific knowledge presupposes a scientific world picture which could not have emerged neither in the antiquity nor in the Middle Ages, but only as late as in the 17th century, and that Robert Boyle is to be noted for his identification and formulation of scientific problems in chemistry according to the principles of a scientific world picture. Since chemistry investigates the qualitative changes of matter, the transformation of substances into different kinds of substances, Boyle felt the need to demonstrate how the scientific world picture, which at the time was based on a mechanico-corpuscular philosophy, could be utilised to make sense of the properties, quality and character of chemical substances—the terms which help us to tell the difference between one substance and another and describe the transformation of a substance without any reference to a special reality, substantial form, mysterious capacity or power. We saw that this goal had indeed been achieved in Boyle's corpuscular philosophy. Yet the general theoretical framework he developed failed to provide any tools for finding answers to specific chemistry problems, e.g., how to analyse the structure of chemical substances, how to demonstrate that one or the other quality of a particular substance, or its particular properties arise from the particular specifics of the corpuscular configuration of that substance, which is evident in this and that. With regard to chemistry, Boyle's approach remained speculative, still rooted in the tradition of natural philosophy, as did the Cartesian chemistry, which emerged at the same time and also fought with substantial forms and mysterious forces. The best known Cartesian among chemists was the Frenchman Nicolas Lémery (1645–1715). While Boyle primarily explained the properties of substances by reference to their structure, Lémery did the same by reference to the shape of their particles. Yet in both cases the assumptions regarding the causes of the properties of particular substances remained *ad hoc* hypotheses, i.e., whenever a hitherto unknown property of a substance was discovered, its explanation always required the creation of a new hypothesis as well. A chemist simply "translated" the results of experiments into the language of mechanical imagery which was arbitrarily married with chemical significance. For the followers of Boyle and Descartes, the principles and laws of mechanics were useless in chemical research: they could not predict the course of a chemical reaction and failed to explain the regularities in different phenomena as the result of a universal law; no experimental corroboration of any mechanical explanation of a chemical property was possible. All in all, the attempts to interpret chemical phenomena in mechanical terms (by simply treating them as mechanical phenomena) remained fruitless.

However, there existed another way to rid chemistry of the mysterious powers and forces, of substantial forms, following the example of mechanics, but not

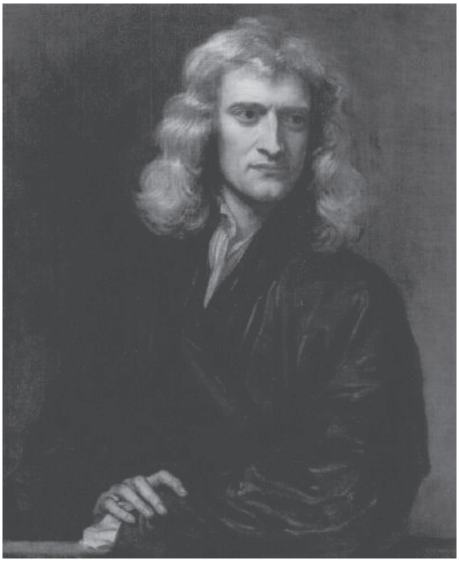

Figure 24. Isaac Newton (1643–1727). Oil painting by Godfrey Kneller (1686). (*Wikimedia Commons*, 2018d)

mechanically. That was the way of Isaac Newton (1643–1727), who continued the work started by Galileo Galilei. Unlike the Cartesian world picture which operated with the concept of contact forces (interaction between two objects was based on their physical contact), the Newtonian world picture was defined by the concept of action at a distance (interaction between two objects requiring no physical contact between them). The concept of force may have initially appeared as a born-and-bred scholastic invention. Yet Newton, and Galileo before him, used it not in the sense of a substantial form, of a mysterious power or capacity, but in the sense of an experimentally measurable quantity. Now, force was something that was placed in a cause-effect relationship, given the form of a mathematical function and subjected to verification in a series of repeat experiments—any mystery surrounding the concept simply vanished. Newton coined several famous slogans which were directed against the wild imaginations of natural philosophy in Cartesian physics: “I feign no hypotheses!” and “Physics, beware of metaphysics!” Natural phenomena started to be experimentally investigated with the specific aim to discover if-then type relationships.

To make the difference between the two abovementioned approaches clearer to the reader, let us consider the concept of chemical affinity (from Latin *affinis*, meaning ‘related’), which was also one of Newton’s research interests. (It may come as a surprise to some that Newton dedicated a substantial part of his career to chemistry, although he achieved no spectacular success in this field.) In practical chemistry, it had already been known for a long time that some substances possess the tendency to combine with each other, while others do not. One of the earlier attempts to explain this phenomenon was the suggestion that the substances that combine have the “affinity” for each other or possess a shared nature (“like attracts like”), and those that do not combine have no such affinity

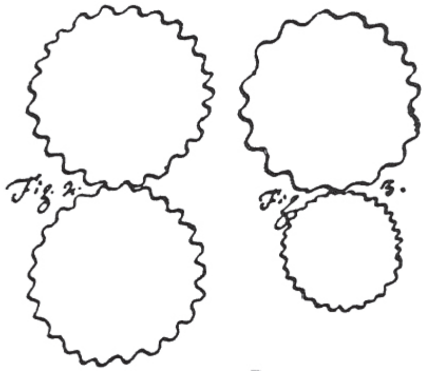

Figure 25. Lomonosov's figure explaining the selective chemical affinity of substances. Similar particles (here Fig. 2) are congruent, while dissimilar particles (Fig. 3) are not.

or do not possess such a nature. This view also gave rise to medieval speculations that the affinity of two different chemical substances is the manifestation of their sympathy for each other, or their natural attraction. Such figurative descriptions were naturally alien to scientific world picture. Robert Boyle and the Cartesians came up with a mechanistic explanation of the chemical affinity: since substances consist of particles, it is easy to imagine the reaction between the substances in terms of compatibility between the shape or structure of their particles, which can be either compatible or incompatible, more compatible or less compatible. It is also certain that, although in this manner we can certainly avoid resorting to any mysterious forces in our explanations of chemical phenomena, the general description of particles' compatibility remains entirely arbitrary. These shortcomings were still present in the theories of Mikhail Lomonosov (1711–1765), although he condemned all arbitrary explanations, all sorts of little imaginary hooks and nooks. Lomonosov tried to explain the so-called elective affinity between substances (why a substance reacts better with one substance than another):

> It is probable that the surfaces of homogeneous particles approach each other more than do heterogeneous ones and therefore their roughness from which, as we assume, friction arises combines them more with each other. Therefore, we assume, homogeneous particles are combined by the roughness, like gears, and in heterogeneous particles, due to the different sizes of the cogs, this does not occur. […] Then there is no difficulty for any reason that homogeneous particles bound by linkages and having internal rotary motion would not move around each other, and heterogeneous ones would not. According to this hypothesis we will call the mutual correspondence of homogeneous particles *congruence*, and we are persuaded by experiment that it can be used to explain chemical and other natural phenomena. (Lomonosov, 1970, p. 152)

Newton chose to tackle this issue differently and left the mechanistic imagery completely aside. The fact that substances react selectively with each other seemed to suggest that the universal force of gravity which affects everything equally on the planet is not a suitable model for explaining chemical processes. Therefore, Newton conjectured that chemical action is to be explained by interparticle interactions which produce forces at minuscule distances only. It is important to note that he made no attempt to explain the nature of such forces, but only proposed their existence to explain the selective reactions in experiments, i.e., he directed the attention of the chemists to the experimental investigation of such forces. Unlike Boyle and the Cartesians who were supposed to produce at least an impression of an explanation, Newton's proposed force explained nothing, only pointed to the objective relationship that exists between substances, but whose nature we know nothing of. Therefore, the postulation of this force was only justified as it helped us to see a hitherto unknown universal causal relationship, to express if-then type relationships between particles. Newton's method indeed turned out to be suitable for chemistry and gave the impetus to the creation of its first unified scientific theory, i.e., the phlogiston theory, and to the compilation of chemical affinity tables on the basis of empirical data. A systematic research began with the aim to determine what substances combine and what is the relative strength of the force that holds them together. (The very first chemical affinity tables were based on displacement reactions where single or multiple elements replace others in a compound, e.g., in aqueous solutions of salts, where the element with a stronger affinity causes the element with a weaker affinity to precipitate from the solution.)

The phlogiston theory was developed and formulated by the German physician and chemist Georg Ernst Stahl (1659–1734).[7] By the end of the 18th century, a substantial chemical industry had already developed, with the metallurgical plants possessing the greatest value and importance. In practice, the industry had to deal with a large number of problems which they could not solve just by trial

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[7] A few biographical details here probably serve to complement the general picture, since although Georg Ernst Stahl was certainly a chemistry celebrity of a calibre equal to Robert Boyle or Antoine-Laurent de Lavoisier, today his name is relatively less mentioned in comparison with the latter two. Georg Ernst Stahl studied at the University of Jena from which he graduated with a medical degree. After graduation, he lectured at the same university as *Privatdozent* (1683–1687), worked as a court physician at Weimar (1687–1693), as the second Professor of Medicine at the University of Halle (1693–1716) and finally as a court physician to Frederick William I of Prussia (1716–1734). He was also a member of the German Academy of Sciences Leopoldina. Stahl postulated the main ideas of the phlogiston theory in 1697 and developed and elaborated these further in many of his subsequent works (Stahl was a prolific scientist), but he never dedicated anything specifically to phlogiston theory alone. Phlogiston served chemistry well for a hundred years.

and error. One of the acutest problems was the significant loss of metal during its extraction from the ore at high temperatures, the base metals had the tendency to "burn up" and became coated in some sort of ash-like film. This phenomenon brought up the concepts of metal extraction and combustion which the humankind had known since times immemorial and contemplated in very diverse contexts (mythological, philosophical and religious) in a completely new situation. Concrete problems of practical chemistry had appeared and required theoretical investigation, such as: Is it possible to reclaim the metal that has "burnt up"? What is the cause of the metal loss? How to conduct the extraction process without losing metal?

Figure 26. Georg Ernst Stahl (1659–1734). Line engraving by J. G. Mentzel, 1715. (*Wikimedia Commons*, 2018e)

Such were the questions encountered by Stahl who took a keen interest in the problems of industrial chemistry, kept abreast of the latest publications in the field, which were already becoming numerous, and learned how metallurgical engineers, textile dyers, brewers, saltpetre workers, etc., conducted their work. Being intimately familiar with the scientific world picture of his time and also with earlier chemistry-related theories and philosophies, such as the doctrine of elements, he now tried to find the proper theoretical framing for the recent problems of practical chemistry, hopefully also leading to their solution. In practical chemistry, thinking in abstract or mechanistic terms was not possible, one certainly had to consider the qualitative character of chemical transformations. In the language of categories, one would say that in chemistry, as it turned out, the category of quality is not optional. It is pointless to engage in a talk about the elements and structure of bodies, and their transformations, until the elements, structures and transformations of these bodies (i.e., chemical substances) have not been identified.

The problem of chemical elements for which Boyle had provided no practical solution was still on the agenda. Corpuscular views had to be put to test in experiments, it was necessary to find out which substances remain unchanged and how these form compounds; which compounds they give rise to and which compounds they do not, etc. To these questions, the corpuscularian conceptions could offer nothing concrete in answer. Although the mechanico-corpuscularian world picture permitted simple and clear interpretations of chemical processes, the arbitrariness of such interpretations can only ruled out when they can be constructively applied in practical and experimental chemistry. The preface to Stahl's lectures which he held in Jena and were collected and later published by one of his students contain the following characteristic lines,

> Mechanical philosophy, though it vaunts itself as capable of explaining everything most clearly, has applied itself rather presumptuously to the consideration of chemico-physical matters. In fact, although I will not spurn a sober use of mechanical philosophy, everyone who is not blinded by prejudice will admit that it has brought no progress in these matters. I am not surprised, for it is lost in doubts, and just scratches the shell and surface of things and leaves the kernel untouched, since it is content with deducing general causes of phenomena from the shape and motion of particles, and is uninterested in the nature, properties and differences between mixed, composite and aggregate bodies. (Stahl, 1723, sig. 2v, quoted in Partington, 1961, p. 665)

While Boyle, in the philosophical scheme of things, emphasised the relative impermanence of substances, their fundamental decomposability, then Stahl, influenced by the Newtonian idea of empirically verifiable stronger or weaker forces of attraction or repulsion between different particle species, focused on their relative stability and permanence instead. By experiment, he identified different types of stability, on which he based his classification of substances. Stahl distinguished between the categories of simple bodies (*principium*), mixed bodies (*corpus mixtum*), combined bodies (*corpus compositum*) and aggregate bodies (*corpus aggregatum*). The simple bodies are indivisible particles which give the substance its original qualities and which do not exist independently in a pure form as a separate body. Amongst these, the most important one is phlogiston, the principle of fire. When different simple bodies combine, they form mixed bodies (such as metals, phosphorus, sulfur), and different mixed bodies form combined bodies (such as sulfur-metal compounds, cinnabar, realgar). An aggregate body is produced as a result of joining of any kind of particles of the same type (either mixed bodies or combined bodies). Chemical change (mostly reactions in solutions) is normally the formation or decomposition of a combined body (i.e., a combined body is what today would be called a chemical compound). The fundamental unit in chemical change is a mixed body that has been dephlogisticated (phlogiston itself is also an element, but of a different kind, since it does not exist independently). For practical purposes, the "elements" which occur in common chemical reactions are phlogisticated mixed bodies, since for phlogistic processes which are related to combustion and fire a separate category is created. Combustion means the release of phlogiston from a substance by way of heating. This process requires air. Fire is the vortex motion in which phlogiston combines with air.

The phlogiston theory naturally has connections with the traditional views in chemistry. The word 'phlogiston' ('burning up' in Ancient Greek) itself was already present in Aristotle's writings. It seemed quite logical then to assume that combustion or burning is essentially a decomposition process. As we burn wood, something appears to go in the air and only ashes remain, and when we burn limestone, what remains is lime. Therefore, it was only logical to call the heating (burning) of metals 'calcination' and the resulting oxide a 'calx' (Latin for 'limestone') of that metal.

To sum it up, the phlogiston theory emerged as a result of: (1) a scientific world picture; (2) a reinterpretation of traditional chemistry dogmas (corpuscular interpretataon of the fire principle and the combustion as a decomposition process) in the context of that scientific world picture; and (3) the problems encountered in practical chemistry, above all in metallurgy, which could not be solved by the traditional trial-and-error method.

What then is Stahl's discovery? What is the principal idea of the phlogiston theory?

Stahl noted that the function of charcoal which was used for extracting metals from ore was not limited to generating heat only, but it also appeared to have a more immediate role in the smelting process. He found that coal (as well as oil, fat, resin) contains a certain substance or element that prevents the metal from "burning up", but each time destroys the film that appears on the surface of liquid metal (the film appears when no more coal is added). Stahl demonstrated that the process of combustion which releases the phlogiston from the substance is the reverse process of the ash or calx regaining the phlogiston. Thus, using the concept of phlogiston, he formulated the principle which in modern terms can be described as the reversibility of oxidation and reduction reactions.

Stahl formulated the problem of metal loss encountered in practical metallurgy as a problem of the composition of the metal and its calx. At the same time, he had to work with the experimentation techniques available in chemistry at the time. These were purely qualitative, i.e., no quantitative methods were used for the determination of the composition of a substance. Consequently, the mathematical formulation of the problem was still not possible. Yet, in the end, the problem itself was mathematical by its very nature, since it concerned the loss of metal, i.e., the amount of metal! The mathematical premise for Stahl's problem can be identified as the formal principle of additivity: whole equals the sum of its parts. The proper application of the principle in practical chemistry (as we saw when analysing Boyle's views) also required the establishment of the qualitative criteria for determining what is the whole and what are its parts, and when the observed process is the whole decomposing into parts or the parts forming the whole. An empirical basis had to exist for the assumption that the whole can be divided in only one way into parts of different kind and these parts can only form the original whole. In other words, it had to be a situation where the structure of the whole is such that it does not permit its division into parts not in any imaginable way, but it always divides into elements of different type whose recombination into the whole (their emergent quality) is not dependent on the structure of the whole or the manner of the recombination; or this recombination is possible in one way only, so that the formation of the whole always depends only on the identity of the elements, i.e., the elemental composition alone. As we recall, Boyle had pointed to the fact that such an assumption does not necessarily hold true: a whole can be divided into parts of different type in very many ways and these parts may combine with each other in very different ways, form a multitude of different structures, all of which possess a different set of qualities.

If the amount of metal decreased during the high-temperature processing, then, first of all, it should have been investigated whether it was due to the metal's decomposition into its constituent parts or its combination with another substance. The fact that the process was conducted in normal atmosphere had to be taken into account. It was also known that, although the amount of pure metal decreased, the combustion product appearing on the metal's surface increased the total mass. This gave rise to hypotheses that construed combustion as metal's combination with “fire matter” (Boyle), suspected that during combustion air enters into the pores of the metal (Rey) or observed combustion as the release of the combustible part of the metal into air and the combination of the non-combustible part of the metal with a specific constituent part of the air or “nitro-aereus” (Mayow). As we see, the latter hypothesis is rather close to the truth (if we discard the notion of a metal as a compound that releases its combustible part into the air), and the others are “almost correct” as well, but none of them found such general recognition as Stahl’s theory. Why it so happened, why the “upright” theories failed to compete with the “upside-down” theory, we will also continue to discuss in our next chapter. But first of all, we will demonstrate that the phlogiston theory, despite being “upside-down”, was nevertheless a decent and proper scientific theory which had a correct base idea at its foundation and was experimentally well supported.

True, Stahl based his theory on the false premise that combustion is a decomposition process, but such was the universally accepted truth at the time. Air was simply considered as a neutral medium which did not partake in normal chemical reactions. The increase of the total mass upon metal’s combustion was roughly explained as follows: just as a piece of lead that is attached to a piece of cork becomes lighter in water and rises to surface, so is metal made lighter in air by the lighter component (i.e., phlogiston) in its composition and heavier when relieved of that lighter component.

Stahl reasoned as follows: if the combustion of a substance means its decomposition, then the recombination of its combustion products should yield us the original substance (whole equals the sum of its parts). That principle can only be realised if the combustion products remain in fixed amounts in the combustion process, i.e., if we assume that the substances do not “vanish into the thin air”. One of these products was easily identifiable in the case of metals: that was the solid calx, the product of calcination. The second product, however, could not be directly observed, since it mostly appeared in the form of flame and dissipated into the air. To capture that product, it was necessary to determine the substance which formed the fire. Fire certainly needed air for its support, but in Stahl’s view also something else which must be present in all combustible substances and absent in all non-combustible ones. So, materials, such as charcoal, which burn with the hottest flame must then be especially rich in that elusive something. Thus, in his line of reasoning, Stahl arrived at the concept of the fire principle, named it ‘phlogiston’ and classified it as a special type of corpuscle, according to the scientific world picture that was accepted at the time.

Having established such a theoretical scheme, Stahl could already conduct experiments of "metal synthesis". He also provided a theoretical explanation to the problem of metal loss and demonstrated how the lost metal could be reclaimed (by adding phlogiston to the calx via phlogiston-rich substance, such as charcoal, oil, resin, fat, etc.). In addition to metals, Stahl's theory permitted the "synthesis" of all other "mixed bodies" (*mixta*), such as sulfur and phosphorus from their acids, by means of phlogiston.

It is important to pay attention to the fact that the phlogiston theory concepts of 'metal', 'charcoal', 'calx', etc., denote empirical objects which have real counterparts, the real metals, coal, calxes, to which they may not be identical, but can be easily linked. The fact of the matter is that the properties on the basis of which the empirical objects are defined are selected from all the possible real ones by experiment (i.e., the real objects have more qualities and properties than the empirical objects). As an empirical object, metal is defined as a certain substance that can be transformed into a calx by calcination, charcoal is a certain phlogiston-rich substance (it burns with an exceptionally hot flame), calx is a metal that has been dephlogisticated in the calcination process. Such concepts as 'mixed body' (*mixtum*), 'phlogiston', 'phlogiston-rich substance', however, already denote generalised theoretical (idealised) objects which cannot be directly linked to any real objects, since their definitions include properties that cannot be found in any real objects. These theoretical concepts have been defined on the basis of the concepts of 'element', 'corpuscle', etc., found in the mechanico-corpuscular philosophy that formed the core of the scientific world picture at the time and on the idealised scheme of combustion and reduction processes as reversible opposites. Now, it is time for us to reconsider the "killer" argument which so often earns the phlogiston theory the label of fantasy. In which sense did the theory assume phlogiston to exist? Certainly not as an object that can be observed in an experiment. After all, phlogiston is the element of fire that independently does not exist, yet which has a defined function in the combustion and reduction cycle. To make a comparison, to call the phlogiston theory fantasy, because phlogiston cannot be isolated in an experiment and collected into a container, is just as good as to call classical mechanics fantasy, since it operates with the concept of "point mass" which also cannot be shown to exist in reality. A specific peculiarity of the phlogiston theory is its purely qualitative nature, i.e., the idealisations which it relied on had been obtained on the basis of substances' qualitative changes only. That means, as long as the qualitative approach alone was enough, the phlogiston theory satisfied the needs of chemistry completely. Let us emphasise that during those hundred years when the phlogiston theory served chemistry, chemistry did not explore the realm of fantasy, but made progress and generated objectively true knowledge, as one would expect from a science. However, when quantitative approach became necessary, the inadequacy of the phlogiston theory became apparent. How this happened, we will see in the next chapter.

IV Debunking of the phlogiston theory

We use the words ‘evolution’ and ‘revolution’ to characterise scientific progress. Evolutionary progress is a continuous and gradual process that flows from the same foundation and premise. The advancement of evolutionary progress sets the stage for revolution which means a break in continuity, a radical change and replacement of the foundation and premise. With the formulation of the phlogiston theory, the foundation had been laid for the chemistry to progress as a science. As long as chemistry retained the phlogiston theory as the general framework wherein its research was conducted, the scientific progress remained evolutionary in character. For a better understanding of the implied nature of such process, we should also consider the etymology of the word ‘evolution’: in the original Latin, *evolvere* means ‘unrolling’. Indeed, for a considerable period, we can see chemistry’s progress as an “unrolling” of the possibilities and the potential of the general idea of the phlogiston theory to develop new scientific knowledge. However, every idea has its limits, while the world which we want to capture with our idea and give shape to with our activity has none. At first, for a time, our idea appears to work just fine, i.e., our activity remains blind to these aspects, regularities, properties which remain outside the limits of the base idea that defines the activity. Sooner or later, however, the idea’s potential becomes exhausted and it needs to be replaced with a new and better one; the phenomena explored by the old idea have to be critically re-examined from the perspective of the new idea, and thus begins our next “unrolling”. This kind of shift in the foundation, in order to find a new perspective, is what amounts to a revolution (from Latin *revolvere*, meaning ‘revolve’, ‘roll back’) in scientific progress. We will now examine how the evolution of phlogiston chemistry led to a revolution, how the phlogiston theory was overthrown and why the Lavoisierian revolution was victorious.

Although our readers hopefully no longer regard the phlogiston theory as a completely unfounded fantasy, it is doubtful that they consider its defeat by the oxygen theory anything other than a foregone conclusion. After all, one of them is clearly right and the other clearly up-side down? Yet, let us not forget that what today seems patently clear to us might once have appeared in a very different light. What exactly convinced the scientists at the time to abandon phlogiston and flock to oxygen is actually not that obvious at all. In this matter, we can see different theoretical positions (or "bias", which was mentioned in the Introduction) clash on the nature of scientific knowledge and the progress of science, while a rift appears between the methods of science. We will now, as briefly as possible, try to explain the gist of the main methods in science, the shared bias and common sense of the scientific community, the stuff of school textbooks. And then we will consider the relevance of these ideas to understanding the chemical revolution in question.

Figure 27. Antoine Laurent de Lavoisier (1743–1794) and his wife, chemist Marie-Anne Pierrette Paulze (1758–1836). Painting by J.-L. David, 1788. (*Wikimedia Commons*, 2019d)

1. Why is one theory abandoned in favour of another?

One of the earliest concepts of scientific methodology in science is inductivism. It proposes that scientific theories are obtained by way of generalisation of observed facts and are also confirmed by these observed facts. Inductive reasoning precisely discards the phlogiston theory entirely for the reason that, unlike Lavoisier's theory, from the very outset it had not strictly been derived from and confirmed by observed facts, but was founded upon the preconceived ideas inherited from the ancient philosophers and medieval alchemists. In the previous chapter, we discussed that the phlogiston theory, in a sense, was nevertheless a fact-based theory and not a mere pre-scientific flight of fancy.

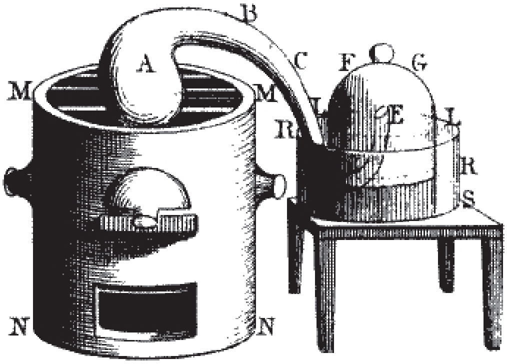

Figure 28. Lavoisier's apparatus for studying the combination of mercury with aerial oxygen in a closed system. On the right, we have the furnace and the retort which contains the mercury, and on the left—a bell jar, containing a carefully measured amount of air and placed in a reservoir of water or mercury. Hand sketch engraving by Madame Lavoisier (Lavoisier, 1798).

Yet this is not what is important here at the moment. What is important here is that the inductive approach is generally overly simplistic and fails to explain the real progress in science. From a purely inductivist perspective, the scientific success of Lavoisier's theory should also be unwarranted, since much of it is also not strictly derived from and confirmed by facts. An inductivist would criticise the phlogiston theory for its central concept being a non-existent substance, yet fail to notice the equally non-existent substances of heat and light in Lavoisier's theory and look conveniently past the fact that one of Lavoisier's central tenets that all acids must contain oxygen is not true.

Thus, the view that Lavoisier won, because the oxygen theory was grounded in facts and the phlogiston theory was not, is erroneous. However, maybe the following explanation has some merit: a theory is abandoned since it has been proven false by an experiment, by observed facts which, according to the theory, should be impossible?

In the case of refutation by facts, the crucial role is played by the so-called critical experiment or *experimentum crucis.* According to a commonly held view, Lavoisier refuted the phlogiston theory by a critical experiment, which he conducted in 1775 (see Fig. 28). Lavoisier heated a measured amount of mercury (according to the phlogiston theory, mercury was a compound, consisting of the calx of mercury and phlogiston) in a closed container and accomplished its complete transformation into red mercury(II) oxide (which is the calx of mercury). The

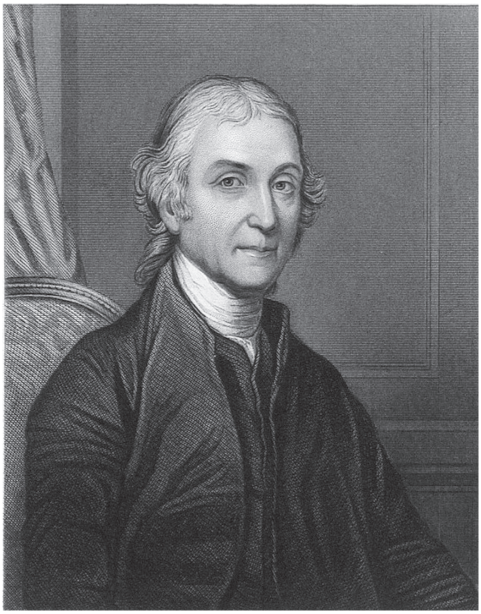

Figure 29. Joseph Priestley (1733–1834). Stipple engraving by W. Holl after G. Stuart. (Wellcome Library no. 7971i)

air volume was reduced by a certain amount and the residual "mephitic" air supported neither flame nor life (a candle was extinguished and a mouse died). The red mercuric oxide weighed more than the original mercury (the phlogiston theory had to come up with a separate explanation for the increased weight, since the process could not have been a synthesis, but decomposition, upon which phlogiston would be released from mercury). Lavoisier then heated the mercuric oxide further until it converted back into mercury whose weight roughly corresponded to the original amount. At the same time, the process also released a gas whose volume corresponded to the amount that had previously been consumed. (The phlogiston theory would describe this stage as a synthesis, not decomposition: the combination of phlogiston with the calx of mercury.) The gas that had been released (i.e., oxygen) caused the candle to burn more vigorously and, when mixed with the residual air from the first reaction, resulted in a normal air.

Can the experiment described above be regarded as the *experimentum crucis*, supporting the oxygen theory and disproving the phlogiston theory? No, it cannot! First of all, we must keep in mind that Lavoisier's experiment was simply a replication of the earlier "dephlogisticated air" experiment of Joseph Priestley (1733–1804), a champion of the phlogiston theory. Before either Lavoisier or Priestley, similar experiments had also been conducted by Carl Wilhelm Scheele (1742–1786), who named the isolated gas 'fire air'. Scheele also remained faithful to phlogiston and never abandoned it. Both Priestley and Scheele explained their discovery of a new gas through the phlogiston theory and could not see any good reason at all why they should change their loyalty. They were by far not the only ones. In fact, most chemists stayed on in the phlogiston camp for quite some time (about ten years) after Lavoisier's critical experiment. Yet nothing of the sort should have happened if the critical experiment had indeed decided the matter once and for all! Even Lavoisier himself did not yet think of the phlogiston theory as necessarily dead and buried. Two years later, he still simply cautioned that the phlogiston theory could not be regarded as proven beyond doubt, “the existence of the matter of fire, of phlogiston in metals, sulfur, etc., is then actually nothing but a hypothesis, a supposition which, once admitted, explains, it is true, some of the phenomena of calcination and combustion” (translated from Lavoisier, 1780, p. 595). However, should he be able to show that “these phenomena may be explained in just as natural a manner by an opposing hypothesis, that is to say without supposing that the matter of fire or phlogiston exists in combustible materials, the system of Stahl will be found to be shaken to its foundations” (Lavoisier, 1780, p. 595).

At the time, chemists actively investigated different “airs” For example, carbon dioxide was described as “fixed air”—being “fixed” in certain salts, from which it could be released. Nitrogen was also discovered and was called ‘phlogisticated air’. Since nitrogen did not support combustion, it was assumed that it could not absorb any more phlogiston, already being rich in it. In the light of new discoveries and facts, the phlogiston theory itself also underwent several changes, naturally, given its hundred years of tenure, it could not have stayed the same as it had been in Stahl’s days.

Priestley’s interpretation of Lavoisier’s critical experiment was as follows: calxes in their free form may contain as much phlogiston as metals, or even more, but they only contain phlogiston because they absorb the “fixed air” (CO_2) which is a product of combustion; when calxes (including the red calx of mercury) are heated, they release “dephlogisticated air” (i.e., oxygen) and produce a metal (i.e., a compound of the calx and phlogiston); the reverse process (combustion) is what it always has been, namely, the liberation of phlogiston from the calx; the latter now absorbs the ‘fixed air’ which accounts for its heavier weight.

Henry Cavendish (1731–1810) discovered in 1766 an “inflammable air” (later identified as hydrogen) that was produced by the action of dilute muriatic and sulfuric acids on iron, zinc and tin, and which, as he initially concluded, could not have been anything else than phlogiston itself, released from the metal (the view was later also adopted by Priestley). Later, in 1784, he corrected that it was not pure phlogiston, but phlogisticated water. Cavendish, Priestley and a number of other chemists did not disavow their allegiance to the phlogiston theory even after the oxygen theory had gained general recognition, since they could not see how the latter would prove the first wrong, as the phlogiston theory could explain the facts at least just as well as the oxygen theory. In the case of these experiments which seemingly disprove the phlogiston theory and corroborate the oxygen theory, it is always possible to question the purity of the reagents. For instance, it is practically impossible to conduct experiments in a completely dry environment (water, however, is "dephlogisticated air" + "phlogisticated water").

We can only speak of a critical experiment if it is possible to demonstrate that the theories that are put to test are indeed applicable to the one and the same set of phenomena and can be thereby simultaneously judged in light of the same experimental fact. The strict satisfaction of the condition that hypothesis B logically rules out hypothesis A if the experiment produces the result F must be guaranteed. In the real history of science, it is difficult to find instances where we can claim with certainty that this condition has been satisfied. Mostly, critical experiments are labelled as such in hindsight, when the new theory has already become established. If a critical experiment actually did not decide the outcome of a battle between the rival theories (since it has already been decided) in real history, then our image of the past can be shaped to make it appear as if it all came down to this single experiment. That is certainly the case with Lavoisier's critical experiment of 1775, which in real history of chemistry did not yet decide anything.

Since no direct proofs of the oxygen theory or debunkings of the phlogiston theory have been shown to bear any significant impact on the course of the real history, attempts have been made to explain Lavoisier's success from a completely different perspective. Conventionalism maintains that scientific theories are not actually based on facts, i.e., they can be neither proved nor disproved, theories are neither true nor wrong, they are simply logical constructs which can be used to frame experiment results. The use of a particular construct by the scientific community is simply a matter of convention, chosen based on its virtue of simplicity. In principle, any theory can be adjusted to fit the facts, but over time such "fitting" tends to make the established theory increasingly cumbersome and unwieldy, so sooner or later a consensus will emerge among the scientists that a simpler unifying framework has to be found to replace the existing one.

Thus, according to the conventionalist logic, the oxygen theory supplanted the phlogiston theory, since the latter had become too cumbersome in providing explanations to empirical facts, while the sleek oxygen theory could perform the same task much more efficiently. Does the real history of chemistry corroborate such a claim?

Even if we ignore the fundamental epistemological shortcoming of conventionalism—convention as an explanatory principle necessarily implies a subjective, idealist construal of human knowledge and history—the conception is flawed due to the vagueness of the concept of simplicity. If we find it unacceptable to take some kind of inexplicable gut feeling of scientists as authority, it will be hard to demonstrate that the oxygen theory indeed was (was, precisely, not is) simpler than the phlogiston theory.

Let us observe what the word "simpler" could possibly mean. Perhaps, what they want to tell us is that the phlogiston theory is more cumbersome than the oxygen theory precisely because of the very concept of phlogiston, an excessive and useless component in its explanations. Indeed, the phlogiston theory construed combustion as a process whereby phlogiston is released from a combustible body already before the discovery of oxygen; the discovery of oxygen as an aerial gas made it possible for the oxygen theory to interpret combustion as a combination with aerial oxygen. The phlogiston theory did not abandon its position, yet was also forced to include oxygen in its general scheme of things to provide an account of what exactly increased the weight of the product upon calcination of metals. Consequently, the oxygen theory uses *two* components (metal + aerial oxygen) to explain the calcination process, while the phlogiston theory requires *three* (metal – phlogiston + an aerial substance, e.g., "fixed air"). Such a reasoning, however, is not historically accurate, since Lavoisier's original theory was a bit more complicated than that. Aerial oxygen, Lavoisier assumed, was not a simple substance, but a combination of the "acid former" and caloric, the substance of heat. During calcination, as he would interpret it, oxygen is relieved of caloric, released as heat, and the "acid former" combines metal.

The trouble with the principle of simplicity and the test of critical experiment is in general the same: they only work strictly on the assumption of *ceteris paribus* ("all other things being equal"), i.e., if it were possible to demonstrate on the basis of real history that, beyond any reasonable doubt, the competing theories are in all aspects equal, except for one of them (the one that in real history proved victorious over the other) being simpler than the other, which can be determined on the basis of a single perfectly precise criterion. This, however, the history permits us not, unless we are willing to accept a distorted view of history.

Should we then concede, perhaps, the futility of our attempts to find the rational criterion that decided the superiority of oxygen theory over the phlogiston theory?

Maybe one of them was neither better nor more correct, but was simply different and, for some reason, was found to be more appealing? Maybe the history of science is, just like the history of fashion, a history of changing trends which keep coming and fading for no rational reason, but simply because the new is interesting and the old is boring—unless you belong to that small stubborn minority who stick to their outdated and backward views until the end of their lives. Over time, more or less credible explanations are found for the triumph of the new trend, while its predecessor becomes an increasingly bizarre curiosity, so much so that one cannot but wonder, how could it have been conceived in the first place, why has it been permitted to exist?

Of course, fashion trends and scientific theories exist in worlds apart and no one would seriously consider the possibility that their underlying mechanism of change is exactly the same. Yet, in fact, a sociopsychological approach exists according to which no true understanding of the progress of science can be hoped for if it does not account for the fact that science is made by humans and no human activity is governed by abstract logic alone.

Such an approach has been proposed by the American historian of science Thomas Kuhn (1922–1996). The central concept of his theory is that of a 'paradigm'. It is the shared research tradition of a scientific community and it involves: (1) a certain world picture[8] (Kuhn regards it as the metaphysical component of a paradigm); (2) a set of regulatory methodological principles which Kuhn sees in the role of the generally recognised and shared values of the scientific community; (3) a set of "symbolic generalisations"—the universal propositions or relationships, readily cast in a symbolic or logical form, expressing the natural laws and the definitions of the symbols deployed by them; and (4) a set of typical techniques, model situations, exemplars of "doing science" which the scientific community employs in their problem formulations and solutions. This last component is the most important one, which is also reflected in the choice of the word 'paradigm' itself (from Greek *παράδειγμα*, meaning 'pattern', 'example', 'sample'). It is from here where the remaining components derive their real meaning—the concrete meaning of a "research tradition". The existence of a paradigm implies that the development of science is in the phase of "normal science": new research problems are being constantly formulated and solved in a manner resembling creating and solving crossword or chess puzzles, in the sense that we know how to correctly build a puzzle and know how to reach a correct

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[8] Within a specific paradigm, the general scientific world picture of the era acquires a much more specific meaning.

solution. When such puzzle-solving runs into difficulties—where the puzzle fails to adequately capture the problem, no solution can be found to a puzzle which, by all accounts, should be solvable; we can no longer tell whether the puzzle has actually been solved or not, the fundamental concepts and principles become the subject of heated debates and disputes—the science enters into a crisis. Normal science also encounters anomalies—such phenomena which resist explanation within the current paradigm or which can only be explained by artificial *ad hoc* hypotheses which are extraneous to the paradigm—but they are not paid any significant attention as long as the paradigm in general works flawlessly. However, in the midst of a crisis, anomalies become the focus of all attention. The crisis can be overcome as a new emerging paradigm develops in response. That is what a revolution in science means. Also, no logical or experimental proof exists to show that the new paradigm is better or closer to the truth. A new paradigm is acquired through a set of new samples and models, by solving new types of puzzles, by seeing the world in a new way. Even the "translation" of the new paradigm into the language of the old paradigm, or vice versa, is not properly possible.

Can such a theory adequately describe the process by which the oxygen theory came to supplant the phlogiston theory in real history? In a sense, yes. We can indeed see the two theories giving rise to different paradigms which can be compared, but which cannot be "translated" into each other's language without distortion, since translation should take into account the contexts in which the two paradigms developed and these involve substantial discrepancies, starting from the world picture and ending with specific experimental situations, i.e., instead of translation we should rather change the paradigm. That the abstract methodological criteria could not prove the superiority of the oxygen theory over the phlogiston theory (if indeed we consider the theories as they actually occurred in history), we already observed. Let us briefly examine how the phlogiston theory and the oxygen theory can be characterised as different paradigms.

In broad principle, the world picture of the phlogiston theory was Newtonian (as opposed to the views of Descartes and Boyle), but remained purely qualitative, just as all traditional accounts of chemistry had been. It characteristically explained the properties of chemical substances and their change by reference to their elemental composition which was construed qualitatively, i.e., elements were defined through the property whose original cause they were believed to be (that we can describe as the qualitatively construed principle of conservation of matter).

The oxygen theory was broadly Newtonian as well and also took a Newton's principle as its premise: matter is mass whose amount can be measured by weight. Lavoisier also sought the explanation for the properties of substances in their composition, yet the determination of a substance's composition was consistently based on quantitative criteria and the quantitative aspect of the principle of mass conservation (quantitatively construed principle of conservation of matter). This criterion of quantitativity proved to be an effective tool for distinguishing elements and compounds.

The differences and similarities of the regulatory methodological principles of the phlogiston theory and oxygen theory in general arise from the differences and similarities of their world pictures. The most obvious and prominent difference lies in the attitude towards quantitative research methods. Lavoisier found qualitative research wholly inadequate and suggested it be replaced with a precise quantitative account of all the details of the progression of chemical processes. However, in defence of the adherents of the phlogiston paradigm, it must be said that it would be wrong to accuse them of disregard of quantitative methods. "Phlogistonists", such as Cavendish, sometimes carried out most rigorous quantitative measurements. The gist of the matter is not in whether any quantitative research was done or how precise the measurements were, but in whether the chemical research itself had a qualitative or quantitative scheme as its premise.

As we recall, the phlogiston research programme argued for its methodological advantage over Descartes' and Boyle's programmes which were shown to be purely abstract, their direct application in experimental chemistry being impossible, only leading to the generation of useless mechanical analogies and countless *ad hoc* hypotheses. It was stressed that a practical method must be found to allow the division of chemical substances into their components, and reversely, the restoration of the original substance from such components. A chemist primarily had to be capable of qualitative chemical analysis. Once the phlogiston paradigm had become established, the active development of its methodological side ceased (this is typical of established paradigms!). When a competing theory emerged, the phlogistonists remained complacent and simply shrugged: the phlogiston theory explains the observed facts at least as well as the new theory, no indisputable evidence has been presented to refute the old theory and therefore no need exists to consider its abandonment. Lavoisier, however, after ten years of work on his oxygen theory, realised that the concept of phlogiston had been lacking a strict definition, as its meaning was subject to change with every new discovery. Thus, Lavoisier, who had assumed an outsider's position, began to notice the same methodological sin being committed by the phlogiston camp which the latter had accused its original competitors being guilty of during its own formative stage of development: namely, in order to explain new facts, it was constantly resorting to the generation of *ad hoc* hypotheses.

Due to the differences in their world picture and methodological base, the "symbolic generalisations" of both paradigms also diverged. Lavoisier's principal tool was the chemical equation which he had tied to the principle of mass conservation. In contrast, the phlogistonists derived their "symbolic generalisations" from the phlogistication–dephlogistication scheme.

At the level of model problems, the differences were also obvious and, generally speaking, were again reflective of the importance either theory attributed to the quantitative determination of substances and their measurement operations. We have already mentioned Stahl's original problem situation, which he solved with qualitative experiments. The phlogistic view was obviously founded on the model process of burning (of wood, limestone, etc.). The nascent Lavoisier's paradigm began to investigate such phenomena or experiments which appeared anomalous from the phlogistic perspective and required additional hypotheses for explanation. The inception of the new paradigm can be pinpointed to Lavoisier's experiments which he made in 1772 on the combustion of sulfur and phosphorus (the experiments themselves were nothing that had not been done before in chemistry). Lavoisier observed that the weight gain of the combustion products of these two substances arose from a *prodigious* quantity of air, fixed during combustion (the experiment was conducted under a bell jar that was placed in water, the ignition was accomplished by means of a burning glass). This discovery also gave him the idea to conduct similar experiments with metals (with tin and lead), as well as to measure the amount of gas liberated in the reduction of litharge (lead monoxide, PbO). What was probably crucial for the development and application of the new model experiment was the magnitude of the effect, suggesting that the precise measurement of weight and volume in calcination and reduction experiments is worth the trouble, since the weight gain of calxes (arising from a less prodigious amount of air) is less noticeable and harder to determine, while the experiments themselves are also technically more complicated.

As we can see, the concept of a scientific paradigm can offer a rather fitting description of our two theories. But how well does it do the *explaining*? By asking this simple question, we are revealed the Achilles' heel of Kuhn's theory. The *transition* to a new emerging paradigm, according to Kuhn, is a process which can only be described and not rationally explained. It certainly requires a crisis of the old paradigm to trigger the search for new approaches; however, for the time being, Kuhn argued, there is nothing that can prove the superiority of the new fledgling paradigm over the old one. It is impossible to be certain of what caused the crisis of the old paradigm and which principles should form the foundation of the new paradigm. Even when the new paradigm has already established a solid foothold and found recognition, it still continues to be confounded by occasional facts it does not have a ready explanation for, but the old paradigm does. For example, before the chemical composition of water and carbon monoxide (CO) was known, in one of its stages, the phlogiston theory identified the “flammable air” (i.e., hydrogen and carbon monoxide) as phlogiston and could provide a plausible account of the reactions involving these gases, whereas the oxygen theory was in trouble. The old paradigm has the tradition working in its favour, since, regardless of the crisis, it has its earlier real achievements to show for, many of which, at least initially, remain outside the new paradigm’s perspective. For instance, in the phlogistic framework, the similar properties of metals are explained by their similar composition, but in Lavoisier’s theory, the similarity of metals remains without a theoretical explanation, as a matter of fact, this question does not even arise, since metals are elemental substances and their similarity is coincidental.

Kuhn claims that a new paradigm is born as follows: the crisis forces the scientists to freely explore any alternative approaches they deem worthy of investigation. The scientists at first rely on their intuition alone, on their belief that the new approach has the potential to prevail and prove successful. What could be the source of such a belief? Kuhn points here to obscure and personal aesthetic preferences and considerations, random past events and coincidences in the scientist’s personal life, which connect somehow in the scientist’s mind with the time period when the current paradigm of his discipline, the one in crisis, was still in the process of formation and was defending its choice of methodology. These purely personal and mostly non-scientific trivia, of course, do not affect the acceptability of the new paradigm, they only serve as the initial trigger for the transition to new methodological principles and ways of seeing the world. Practice, of course, is where the acceptability of the paradigm is tested and proven. The search for the one single argument that can be shown to be decisive and convincing for all scientists is doomed to fail, as different scientists are persuaded by different arguments. The truth of the new theory and the falsehood of the old theory, after all, is not a matter of logical or experimental proof, but of persuasion purely, not unlike conversion to a new faith. After a while, the number of arguments has grown, the case for the paradigm is stronger, more "levers" are found that can steer the focus and improve the clarity and precision of the new picture. Along the way, the paradigm's supporters' ranks swell, its arsenal of model experiments expands, improvements are made on research instruments, scientists write heaps of new research articles and books, eventually also textbooks—which all makes the science normal, once again.

However, perhaps there is still a way to understand the "paradigmatic" nature of science, the process of paradigm formation and paradigm shift in such a manner that places the locus of the paradigm's inception not in the purely personal beliefs of individual scientists? Perhaps we could find a different perspective on the process of paradigm shift, without the comparison to religious conversion? We will explore these possibilities in our next section of this chapter, continuing our analysis of the origin and causes of the eighteenth-century chemical revolution.

2. Why, then, did the chemical revolution happen?

As we saw, Kuhn's approach to the history of science and its progress provides, to a very large extent, an excellent account of the real history of science. He truly hits the mark with the concept of paradigm, as discussed in the previous section of this chapter, and its premise that science and its progress are never a matter of abstract logic and methodology alone, but should be regarded as a specific human activity. Yet it is also here, in this latter part, wherein we find the weakness of Kuhn's philosophical foundation and the source of his theory's shortcomings. For Kuhn, the concept of human activity does not extend beyond the scientific activity by an individual or by a group of individuals—the scientific community. The way of seeing and thinking that develops in a scientific community when they work with models and exemplars, of which Kuhn speaks, actually finds its explanation in the Marxist principle that the human cognition is based on our sensory, object-oriented practical activity. Humans and human activity should be understood as part of a wider system of sociohistorical practice (ultimately that of production). The specific domain of human activity which we call science only opened up as a result of the emergence of a particular type of culture. The characteristic "thingness" of this culture that formed the foundation of the scientific world picture and knowledge and scientific cognition, is eventually also where the origin of the paradigmatic nature of science lies. Why? The way the Age of Science perceives the world is, in a sense, a paradox: on the one hand, the world is infinitely diverse, inexhaustible, a testing ground for any kind of experiments human imagination can conceive, but on the other hand, governed by strict laws, relations that are relentless, inevitable, univocally defined, recurring and formalised. How, then, should such a world be perceived? It is the principal task of science to constantly produce knowledge that is constructive and strictly unambigous. Since the world has not divided itself into the objects of different sciences, theories, experiments, but such a division must be accomplished by science, accurately and rationally, yet the world can be seen through a multitude of constructs which may differ both in terms of their components and the ways these components are connected, may require different degrees of precision in their construction, then, in order for the results to meet the desired standard, it is important that different constructs are not mixed up, that all such individuals who are engaged with the same construct actually see the world as required by this construct. That is why paradigms are formed in science. Science in general, within a particular phase of its development, can be observed as a single big paradigm, different development phases of science and its disciplines by themselves can be viewed as separate paradigms, and each discipline has itself several different smaller and larger paradigms. On all levels, from time to time, old paradigms are dislodged and supplanted by new ones, and the paradigms with narrower meaning, of local importance, are subject to a more frequent shift, of course.

The cognitive method of a scientific community, no matter how peculiar and specific the paradigm which governs it, is never formed through the activity of that scientific community alone. A scientist is, first and foremost, regardless of the specific character of his or her activity, a human being living in a distinct era, whose thinking is informed by the particular logic of categories evolved in the socio-historical practice and reflected in the general scientific world picture of the era. Specific scientific activity also cannot deviate too much from the type of the practical activity characterising the era. All in all, any paradigm emerges as a peculiar form of socio-historical practice, it can only realise such possibilities which the practice of the era permits. The general possibilities can be identified in the way of thinking, system of categories, world picture, the more specific possibilities, however, depend on the technology available to conduct the experiments at the time.

Of course, the role of the scientist's personal convictions, past coincidences, etc. in the germination of ideas cannot be denied either. The formation of a scientific community most likely has its socio-psychological aspect as well. But delving into such facts and circumstances certainly will not lead us to the mechanism of paradigm emergence and shift, since this is surely shaped by the patterns found in the evolution of social cognition, which can be gleaned from the structure of the practice and its development stage.

Kuhn is right: scientists working under different paradigms live in different worlds. Their logic of reasoning, methodological principles, theoretical foundations of their work have through certain model situations and exemplars acquired a specific content. By the virtue of new model situations and exemplars, that content is different in a new paradigm, rendering meaningful communication between the scientists representing different paradigms impossible. Indeed, in order to compare paradigms and understand their genesis, one needs to consider and separately analyse the relevant theoretical positions, methodological principles, world pictures and categories of thinking in the wider context, not limited to the paradigm itself, and eventually in the context of the sociohistorical practice. This means that the scientist aspiring to mastermind a paradigm shift must be able to "leave" the existing paradigm and have a strong background also in methodology, history of science and philosophy, or must already be an outsider, entering the paradigm's sphere of influence with a different perspective from the start.

Let us now turn our attention to the paradigm shift from phlogiston to oxygen. We observed that the Stahlian chemistry was qualitative in its core, while Lavoisian chemistry relied on quantitative methods. From the perspective of the logic of categories, this amounts to the change of base category: category 'quality' was replaced with category 'quantity'. A random coincidence? Certainly not. All perception of any phenomenon begins with seeing the phenomenon in the first place, we must be able to distinguish, to separate it from the background. For that reason, qualitative research of a phenomenon must come first. For a more detailed and accurate overall picture, the application of quantitative methods, measuring, must then follow. To do it in the reverse order would not be possible logically. Before we can measure, we must have something to measure. Even when we speak of the category of quantity, to make the distinction, a prior awareness of the category of quality is already required, since quantity is also a certain quality, certain delimitation, i.e., that something which we must be able to distinguish. A quantity is a difference in one and the same quality (its size or amount).

Therefore, the logical conclusion that we draw is that the qualitative method of cognition of the phlogiston paradigm was inevitably bound to be, sooner or later, supplanted by a quantitative method of cognition, i.e., Lavoisier's paradigm. Yet this simple conclusion, obtained via derivation from the logic of categories, is naturally still far too abstract to explain the paradigm shift, since it even cannot tell us when the quantitative approach will have reached its limits. In abstract sense, such limits may not exist at all, since the discovery of new phenomena whose qualitative description must come first may never end! And just the same, as soon as a qualitative definition is made, a quantitative investigation must immediately follow if a more thorough and detailed description is to be had!

A rational explanation of paradigm shift must also include a methodological analysis (the requirements which the social practices of the Age of Science set to the development of scientific knowledge specifically took the form of scientific methodology). We already know that the paradigm shift, i.e., revolution, is preceded by a crisis which begins with an onslaught of anomalies. The crisis and the anomalies are what signal the need to examine the paradigm itself, its methodology and philosophy (on the level of categories), from an external position.

Some of the phlogistic anomalies which were not left without explanation, albeit in the form of *ad hoc* hypotheses, we have already met earlier. Why does the weight of metals, sulfur, phosphorus increase upon combustion? (That was certainly the central anomaly, treated with several different solutions). Why is the amount of air reduced and why does the burning soon stop if it happens in a closed vessel? Why is combustion not supported in airless space? (The latter two necessitated the grafting of the *ad hoc* hypothesis onto the main theory that air is needed for the absorption of the phlogiston released in combustion. It was also postulated that the air had the capacity to absorb a finite amount of phlogiston only, while the volume of phlogisticated air would be reduced just as cotton balls would shrink when wetted.) While throughout its entire existence the phlogiston theory preserved its central idea—combustion (calcination) involves the release of phlogiston and reduction involves the absorption of phlogiston[9]—it took the licence to freely generate additional suppositions and hypotheses which served to ensure the compatibility of that central idea with the immediate experiment and the interpretation of facts. The weight gain of combustion products would appear as an anomaly if we accepted as true the following two modifications to the phlogiston theory: (1) phlogiston is a substance with a specific weight; (2) the weight of a body should decrease when it releases phlogiston and does

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[9] If we were to interpret electrons as phlogiston, this central tenet of the phlogiston theory would not be untrue even today.

not take up any other substances. We already observed that the second of these suppositions was not recognised by the phlogiston theory during its primary development phase (phlogiston was presumed to be lighter than air, therefore a phlogisticated body weighs less in air than the dephlogisticated version of the same body). Several variants of the theory, which, however, were not taken too seriously at the time, rejected the first postulate entirely and attributed negative weight to phlogiston. The later versions of the theory discarded the last part of the second supposition, i.e., it was found that the combustion products gained weight while they were releasing phlogiston, because at the same time something was added as well.

It was mentioned in the previous chapter that, already before the phlogiston paradigm had become properly established, hypotheses were being put forward to suggest that the weight gain of combustion products could be attributed to their earlier combination with an unknown substance during combustion. However, at the time, these hypotheses were too vague for experimental chemistry and failed to contribute to furthering the principal goal of science—the steady generation of new constructive scientific knowledge. In the 1770s, things changed, and the hunt for the unknown substance causing the weight gain in combustion products could begin in earnest as the accuracy required in chemistry became achievable. The oxygen theory superseding the phlogiston theory offered the most radical solution. We will now turn our attention to the genesis of this new approach and its triumph over the Stahlian system.

As mentioned before, the paradigm shift began with the application of precise quantitative methods in the exploration of the wide assortment of measurable chemical phenomena revealed by prior qualitative investigations. John Desmond Bernal (1901–1971) has made a very apposite observation in his *Science in History*, “It is characteristic of these early days that the real advances in chemistry were not done by chemists. Chemists knew too much, they had theories that explained everything; it was for the physicists, who knew nothing, to provide fool or common-sense explanations” (Bernal, 1954, p. 449). Lavoisier, who by his university training should have been a lawyer, also approached chemistry like experimental physics. He found that chemistry had become complacent with analogy and verbal descriptions. From the outset, the precise determination (adjusted for measurement error) of the weight of reactants and products involved in chemical reactions and the corresponding improvement of required laboratory instruments were considered of paramount importance by Lavoisier. One of the first instruments whose design Lavoisier did improve was the constantimmersion hydrometer, used for measuring the density of liquids. He first used this for the impurity analysis of mineral waters. While Lavoisier was investigating the maximum purity of water that can be achieved by repeated distillations, he also began to wonder if this process could have an effect on the water's properties. This, in turn, led him to consider the ancient notion of elements and their transmutation (in particular, the conversion of water into earth, and vice versa), whose evolution he critically observed from antiquity to modernity. This problem appeared to be pertinent in some way to the investigation at hand, since repeated distillations of water left a slight earthy residue of unknown origin in the glass vessel. Lavoisier solved it by a quantitative experiment: a weighed sample of pure water, eight times distilled, was sealed in a piece of laboratory apparatus called a pelican which was kept at a constant heat for 101 days. The careful gravimetric analysis of the residue that had accumulated in water led him to conclude that it consisted of the particles dissolved from the apparatus alone and the water remained unchanged. It is interesting to know that Carl Wilhelm Scheele, a Swedish pharmaceutical chemist and a phlogistonist, solved the same problem by qualitative analysis.

Lavoisier based his reasoning on his conviction that the total mass of reagents and products in a chemical reaction always remains the same. He only defined the principle and elevated it to a law in 1789 in his acclaimed chemistry textbook *Traité élémentaire de Chimie* ('Elements of Chemistry'). And even there, it makes its appearance not on the first pages, but in the latter half of the book, in a chapter where he discusses "vinous fermentation":

> it is necessary to be previously acquainted with the analysis of the fermentable substance, and of the products of the fermentation. We may lay it down as an incontestible axiom, that, in all the operations of art and nature, nothing is created; an equal quantity of matter exists both before and after the experiment; the quality and quantity of the elements remain precisely the same; and nothing takes place beyond changes and modifications in the combination of these elements. Upon this principle the whole art of performing chemical experiments depends: We must always suppose an exact equality between the elements of the body examined and those of the products of its analysis. Hence, since from must of grapes we procure alkohol and carbonic acid, I have an undoubted right to suppose that must consists of carbonic acid and alkohol. (Lavoisier, 1789, pp. 140–141)

In connection with the law of conservation of mass, we should also point to a common misconception. As with the concept of chemical element, too much importance is attributed to a particular phrasing of the law. Essentially, what it expresses is the principle of the indestructibility of matter, already known in the antiquity. The same principle—nothing can be produced from nothing, all things are put together of everlasting seeds—for instance, has been invoked by the Roman poet and philosopher Lucretius (*c.* 99 BCE – *c.* 55 BCE) in his poem *De rerum natura* ('On the Nature of Things'). In the Newtonian world picture, matter was identified as a permanent substance, assumed to be ultimately composed of indivisible and immutable particles (essentially resurrecting the core idea of the atomism of Leucippus and Democritus, *sans* the particular shapes and sizes the ancients imagined the atoms to have). Newton begins his *Philosophiæ Naturalis Principia Mathematica* (1687) with the concept of quantity of matter and defines it as the product of density and volume, for the reason of the quantity of matter being directly related to the number of elementary particles or corpuscles in the given amount of space. Hence, we can understand why the Newtonian world picture which had come to mean the scientific world picture in general interpreted the principle of matter conservation as mass conservation. This principle had always been tacitly assumed anyway, one way or another, when the weight of the reactants and products was measured and compared. In the hands of Lavoisier, however, it was elevated to the role of a "symbolic generalisation", one of the components of the unified chemistry paradigm. As we recall, it means a universal proposition or relationship, readily cast in a symbolic or logical form, that has become implementable, "operative" in experimental activity by virtue of the other components also being there in the paradigm's structure, above all, the model situations and exemplars. This is the reason why the exact verbal or mathematical formulation of the law of conservation of mass in itself is of no special importance. For that reason, at least from the perspective of the history of chemistry, it is also a trivial matter that the law of conservation of mass was formulated by the illustrious Russian scientist and poet Mikhail Lomonosov in a letter sent to Leonhard Euler in 1748, confirmed by experiment in 1756 (the results remained unpublished) and published in Russian and Latin in 1760. Lomonosov's dissertation must have been known to Lavoisier as well, yet he makes no mention of Lomonosov as the original author of the law of conservation of mass. That is all true, but so is the fact that Lomonosov's law essentially remains an articulation of a world picture, regardless of the existing evidence that he may also have conducted experiments to test the law. Lomonosov remains close to Boyle in the style of his approach to chemistry, in only very few cases does he provide experimental results.

Figure 30. Mikhail Lomonosov (1711–1765). Engraving by E. Fessar and K. A. Wortman (1757). (*Wikimedia Commons*, 2018f)

We already mentioned the experiments which Lavoisier carried out in 1772 on the combustion of phosphorus and sulfur and on the calcination and reduction of lead and tin. These experiments he still interpreted in conformity with the phlogistic orthodoxy, yet he already boldly declared that the fixation of air upon calcination and combustion and the release of a certain air upon the reduction of the calx to the metal, as revealed by his measurements, "were one of the most interesting discoveries that had been made since Stahl", i.e., he essentially put his findings on the same pedestal with the core phlogistic principles.

In 1774, Lavoisier decided to reinvestigate Boyle's experiments which originally had been intended to demonstrate that the increase in combustion products' weight was caused by the fire particles combining with metal. (Several interpretations of phlogiston were also based on these experiments.) Boyle did the experiment as follows: a known weight of tin was placed in weighed retort, which was then sealed. The retort was heated for two hours, then allowed to cool and opened. The calx was removed from the retort, weighed and found to have gained in weight in comparison to the original amount of metal. It was Lavoisier's hypothesis that the calcinated metal obtained its extra weight by taking it from the air in the retort (while in Boyle's days, and also in Stahl's days, air was seen as nothing more than "empty" environment and no one would even consider the weight of air as something deserving investigation, it was rather the opposite in Lavoisier's days, air was most certainly no longer "just air", without substance and consequence). To prove his theory, Lavoisier first measured the weight of the original metal and the retort, air included, and showed that the total weight did not increase upon heating (within the margin of error), nothing could be gained from the outside and the only possible source for weight gain was the air inside the sealed vessel. (There is evidence that similar experiments had already been conducted by Lomonosov in 1756, to prove his law of conservation of mass, but he never published the results. Before Lavoisier, Boyle's error had also been noticed by other researchers, including Lavoisier's archrival Priestley.) The difficulties of establishing a working quantitative paradigm in chemistry are apparent in the technical challenges that needed to be overcome in order to ensure the necessary accuracy and precision of the experiment results. (Retorts broke easily and were inconvenient to handle when hot, the weight gained by the oxide was hardly noticeable. For instance, in his tin calcination experiment, Lavoisier used 8 ounces of tin whose weight was increased by 3.12 grains, i.e., a mere couple of hundred milligrams for almost a quarter of a kilo of metal.) In addition to his physicist's mind and exceptional experimental skills, Lavoisier was certainly also helped here by his prior combustion experiments with sulfur and phosphorus, where the results were more pronounced and easily observable.

Based on his experiments of 1774, Lavoisier came to several important conclusions. Since the burning always stopped before consuming all air available in the vessel, Lavoisier argued that the common air is a mixture of two species of air: the combustion-supporting "pure air" and a residual air that supported neither combustion nor respiration. As a logical conclusion, the air released upon calx reduction had to be "pure air", since that is what the metal combines with—a claim to be confirmed by experiment. However, contradicting this prediction, normal calx reduction experiments released "fixed air" (CO_2) instead. Lavoisier solved this by giving the following explanation: these experiments had used—in line with the phlogiston theory principles—a phlogiston-rich substance, normally charcoal, in combination with the calx to produce the metal when heated together and therefore it was only to be expected that the air that was evolved is the result of the combination of the "pure air" disengaged from the metal and the "elastic fluid" disengaged from the carbon. Essentially, that is what "fixed air" is, then, a combination of these two and in that form not present in the calx, as claimed by the phlogistonists. Lavoisier therefore concluded that, in order to obtain "pure air" from a calx, the reduction process should be accomplished without any addition to the calx. In this manner, Lavoisier came to the theoretical prediction of "pure air" being a component of common air and described the composition of "fixed air'" However, he was unable to immediately find a way for the sufficiently precise experimental verification of these conclusions.

The editorial board of the memoirs of the Royal Academy of Sciences in Paris, where Lavoisier published his article on his reinvestigation of Boyle's experiments, provided the following comment,

> The combustion of metals is therefore not simply the release of phlogiston from the calx, this combustion involves the calx's recombination with air; air which for long time in this operation had been regarded as necessary, but purely mechanical agent, now appears as a necessary chemical agent, it is the mediator which by combining with calx releases the phlogiston from the metal. At least such is the explanation if one aspires not to disregard Stahl's theory, since what has been known to be true for a long time, now appears as target for attack; yet Stahl provided so many facts for its proof, these facts indeed were also very well analysed, so let us not be hasty with abandoning the theory. (Translated from *Histoire de l'Académie Royale des Sciences*, 1774, p. 21)

We already know that the crucial experiments for Lavoisier's theory had originally been conducted by Priestley (and Scheele as well, but he did not publish his results at the time), who worked under the phlogiston paradigm. They were preceded by the investigations of Pierre Bayen (1725–1798) who found that the red calx of mercury can be reduced by heat alone (under lens), as a result of which "fixed air" (CO_2) is released. This experiment was what Priestley wanted to retest, since its phlogistic interpretation would have confirmed that calxes contain "fixed air" which they have absorbed from air. Yet Priestley showed that Bayen had been wrong, since the "air" which was released in the process did not form carbonic acid when dissolved in water. After several repeat experiments, Priestley (in 1774) came to the conclusion that he had coincidentally discovered a new type of air which he named "dephlogisticated air". Before the publication of his results, Priestley shared the news of his discovery with Lavoisier in Paris. Lavoisier considered what he had heard and made Priestley's experiment part of his own investigations, to confirm that his theoretical predictions had been correct, yet when he presented his initial results (1774–1775), he failed to give any credit to Priestley for his contribution, of which the latter took notice and reminded Lavoisier of his oversight in an article he published in 1777. In the same year, Lavoisier addressed the matter as follows,

> I wish to state that I was not the first to perform several of the experiments presented in this memoir; indeed, strictly speaking, only Mr Priestley can claim originality in this regard. However, since the same facts have led us to diametrically opposed conclusions, I trust if I am criticised for having borrowed demonstrations from this celebrated scientist, the originality of my conclusions will not be challenged. (Lavoisier, 1776, p. 672)

This shows that Lavoisier saw the value of the experiment as inseparably linked to its interpretation, conclusions, theoretical context.

In the light of the above, the question of who can claim the discovery of oxygen turns out to be equally problematic, as is also the case with other similar discoveries. Apparently no definite answer can be given at all. Do we regard simply the first-time isolation of the gas in an experiment as its discovery? Or do we also need to know the true identity of the gas in addition to its experimental isolation? As a matter of fact, in either of the cases we have no way of knowing of who and when exactly discovered the oxygen! The gas which we today refer to as oxygen was isolated in an experiment not only by Scheele and Priestley, but other scientists (Bayen, Hales, etc.) as well. And Lavoisier also did not discover oxygen as we understand the element today, since he thought that it was a combination of the "acid former" and caloric.

The discovery of oxygen in Lavoisier's sense marks the birth of Lavoisier's (or oxygen) paradigm in chemistry, yet initially only as a rival of the Stahlian system. We already know that, regardless of the success of Lavoisier's theory, no sufficient grounds existed for the outright abandonment of phlogiston. In terms of methodology, both paradigms appeared to be more or less on an equal footing. At first, Lavoisier could not say anything better in support of his method than that these phenomena which had been investigated by Stahl's theory may be explained in just as natural a manner by an opposing hypothesis. Lavoisier's paradigm constantly encountered its own anomalies, which sometimes favoured phlogistic explanations. These, however, Lavoisier did not concern himself with too much, since it was always possible to ward them off by casting doubt on the purity of the used reagents and the conditions of the experiment (which indeed turned out to be true in most cases, as it was later learned), etc. Admitted, the same technique served both masters equally, as the phlogistonists used it just as effectively to fend off their anomalies. The outcome of the battle of paradigms is decided on their ability to perform the principal function of science better than the rival—to constantly generate new constructive knowledge, to formulate problems which are not yet solved, but are solvable. That is why the birth of a competing paradigm is related to the resolution of existing anomalies (or at least some of them). These have also been resolved by the old paradigm, at least in most cases, but by *ad hoc* hypotheses only. In the ensuing competition, it is important for the new paradigm to show that it can also solve these problems which originally had paved the way for the old paradigm's success, and by doing this, also uncovering new solvable problems.

Lavoisier began retesting the acid experiments of Priestley and other phlogistonists and reinterpreted their results in his new framework. (We would also like to point to the fact, which the reader must surely have noticed by now: Lavoisier constantly repeats the experiments which are already well-known and have been done many times before, yet makes numerous new discoveries along the way, since he has a completely different perspective of the situation.) As we recall, he initially observed the combustion of phosphorus and sulfur simply as their combination with air. Now, of course, it is clear that the "acid spirit of phosphorus" and the "vitriolic acid" (today these would be phosphorus pentoxide and sulfur trioxide) are compounds of phosphorus and sulfur with the "purest" part of the air, just as carbon dioxide (CO_2) which was known as "fixed air". The acids of the "noxious air" (nitrogen oxides) were also identified as oxygen compounds. The "purest" part of air was named *oxygen*, derived from the Greek words meaning "acid former" (aerial oxygen as a gas was envisioned by Lavoisier as a combination with caloric). Lavoisier's oxygen theory of acidity predicted the existence of an entire new class of acids: the oxidation of *organic* compounds should produce *acids*. This indeed found confirmation in experiments. However, muriatic acid (HCl) was an exception, as it contained no oxygen. Lavoisier nevertheless held to his belief that it still must be an oxygen compound, considering chlorine an oxide of "muria". The next anomaly, a more serious one, occurred in relation to Cavendish's experiments (see previous section of this chapter). These led the scientific community to believe that phlogiston was the "inflammable air" (hydrogen) which was obtained by dissolving metals in dilute acid. According to Lavoisier's theory, this "air" was supposed to be released from acid upon metal's combination with oxygen and, therefore, combination of this "air" with oxygen (combustion) should yield an acid. This prediction, however, could not be confirmed by experiment, since the corresponding experiment resulted in no detectable substance at all. Priestley, however, on the phlogistonists' side seemed to score a win for their team, since, if the "inflammable air" truly is phlogiston, then this air should be extractable from phlogiston-rich substances, especially coal. And Priestley indeed pulled it off! For instance, he heated a piece of coal using a lens and an inflammable air was released (this time, CO, however). Also, calx, when heated in this air (in phlogiston!), should convert into metal. This was also experimentally verified by Priestley. In fact, he carried out the reduction of red lead:

$$Pb_3O_4 + 4H_2 \text{---->} 3Pb + 4H_2O$$

or, according to the phlogiston theory: red lead + phlogiston=lead

Cavendish, from the opposing camp, helped the oxygen theory to overcome these difficulties, when he demonstrated that “inflammable air” and “dephlogisticated air” combine to produce water. Upon hearing about this, Lavoisier immediately repeated the experiment and now realised that the combination of inflammable air and oxygen, which he had predicted to be an acid and did not find it, was, in fact, water. Next, a plan was hatched to shoot down the red lead reduction experiment as proof of the phlogiston theory. Lavoisier pointed to the following oversight on Priestley’s part (again, according to the paradigm built on the law of conservation of mass!): the weight of metal should have increased upon the combination of red lead and phlogiston, but instead it decreased, i.e., something was removed from (and not added to) the red lead. That something was supposed to be the oxygen which had been present in the red lead in a corresponding amount of weight. No gas, however, evolved in the experiment and the “inflammable air” vanished. Therefore, the inflammable air must have combined with oxygen to produce water, whose formation Priestley failed to notice, since he had conducted the experiment on the surface of water. This immediately led to the suggestion (i.e., Lavoisier once again made an experimentally verifiable prediction on the basis of his theory): if the experiment was to be conducted on the surface of mercury, the formation of water would be noticed. That was proven by... Priestley! The formation of “inflammable air” by dissolution of metals in *dilute* muriatic or sulfuric acid was also given an explanation: it was the decomposition product of water. Concentrated acids were unsuitable for the task, producing no “inflammable air” (since there was no water!). The last fact was an anomaly from the phlogistic point of view. Lavoisier’s theory also made possible the prediction that water, the regular fire extinguisher, was not necessarily always that in every conceivable case, since chemically combustion means combination with oxygen, and while water contains oxygen, then a certain kind of combustion can also take place in water, whereas it involves the release of hydrogen. This prediction was later also confirmed: iron powder rusts in water, releasing hydrogen in the process.

The discovery of the elemental composition of water forced the scientists once again make modifications to the phlogiston theory. Now (in 1784), hydrogen was no longer seen as phlogiston, but as “phlogisticated water”. “Dephlogisticated air” turned out to be the same as “dephlogisticated water”, thus “phlogisticated water” + “dephlogisticated water”= water. Phlogiston itself had to be relegated to the category of a weightless fluid. As we can see, these modifications succeeded in bringing the phlogiston theory no less into conformity with the facts than the oxygen theory. Also, the oxygen theory was not simpler than the phlogiston theory by any single clear criterion. There was also nothing strange about phlogiston turning out to be a weightless fluid, since such fluids were not at all uncommon in the science at the time, including in Lavoisier's own system (the substances of heat and light), and played a rather progressive role in the history of science. It is historical irony that the respective theories in physics and chemistry came to be based not on Lomonosov's conception of heat as a form of motion, which is a far more modern concept, but on the caloric theory, firmly rejected by Lomonosov!

And yet, the Stahlian system bowed to Lavoisier's theory and practically vanished from chemistry by the end of the 18th century, although a handful of true faithfuls, such as Priestly, remained. As late as 1819, an English chemist Robert Harrington published a book in defence of the phlogiston theory and offered a £100 prize to anybody who could prove it false. The prize money was never claimed, since no one could produce the undeniable proof required! Regardless, what could not be denied was the fact of the victory of Lavoisier's revolution in chemistry. So why did it happen?

The answer should be clear by now, but we'll give a rundown of the main points.

First, it should be stressed that we can find a general answer in the logic of categories: the Lavoisierian chemistry was quantitative and therefore bound to supplant the qualitative Stahlian chemistry sooner or later.

Next, we will call the reader's attention to the methodological superiority of the Lavoisierian chemistry over its rival. Of course, this we can see properly only if we consider the facts and circumstances surrounding the development of both paradigms and assess the theories in their historical context.

After ten years of work with his theory (in 1783), Lavoisier finally knew what the primary weakness of its rival was: phlogiston changes its form every instant, like the Greek sea-god Proteus. Between 1770 and 1785, the Stahlian chemistry made progress only in the realm of *ad hoc* hypotheses. It no longer formulated and solved its own problems, but was always on the defence, saving its phlogistication/dephlogistication scheme from sinking and building a rapidly growing arsenal of secondary explanations and subsidiary assumptions to deal with new facts which it had not been able to predict and which did not fit into its natural evolution of ideas. In contrast, Lavoisier's paradigm evolved as a balanced and coordinated system: every new step, new problem, new hypothesis, new idea was a logical and congruous continuation of the foregoing. Although theoretical predictions did not necessarily always find immediate empirical confirmation, the observed facts sometimes seemingly supported the opposite instead, only later to be shown to have been in full agreement with the theory all along, and some facts were never explained. In short, Lavoisier's paradigm settled into the routine of science, doing what the society demanded of it, doing it better than the phlogiston theory.

V Atoms, foundation of chemistry

In present day, the very first theoretical concepts which children learn in their chemistry class are those of an atom and molecule. The 7th-grade textbook states that a molecule is the smallest identifiable unit into which a substance can be mechanically divided and which still retains the chemical properties of that substance. The process of molecules decomposing into their constituent parts or of such parts recombining to form new molecules is called a chemical reaction. The elemental parts which a molecule is composed of and which cannot be reduced any further by chemical decomposition are atoms. Next, the textbook proceeds to explain such notions as 'atomic mass', 'chemical element' (a species of atom), 'simple substance' (made up of only one element) and 'chemical compound' (made up of two or more elements), 'pure substance' (a sample of matter consisting of the molecules of a single substance only) and 'mixture' (a sample of matter consisting of the molecules of different substances), the law of definite proportions, 'chemical formula', 'molecular mass' and 'molar mass'. It is only then that we arrive at the definition of the law of mass conservation and the concept of chemical equation. This way, the fundamental concepts of chemistry are presented clearly and accessibly in their logical order. Historically, however, as we saw, Lavoisier made the principle of mass conservation the bedrock of his chemistry and arrived at the concept of chemical equation even before the modern atomic and molecular theories in chemistry had come to existence. Molecules, the concept upon which everything is built in modern chemistry education, began to be distinguished from atoms only with the emergence of organic chemistry as a distinct chemistry discipline. Yet, organic chemistry courses are among the last ones taught at school. When the periodic law of elements was discovered, the classical theories of chemical structure had already been formulated in organic chemistry. So why has the progress in chemistry followed such an illogical path? Or is there perhaps a different kind of logic to be found in this progress?

Karl Marx observed that in the history of science problems are often discussed in a complex form before their elementary form is solved. The real point of departure is reached only through "a hopeless confusion of intertwined movements" (Marx, 1904, p. 117). "Unlike other builders, science not only erects castles in the air, but constructs separate storeys of the building, before it has laid the foundation." (Marx, 1904, p. 64). How can this be?

So let us venture an abstract reflection. The edifice of science surely must have a foundation of some kind. Is it perhaps the foundation of a different and older edifice which it has borrowed and builds upon? Or, perhaps, "builder" is not really an apt metaphor for science? We can imagine that, as presented in textbooks and monographs, science is indeed comparable to the work of a master builder, governed by the principles of construction. However, the historical progress of science is rather a reflection of the development of the builder's skills and art over time. The logic in the progress of science is not that of a mechanical (formal) system, but of an organic system. As a historical phenomenon, science is not assembled of ready-made parts (elements, components) which form a logical and anticipated structure, a whole with its specific and particular functions. Rather, it is the opposite: the differentiation of an initially undifferentiated whole, emergence of a relatively independent structure which corresponds to an already existing function. If such a structure has been established, functions can already be analysed, derived and "made to work" on its basis. Real progress and development, however, follows a reverse pattern: the function does not arise in the special structure to which it corresponds, but within a more general system, and it is the function which gives rise to the special structure that corresponds to the function. The edifice of science is indeed such a structure which historically has been constructed and shaped by the knowledge-building function of the general human activity. This is why separate habitable storeys are constructed in the science edifice before the foundation stone has been laid, and even when the foundation stone has been laid, sooner or later its inadequacy to support the growing structure will become apparent and lead to its replacement with a new and better one.

In this chapter, we will examine how Lavoisier built his edifice of chemistry without laying the foundation stone and how that foundation stone was eventually found in the doctrine of the atomic and molecular structure of matter. The story of the conception and development of the atomic theory is also notable for the fact, as Friedrich Engels once observed, that "atoms and molecules, etc. cannot be observed under the microscope, but only by the process of thought" (Engels, 2010, p. 486).

1. Composition of chemical compounds—fixed or variable?

This was the question at the heart of a key scientific controversy that raged among chemists for eight years in the early 19th century. The principal champions of the opposing sides were Joseph Louis Proust (1775–1826) and his fellow Frenchman Claude Louis Berthollet (1748–1822), both eminent chemists. Their dispute can also be cast as a clash of different paradigms. The source of confusion, in truth, was the question of what exactly can be regarded as a true chemical compound. In the eighteenth-century chemistry, no need had yet arisen for a strictly defined distinction between chemical and physico-mechanical processes. Changes in substances were automatically identified as chemical when they involved such effects as the generation of heat and light, appearance of a different colour, taste or smell, evolution of gas bubbles or formation of a precipitate. In the same manner, substances which did not contain any discernible different components and could not be mechanically separated into different constituents (or elements if no further chemical decomposition could be accomplished) were regarded as individual chemical species. This meant that the category of chemical compounds at the time also included solutions, metal alloys, gas mixtures, etc. The Newtonian world picture which laid the groundwork for chemistry also presumed the substances ultimately to be composed of elementary particles. Combination of substances, their capability to react with each other (or lack thereof) was thought to result from the reciprocal chemical "affinities" of the corresponding particles. By definition, this force had to be present and empirically observable in chemical processes, so it was studied, measured and presented in numerous affinity tables.

Berthollet's investigation of affinities was tied to the method of displacement reactions. In his works (1799, 1801, 1803), he concluded that the combining proportions of the products of a chemical reaction are not invariable and depend on the physical circumstances of the reaction, primarily on the weight proportions of the reactants. Berthollet stressed that the "chemical action" is exerted not only according to the affinities of the reactants, but their mass as well. In other words, a large quantity of a substance having a weak affinity for another will be sufficient to decompose a small quantity of a compound composed of this other and a third substance, between which there is a strong affinity. That is, a weaker degree of affinity could be compensated by an increase in quantity.

Berthollet's paradigm was founded on the model situation of displacement reactions of salts. He was among the first scientists to recognise the phenomenon of reversibility in chemical reactions and is noted for his contribution to the theory of chemical equilibria. He demonstrated that, in addition to the quantities of reactants (or products), the equilibrium of a chemical system is also affected by the formation of insoluble or volatile species which are effectively removed from the system, causing the equilibrium to swing in favour of the products and driving the reaction to completion in one direction.

Figure 31. Claude Louis Berthollet (1748–1822). Photogravure by H. Liffart. (*Wikimedia Commons*, 2014a)

Berthollet's chemical affinity investigations and Lavoisier's work on the determination of the reactants and products of a chemical reaction shared, in a certain sense, a similar path. Namely, both made the transition from qualitative to quantitative research, but lacked the specific measurement units. Before Berthollet, the research focus was only on the identification of the reciprocal affinities of substances and on the creation of ordered displacement affinity series. Berthollet, however, chose to investigate how the different weight proportions of reactants might alter the course of chemical change. In measuring the quantities of substances, both Lavoisier and Berthollet relied on the Newtonian principle that supposed the existence of some sort of universal or elemental matter whose quantity equals the number of its elementary particles or corpuscles in a given amount of space. By implication, what the quantities of the reactants AB and C and the products AC and B were supposed to express were not actually the quantities of the corresponding substances AB, C, AC and B, but the amount of matter contained in these substances.

Lavoisier deemed it impossible to have any meaningful scientific discussion about the fundamental structure of substances at the microscopic level. He was satisfied to confine his chemistry research to the macroscopic level. Lavoisier declared his methodological creed, "I have imposed upon myself, as a law, never to advance but from what is known to what is unknown, never to form any conclusion which is not an immediate consequence necessarily flowing from observation and experiment" (Lavoisier, 1790, p. xviii). Regarding the concept of a chemical element, he explained his approach as follows,

> All that can be said upon the number and nature of elements is, in my opinion, confined to discussions entirely of a metaphysical nature. The subject only furnishes us with indefinite problems, which may be solved in a thousand different ways, not one of which, in all probability, is consistent with nature. I shall therefore only add upon this subject, that if, by the term *elements*, we mean to express those simple and indivisible atoms of which matter is composed, it is extremely probable we know nothing at all about them; but, if we apply the term *elements*, or *principles of bodies*, to express our idea of the last point which analysis is capable of reaching, we must admit, as elements, all the substances into which we are capable, by any means, to reduce bodies by decomposition. (Lavoisier, 1790, p. xxiv)

Berthollet, however, already looked for the connection between the micro and macro levels, in the sense that he interpreted the chemical process of substance formation in terms of motion and interaction of elementary particles of involved substances. Yet he also chose not to put forward any specific hypotheses about the microstructure of matter. In his interpretation of his experiment results, he only suggested that the chemical action between the particles depends on their shape (which determines the specificity of the particle's affinity and the strength of the force holding the combined particles together, i.e., how well certain particles fit together), amount, reaction conditions (such as temperature) and physical properties of density and elasticity which cause the formation of either precipitates or volatiles. The process of chemical change eventually reaches the point of saturation, which can be understood as the moment when the particles can no longer exert attraction toward each other, i.e., no free space remains on their surface where others could attach themselves. Such particles which fit together better (due to having a larger contact surface) are required in smaller amounts in order to achieve the saturation, those which fit together worse are required in larger amounts. Such speculations indeed lead to the conclusion that, up to the saturation point, chemicals can be combined in continuously variable proportions, i.e., a chemical compound may be composed of elements in any ratio, depending on the conditions of the reaction, among which the most important is the weight ratio of the reactants. Berthollet's reasoning also implicitly assumes that the quantity of the particles of different substances is always directly related to the weight of the particular substance, since otherwise there would be no grounds to claim that a weighed amount of a particular substance characterises the quantity of that substance. (Berthollet, 1804)

In 1799, the same year when Berthollet published the first results of his research, Proust also presented his findings to the public. Contrary to Berthollet's views, he had come to the conclusion that the elemental composition of a chemical compound, regardless of whether it is artificially made or naturally found, is always the same. In other words, the proportions by weight in which elements enter into a compound are invariable. Proust was a laboratory chemist who adhered to the Lavoisian school in his work. He was strictly interested in the composition of reactants and products only and had no concern for the mechanism of chemical processes which was Berthollet's focus. In his dispute with Berthollet, Proust based his claims on the evidence derived from his experiments with metallic oxides and sulfides, which were shown to always contain the same proportion of oxygen or sulfur by weight. The same elements could also combine in a different fixed ratio, but in this case also resulting in a different compound, i.e, the composition of a substance always changes with a sharp jump if a chemical compound is produced, not continuously. Thus, combinations of variable proportions are simply not chemical compounds or pure substances. Solutions and alloys would qualify as chemical combinations in Berthollet's system, but not so in Proust's.

In this controversy, Proust's position eventually prevailed, since the fixed composition of chemical compounds was a completely logical assumption in the paradigm which was conceived by John Dalton and offered a new perspective on the world of chemistry. However, does this mean that Proust delivered pure undiluted truth and Berthollet was in complete and total error? Not at all. Berthollet's investigations were very well supported by experiments and he could also interpret Proust's results within his system (in Berthollet's view, Proust worked under conditions which were atypical for chemical reactions). In hindsight, Berthollet's ideas have been found ahead of his time, and precisely for that reason forgotten, never properly understood. Yet, why do the ideas which should, in fact, be sound and scientifically fertile remain dormant for such a long time? How should we understand the phrase "the world was not ready for his ideas"?

It is the view of the author of this book that the concept of scientific ideas which are ahead of their time and fail to find recognition and resonance only because their contemporary audience is irrational and unreceptive can only arise because

Figure 32. Joseph Louis Proust (1755–1826). By A. Tardieu. (*Wikimedia Commons*, 2018g)

of a methodological conception (wrong preconception) that is unsuitable for the analysis of the history of science. In truth, the emergence of successful paradigms is governed by the general logic of development of our cognition and the methodological principles observed in the *historical* context. If we are to examine the situation from this perspective, it will become clear that it was not the world that was not ready for Berthollet's ideas, it was rather Berthollet's ideas that were not ready. Berthollet's ideas could not have been fertile even from a purely logical perspective. There is no need to speak of being ahead of time, instead, we need to speak of the fact that the problem was unjustified from the perspective of the logic of categories and that its solution did not yield methodologically justified results, which is why it was discarded, quite expectedly.

The impression of being ahead of one's time can be well understood on the basis of the dialectical laws of the unity and interpenetration of opposites and of the negation of negation. Vladimir Ilyich Lenin has stressed that the law of cognition, whose correctness must be tested by the history of science, is "the splitting of a single whole and the cognition of its contradictory parts" (Lenin, 1976, p. 357). At the level of the categories of thinking, any phenomenon can be characterised in terms of the unity of opposites. The process of cognition creates conceptions whose central ideas, if expressed in categories, are mutually exclusive. We witnessed such a "splitting" in the case of Berthollet's and Proust's conceptions regarding the composition of a chemical compound. Further cognition leads to the domination of one conception, while the other is abandoned. In our example, Berthollet's conception in its general idea was the continuation of the original whole, the "unsplit" notion, since only after the works of Proust and

Dalton, the fixed composition of chemical compounds became an established truth, while solutions, gas mixtures, alloys, glasses and other substances and materials with variable composition were no longer regarded as chemical combinations. Berthollet, however, did not accept this new perspective and wanted to prove the contrary with his special investigations. The "splitting of a single whole" indeed means the turning of the "single whole" into its opposite in the sense that the "single whole", i.e., certain initial undivided whole "splits" into opposites, but also in the sense that in "splitting" that opposite comes to the fore, "gains victory", which in the initial whole was not visible at all, which is why it now negates its opposite as an expression of the initial "single whole", as the new conception negates the old conception (Berthollet, 1803). However, since, in fact, that "victorious" opposite is only one side of the whole phenomenon, then what follows sooner or later is the transcendence of the one-sidedness, i.e., return to the discarded opposite on a new foundation—the negation of negation. Therefore, it might appear, when we observe the history of science, that the abandoned opposite conception had, in fact, been a stroke of genius and was left aside only because it had been too much ahead of its time... Unfortunately, in that case, it will be forgotten that the abandoned conception has become a stroke of genius only because it had been cast aside in favour of the development of its opposite conception, which now also gives new meaning to its rival. In truth, what we have is not the return to the abandoned opposite conception but the resumption of the unity of opposites, the restoration of the "single whole" after the investigation of the independent contradictory parts resulting from the "splitting" and the discovery of the connections between them.

On the basis of the logic of categories, Friedrich Engels has formulated the following rule in the history of science, "It was necessary first to examine things before it was possible to examine processes. One had first to know what a particular thing was before one could observe the changes it was undergoing. And such was the case with natural science." (Engels, 1946) Here it might be relevant to note that the discernment of objects and cognition of their properties occurs by virtue of processes, relations and connections with other objects. An object which is completely immutable and unchanging, placed outside of any kind of relations and connections, is a mere empty abstraction. What we are talking about, however, is that at first we cannot obtain any specific knowledge about the processes themselves, but about the objects which have been extracted from those processes, although before we begin studying objects, we do have a certain general picture of the undifferentiated whole, of some kind of "general process".

Berthollet, however, wanted to act contrary to that law: he started to investigate processes even before one properly knew the entities involved in those processes, the nature of chemical compounds and of chemical change. Berthollet tackled these questions only after he had already developed a certain conception of chemical processes, which also necessarily shaped the answers he gave. Yet, since his conception had been developed on the basis of "non-chemical objects", as "chemical objects" were yet to be determined, his entire theory naturally turned out to be defective.

From the perspective of logic, chemistry's focus necessarily had to turn on the category of 'measure'. This is also evident in Berthollet's case: he needed to take into account the quantity of the reacting substances, of the reacting particles, but he had no units in which it could be measured. He could not apply in his investigations of chemical equilibria any precisely formulated physical principles or laws. Proust, however, conducted his research while staying on the highway of the field's evolution, since the determination of the weight of the components (their percentage) in "ready" chemical compounds (obtained outside of the chemical process) was an important link in the chain of cognition, leading to the conclusion that their composition is fixed and, eventually, to the discovery of the necessary measurement units as well.

What is expressed by the category of measure? Measure is the link between the categories of quality and quantity. Quantity expresses a non-qualitative difference, as we know, and characterises a quality which is known. If quantity is changed, the quality will remain the same. However, this quantitative difference or change has no effect on quality, remains indifferent, only to a certain extent—which is what we call 'measure'. Measure (or rate) is therefore a qualitative quantity: a quantity that has been defined (fixed) for a particular quality. Awareness of measure leads to such quantitative cognition which connects directly with the quality of the object, explores the basis of the quality, conducts measurements with its own measurement units and formulates quantitative laws.

Lavoisier's paradigm was formed as a result of the direct transposition of the "alien" measurement technique and measurement units of physics into the qualitative research in chemistry. From the perspective of chemistry, that quantitative approach was, in fact, the continuation of the earlier qualitative research, only with other, more precise and sensitive tools. Indeed, no quantitative laws or constants of chemistry were offered by Lavoisier's paradigm! The precise measurement of the weight of substances and the volume of gases, and the application of the law of mass conservation, allowed the distinction of chemical substances and the determination of the nature of the process (such as whether it was a decomposition or synthesis) even when it was otherwise impossible.

While we did mention the difference between the physical and chemical approaches, we should now try to clarify this difference a bit further. On what grounds do we differentiate a chemical phenomenon from a physical phenomenon? This question has no easy or simple answer at all. It is also clear that the physical and chemical phenomena are closely related, mutate into one another, etc. In nature, no separate chemical or physical phenomena exist. Why should the operation with mass units amount to specifically physical and not chemical measurement? Mass is a general property which characterises a body regardless of the specific substance that it is composed of. Physics indeed deals with bodies (which are influenced by a force, field, energy, etc.), while chemistry concerns itself with the substances of which these bodies are made of, what they are composed of. Of course, in reality nothing is simply a substance without being a body at the same time (already the different states of matter imply that a substance can occur as different bodies) and vice versa, yet the properties of a chemical substance and the properties of a physical body, chemical change and physical change, chemical laws and physical laws can be distinguished. Why is that so? How have the concepts 'substance' and 'body' developed? If the nature itself has not split into bodies and substances, maybe drawing a distinction between them is purely arbitrary?

As with all objects of cognition in general, the objects of physics and chemistry are not simply "given" to us by nature, but they have formed in the sociohistorical practice. Seeing nature as physical phenomena occurring with bodies or chemical phenomena occurring with substances has developed in the different spheres of sociohistorical practice, to which correspond different branches of production and in science different experimental activities. Nature begins to be seen as a world of physical phenomena through technological tools—starting with various simple mechanisms, some of which were already known in the antiquity, and ending with modern state-of-the-art electron computers, nuclear reactors and scientific instruments. We can say that a physical phenomenon is something that we know how to engineer in technological tools, i.e., the corresponding natural phenomenon will then be known to us as physical (let us emphasise once again that in nature no separate physical phenomena exist, but this is not to be taken to mean that the distinction between physical and non-physical phenomena is arbitrary). Chemical phenomena in nature, however, begin to be seen through the task specified in the social production, which is to obtain substances with desirable and necessary properties, including for those bodies which are constructed by technological engineering. The activity for the production of substances with required properties (in the course of which the concept of a substance itself develops) differs from the operation with bodies, their construction and engineering. Substance is of one or the other kind, a body, however, has been *engineered* to be one or the other way. The production of substances—a chemical phenomenon—is the engineering of a technology for the generation of substances with required properties. Substances are not engineered (like machines, mechanisms or apparatuses), but they are allowed to be formed from each other. Yet the science of chemistry, just like physics, attempts the theoretical engineering of objects. This means that, as a science, chemistry contains a certain paradox at its core. However, this is already a special problem which we will try to analyse in the final chapter (see 'By way of conclusion').

2. How was chemical atomism conceived?

So, physics makes no distinction between different substances, only between different bodies which are composed of matter whose amount is expressed in mass. John Dalton (1766–1844) was a physicist before he became the chemist who introduced the atomic theory into chemistry (a notable fact which deserves a special mention). Dalton's interests lay in the constitution of mixed gases. Boyle's experimental gas law—the product of the pressure and volume of a gas is constant when temperature is constant ($pV = \text{const}$)—was given a theoretical interpretation by Newton who, to be exact, was the one who actually elevated this relationship to the status of a law. Newton took a geometrical approach and postulated the following: a gas is composed of particles which exert on their neighbours repulsive forces which are inversely proportional to distance. Dalton wanted to delve further and also give an explanation for the cause of these repulsive forces. This he identified in a special weightless fluid, caloric, the supposed substance of heat. As we recall, caloric was also an important concept in Lavoisier's theory. As Dalton explained, the spherical particles of matter are drawn to each other by forces of attraction, but since they are contained in a shell of 'caloric' or heat (this was also how Lavoisier understood it), which is the cause of repulsion, under normal conditions they cannot get close enough to each other to be bound by forces of attraction. He also used a similar model to describe the constitution of mixed gases. Berthollet and other chemists viewed the formation

Figure 33. John Dalton (1766–1844). Engraving by W. H. Worthington (after J. Allen). (Roscoe, 1895, frontpiece)

of a gas mixture as similar to dissolution and essentially a chemical process, governed by the forces of affinity between the particles of different species (such as air and steam). This chemists' doctrine was shown by Dalton to contain a serious inconsistency: it was discovered that water evaporates into empty airless space exactly the same way as it "dissolves" into air. This led Dalton to ponder the following puzzle which for the chemical theory did not exist: if a mixture of gases is not a chemical combination, but a mechanical mixture of particles, how can we explain its uniform composition, irrespective of the different weights of its components which fail to separate according to their weight, as do the layers of immiscible liquids. First, Dalton demonstrated by experiment that the formation of a gas mixture is independent of the type of chemical species involved (if the process were chemical, the formation of a uniform gas mixture should have been dependent of the chemical affinities of the species). Next, he also showed that the partial pressure of a gaseous 'solute' is also independent of the density of the gaseous 'absorbant' or its presence altogether. This discovery is known as Dalton's law of partial pressures: in a mechanical mixture of gases that do not react chemically, each gas or vapour exerts its partial pressure which is exactly the same as that it would have applied if the gas was separated from the mixture and occupied the space alone.

Thus, Dalton arrived at the conclusion that a gas mixture is not a chemical combination. But what exactly makes it different from a chemical combination? Dalton based his explanation on the concept of atoms: mechanical mixing of gases does not affect their atomic structure, while chemical combination results

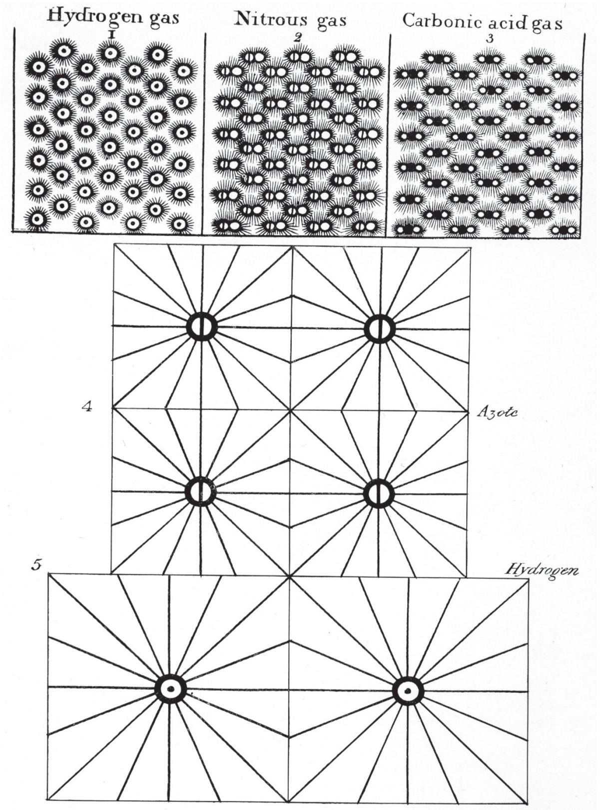


Figure 34. Dalton's diagrams depicting gaseous atoms which are surrounded by an atmosphere of caloric (shown by the "rays of heat" emanating from the centre): 1) four atoms of nitrogen; 2) two atoms of hydrogen (Dalton, 1810b, Plate 7). Courtesy of Science History Institute.
Figs. 1–3 here represent profile views of the disposition and arrangement of hydrogen, nitrous, and carbonic acid gas particles. Fig. 4 is the representation of four particles of azote with their elastic atmospheres, marked by rays emanating from the solid central atom. Fig. 5 represents two atoms of hydrogen drawn in due proportion to those of azote, and coming in contact with them.

in the rearrangement of the gas particles, or atoms, which are converted into new stable particles (compound atoms). A chemical union of the two elements can be made possible by breaking in some manner, such as by electric spark, the "atmosphere" of heat surrounding the particle, allowing the power of affinity to prevail. If two simple atoms of two different gaseous species have in this way combined into a new compound atom, then a new (combined) atmosphere of heat will form around it and the new compound atom as a new physical body will behave like any other gas particle. From a chemical perspective, however, a new species has emerged. Since pure substance is composed of a single type of atoms only (simple or compound), each of which is surrounded by an atmosphere of heat, exerting repulsive force, and a chemical reaction means the transformations of one type of atoms into another, then from it follows that the composition of an individual chemical compound (pure substance) must be definite and the substances can combine in simple whole-number ratios only.

This is how Dalton arrived, at least theoretically, at the formulation of the law of multiple proportions, as well as the law of definite proportions (Dalton, 1803). As we saw, Proust reached the same conclusion based on empirical observations and evidence, yet it was nevertheless Dalton who elevated it to a law proper. Dalton was initially probably not even aware of Proust's work, but that is actually not that important. What is important, however, is that as a theoretical conclusion, the law of definite proportions was formulated by Dalton, Proust is left with the honour of providing the empirical proof of the theory.

In his dispute with Berthollet, Dalton also drew attention to the failure of the chemical theory of gas mixtures to explain Boyle's law ($pV = \text{const}$).

We could say that Dalton applied the category of measure most skilfully and understood the meaning of a qualitative leap perfectly, while Berthollet failed to grasp the relationship between the qualitative and the quantitative. Both Dalton and Berthollet had atomism as the foundation of their theories. Yet Berthollet's version lacked clarity and remained too vague. For example, Berthollet could not answer when substance A combines with substance B to give rise to a new quality AB and when they simply mix. Essentially, he imagined that a new substance AB is always produced whenever substances A and B are combined. Substance AB may contain components A and B exactly in the same ratio that these substances were initially taken. Different ratio of reactants only influences their affinity (which was a force analogous to gravity, whose effect depended on how well the tiny particles fit together, on the area of surface of the particles coming into contact with each other). In Berthollet's view, there was no qualitative difference in the manner of particles' combination, regardless of whether the result was a physical mix or a chemical compound. This is why he could simply use the mass units which, however, in truth did not permit the determination of the quantity of one or the other chemical substance (i.e., the number of particles of this particular substance). Berthollet could only speak of a larger or smaller mass of substance, but he had no way of telling what the minimum possible amount of that particular substance is without losing its quality and what exactly is required for that quality to arise.

Dalton, however, knew these things with absolute clarity, as we already saw earlier. He explained,

> I have chosen the word *atom* to signify these ultimate particles [which is the lower limit of divisibility of a substance—*R. V.*] in preference to *particle*, *molecule*, or any other diminutive term, because I conceive it is much more expressive; it includes in itself the notion of *indivisible*, which the other terms do not. It may, perhaps, be said that I extend the application of it too far when I speak of *compound atoms*; for instance, I call an ultimate particle of *carbonic acid* a *compound atom*. Now, though this atom may be divided, it still ceases to become carbonic acid, being resolved by such division into charcoal and oxygen. Hence I conceive there is no inconsistency in speaking of compound atoms and that my meaning cannot be misunderstood. (Dalton, 1810a, quoted in Freund, 1904, p. 288)

Let us now return to the law of multiple proportions and its genesis. For Dalton, his discovery of the law of multiple proportions was directly related to the idea of relative atomic weights. Namely, while investigating the mechanism of diffusion, he came to the conclusion that the atoms of different gases must be of different size, since otherwise they would not mix. As he wanted to calculate the diameters of atoms, he needed, in addition to the densities of different gases which could be measured, a scale of relative atomic weights. Dalton made the atom of hydrogen, the lightest of gases, the basic unit of his system of atomic weights. The diameters of atoms in their shell of caloric, however, he calculated as relative to the atom of water (in liquid state) whose diameter he also took to equal one unit. Next, he assumed that the atoms exist and combine in the simplest of manners. Chemical elements are composed of simple atoms. If two elements combine to form a single compound, this compound will consist of diatomic compound atoms. If the same elements, however, combine to form two different compounds, then the second (and possibly the third) of these will already consist of triatomic compound atoms (two atoms of element A and one of element B; or two atoms of element B and one of element A), etc.

This means that Dalton, on the basis of the logic of categories and atomistic world picture, and in the course of identifying and solving problems of physics, formulated a simple principle of multiple proportions as a symbolic generalisation (if we use Kuhn's framework). He obtained a formal scheme that in his hands began to work as a chemistry law and a definition of the corresponding concepts (chemical compound, simple and compound atom, etc.). Dalton also had firm methodological convictions which coincided with those of Lavoisier, although at a new level of cognition, in a new context. In his view, "Facts and experiments, however, relating to any subject, are never duly appreciated till, in the hand of some skilful observer, they are made the foundation of a theory by which we are able to predict the results and foresee the consequences of certain other operations which were never before undertaken" (Dalton, 1896, p. 99).

Following the principles described above, Dalton compiled a list of the relative weights of the atoms of a number of elements and their compounds (in the case of compounds, their "atoms" would be molecules today), found in his laboratory notebook dated 6 September 1803. He also calculated the diameters of the particles in gaseous state, which, indeed, all turned out to be different. This he considered sufficient proof of his hypothesis regarding the diffusion of gases.

In his first table of atomic weights (and diameters), Dalton applied the principle of multiple proportions in respect to already known compounds. The first compounds whose composition he determined himself and derived their formulas in accordance with the principle of multiple proportions were the "carburetted hydrogen" (methane) and "olefiant gas" (ethane). Dalton found that these gases are composed of carbon and hydrogen and that the "olefiant gas" has two times more hydrogen in its composition. Therefore, he regarded ethane particles as diatomic and methane particles as triatomic (1 carbon atom + 2 hydrogen atoms).

Dalton unveiled his atomic theory to the wider public for the first time in a reputable series of lectures he had been invited to hold at the Royal Institution of London in December 1803 and January 1804. Much of its early spread and impact can be attributed to the authority of Thomas Thomson (1773–1852) who included an account of Dalton's atomism in the third volume of his *System of Chemistry* (1807). Dalton's own magnum opus, bearing the appropriately provocative and revolutionary title *A New System of Chemical Philosophy*, consisted of two volumes, the first of which was published in two parts in 1808 and 1810 (in 1812 also in German) and the second in 1827. Dalton built the bridge between the empirical facts and the idea of the atomic structure of matter, which had already existed in speculative natural philosophy for a long time. He only permitted his atoms to have such properties and attributes which were not inconsistent with experimental facts. The "translation" of chemical behaviour of substances into the "language" of atoms was essentially the creation of idealisations. In Dalton's theory, atoms had the following properties: 1) atomic weight (as a speculative idea, differentiation of atoms by weight was already known in the antiquity) as the chemical unit of the substance's mass; 2) all atoms of one and the same substance are completely identical (an ideally pure substance); 3) a simple substance consists of the atoms of one and the same chemical element, these are indivisible simple atoms (pure substance + the idea of the indivisibility of a chemical element); 4) the atoms of a given element (i.e., simple atoms) can combine with a different number of atoms of another element, resulting in a different compound atom (a compound as a pure substance + law of definite proportions + chemical reaction as a qualitative change of substance + principle of multiple proportions).

In the early 19th century, chemists (Dalton himself, as mentioned earlier, was originally a physicist) were generally so heavily inclined towards empiricism that even Dalton's atomism appeared to them speculative (in a sense, the more empirical leanings of chemists, as opposed to physicists, are logical, if we think of the difference of physics and chemistry of which we spoke earlier). Even Thomas Thomson, who had from the outset given his full support to Dalton's theory, presented in his book Dalton's discovery of the principle of multiple proportions in the context of the empirical determination of the composition of methane and ethane. Dalton himself had introduced him this idea as specifically linked to these experiments, he told. Thus, the story of the empirical genesis of the law of multiple proportions became commonly accepted. It is appropriate to stress here that after the paradigm has become established, it is quite common that laws begin to appear as straight written down from the facts, although the actual mechanism of cognition is rather opposite: the empirical relation is found and the facts are obtained on the basis of a conception, a certain way of seeing, which has already been formed earlier. As we saw, this was clearest in the case of Dalton. Dalton's law of multiple proportions was accepted by chemists—especially after the experiments of William Hyde Wollaston (1766–1828) and Thomas Thomson—when they were convinced of its empiricism. The concepts of atoms and atomic weights appeared to chemists as speculative hypotheses that did not necessarily deserve recognition. Instead, the notions of 'equivalent weights' of William Hyde Wollaston or 'proportional numbers' of Sir Humphry Davy (1778–1829) were deemed more justified, since these concern themselves only with ratios of weights, with no connotations of imaginary abstractions.

The law of equivalent proportions was discovered by Jeremias Benjamin Richter (1762–1807). Prior to him, similar observations had also been made by Carl Friedrich Wenzel (1740–1793) and other chemists. Richter studied the neutralisation reactions of acids and bases and observed that those amounts of different bases which can saturate the same quantity of a particular acid are equivalent to each other and can therefore be neutralised by the same quantity of another acid. Richter measured such equivalent weights for acids and bases and collected the results into corresponding tables. However, Richter's and his predecessors' work failed to attract any attention at the time. The law of neutralisation gained some recognition after Ernst Gottfried Fischer (1754–1831) had prepared and put out a German translation of Berthollet's *Recherches sur les lois de l'affinitié* in 1802 and annexed to it a table of "combining weights" on the basis of Richter's equivalent weights of acids and bases. However, it still remained a coincidental and inconsequential footnote until Dalton laid the theoretical groundwork for the new paradigm. Dalton provided the law with an atomic interpretation. This law was a logical extension of the atomic theory not only as the law of neutralisation, but as the general law of substances combining in ratios of equivalent weights, in fixed proportions (according to the chemical units—the atomic weights). The term 'stoichiometry' (from Ancient Greek *στοιχεῖον stoicheion* 'element' and *μέτρον metron* 'measure') which Richter had coined in his *Der Stochiometrie oder Messkunst chemischer Elemente* (1792–1794) was introduced into general use only later. The three laws of stoichiometry are the law of definite proportions, the law of multiple proportions and the law of equivalent proportions.

Richter, by the way, was a student of the famous German philosopher Immanuel Kant (1724–1804) in Königsberg, where he defended his doctoral dissertation on the use of mathematics in chemistry (1789). Kant's view of chemistry was more that of an art than science, since chemistry at the time hardly applied any mathematics to its objects. Yet Kant's measure of a science was mathematics: how little or how much of it was integrated into a particular discipline. It was indeed Richter's goal to make chemistry meet Kant's standard and he set out on a search for mathematical regularities and patterns in chemistry. However, he did not understand the relationship between mathematics and idealised experimental situations, which we discussed in connection with Galileo's method in Chapter 3. (This is not an uncommon shortcoming even today, especially in biology, sociology, etc.) He looked for mathematical regularities in chemistry randomly and arbitrarily. Thus, without any proper and correct empirical poof, he claimed that the combining weights of acids progress geometrically and the combining weights of bases follow an arithmetical series. This botched attempt to introduce mathematics into chemistry was probably one of the reasons why

Figure 35. Jeremias Benjamin Richter (1762–1807). Engraving by Meisenbach, Füffarth & Co. (1892). (*Wikimedia Commons*, 2017b)

Richter's research was ignored and its rational content was only recognised after the establishment of Dalton's paradigm. "Richter's case" also shows that measurements by themselves and the good intention to apply mathematics in the discipline are not a guarantee of success, even when some of the results are actually solid. Measurements and mathematics bear fruit when applied consistently within a paradigm.

What was paramount in Dalton's paradigm was certainly the introduction of the concept of atomic weight, the chemical unit of mass, and the concept of an atom (simple and compound), the corresponding fundamental unit of a pure substance, regardless that the chemists deemed it necessary to stress: what is important are the real empirical relations that have been found, which in themselves can simply be taken as laws, with no unnecessary speculation what lies behind them, that an atom is simply a quantity of substance corresponding to its atomic weight. The empirical caution of chemists did have some historical justification, since Dalton's theory indeed also contained a few experimentally unfounded speculations, such as the "rule of greatest simplicity" in what pertains to the occurrence of elements as simple substances and the structure of compound atoms. It was nevertheless thanks to Dalton that the new units took hold in chemistry. Instead of two unrelated qualitative and quantitative approaches in chemistry, it meant the introduction of a qualitative quantity, i.e., measure, which placed all existing empirical observations into a completely new light. If earlier it had been almost impossible to notice the existence of the laws of stoichiometry in chemistry, then the new units made it impossible not to notice their existence. Indeed, it is hard to see any regularity in the fact that carbon monoxide is 44% carbon and 56% oxygen, while carbon dioxide is 28% carbon and 72% oxygen. Yet, if we assume that a pure substance consists of identical atoms (either simple or compound), that a chemical combination means the transformation of one type of atoms into a different type of atoms, while all atoms of the same type have their specific fixed weight, then we will realise that a particular component's share by weight in a given substance probably cannot tell us anything about the chemical composition of that substance. We need to take into account the difference in the atomic weights of the component elements to find out the ratios of component atoms in their compounds. Therefore, we need to know, in the given example, the mass of oxygen that combines with the same mass of carbon in both compounds and compare the ratios thus obtained. Having done so, the picture will become clear: 1 mass unit of carbon combines with 1.3 or 2.6 mass units of oxygen, i.e., the ratio of oxygen to carbon in these compounds is exactly 2:1.

Dalton's paradigm, once it was established, immediately revealed a multitude of well-defined and solvable research problems. First of all, the determination of atomic weights. Then, the "chemical re-measurement" of all chemical processes, i.e., their observation as a combination or decomposition of atoms, creation of a corresponding chemical language which would describe chemical formulas and reactions based on new units and allow the chemists to operate with those formulas and reactions also outside direct experimental activity. Dalton's atomism also encountered several problems for which it itself could not yet offer any apparent solution. Above all, these included the justification of Dalton's own "rule of greatest simplicity" or its replacement with something else, i.e., the task was to find the laws which determine the atom's capacity to combine with a certain number of other atoms. The concept of atomic weight also needed further justification. Entire Dalton's atomism had a fully Newtonian foundation. It presupposed that the future development of the atomic theory would have to conform to the fundamental principles of the Newtonian world picture (or otherwise the limits of that world picture would be shown). The fundamental Newtonian tenets also included the view according to which all properties of a substance should be tied to the principal property of all matter, that is, mass. The first step towards this indeed had already been made with the formulation of the concept of atomic weight, which showed that a chemical element is characterised by a specific weight that is unique to it. However, any relationships between mass and the chemical properties of an element remained unknown.

The latter problem was solved by Dmitri Ivanovich Mendeleev who discovered the periodic law of elements. The replacement of Dalton's "rule of greatest simplicity" with an objective criterion could have been accomplished by Gay-Lussac's and Avogadro's hypotheses, just as it is currently done in school textbooks. However, Dalton rejected Gay-Lussac's law, and Avogadro's hypothesis, which could have solved all the mysteries, had to wait for half a century for recognition. In this instance, the phrase "the world was not ready for the discovery" is also not appropriate, since this particular discovery was exactly what was needed for solving the problem. At least this is how it looks from the perspective of the atomic-molecular theory. Why then did the chemists remain blind to the correct solution offered to their problem for roughly fifty years?

3. Why did Avogadro's hypothesis fail to be recognised?

In 1808, precisely when Dalton's atomic theory was starting to generate buzz in the scientific community, the French chemist Joseph Louis Gay-Lussac (1778–1850) formulated an empirical law stating that the ratio between the volumes of the reactant gases and the gaseous products can be expressed in simple whole numbers. He had already established in 1805, with his Prussian colleague Alexander von Humboldt (1769–1859), that 2 volumes of hydrogen combine with 1 volume of oxygen to form 2 volumes of water vapour. Now, he concluded that similar simple whole number volume ratios are also applicable to other gases (1 volume of chlorine + 1 volume of hydrogen = 2 volumes of hydrogen chloride; 3 volumes of hydrogen + 1 volume of nitrogen = 2 volumes of ammonia, etc.). This seemed to be in perfect agreement with Dalton's law of multiple proportions.

Of Gay-Lussac's discovery, Dalton had the following to say, "In fact, his notion of measures is analogous to mine of atoms; and if it could be proved that all elastic fluids have the same number of atoms in the same volume, or numbers that are as 1, 2, 3, etc., the two hypotheses would be the same, except that mine is universal, and his applies only to elastic fluids" (Dalton, 1808a, p. 556). However, Dalton had discarded the hypothesis about the same number of atoms in the same volume as untrue. He observed, "Gay Lussac could not but see […] that a similar hypothesis had been entertained by me, and abandoned as untenable" (Dalton, 1808a, p. 556). Dalton referred to his early theory of mixed gases and his proof that the diameter of the particles (atoms surrounded by an atmosphere of caloric) of different gases is never the same, thereby also implying that different gases cannot

Figure 36. Joseph-Louis Gay-Lussac (1778–1825). Litograph by François Séraphin Delpech. (*Wikimedia Commons*, n.d.)

have the same number of particles in the same volume. This, as Dalton had found, was apparent, for instance, in the fact that 1 volume of nitrogen and 1 volume of oxygen yield roughly 2 volumes of nitric oxide. According to the atomistic interpretation, the reaction proceeds as follows: 1 nitrogen atom + 1 oxygen atom = 1 atom of nitric oxide. Since it is impossible for the two volumes of nitric oxide to contain more gas particles than in the one volume of either nitrogen or oxygen, the nitric oxide particle must be in diameter roughly twice the size of either nitrogen or oxygen. With regard to the density of gases, Dalton also pointed to the fact that the density of steam is less than the density of oxygen, yet steam is made up of compound atoms (an oxygen atom is joined by a hydrogen atom), and is therefore expected to have greater density if the same volume contains the same number of particles. Since this is not true, the number of oxygen atoms packed in the same volume must be larger.

Gay-Lussac had no interest in atoms and atomic theory. For him, his law was simply a purely empirical generalisation of observed facts. Dalton tried to show that Gay-Lussac's generalisation, which had no support of theory, could also find no support in empirical evidence, i.e., the combining volumes of gases cannot have perfect integer proportions.

The Italian physicist Amedeo Avogadro (1776–1856) proposed a hypothesis (in 1811) which offered to resolve those anomalies which emerged with the atomistic interpretation of Gay-Lussac's law. He returned to the same assumption that Dalton had already entertained and abandoned as untenable: equal volumes of all gases, at the same temperature and pressure, have the same number of molecules. Avogadro used similar language as Dalton, but had 'molecules' instead of 'atoms'. However, Avogadro explained, we need to assume that the constituent molecules of any simple gas are not formed of a solitary elementary molecule, but are made up of two or more such elementary molecules; in a chemical reaction, the gas molecules split into elementary molecules (allowing the aforementioned nitric oxide reaction to be explained as follows: the molecules of nitrogen and oxygen, both composed of two elementary molecules, split in half in the course of reaction and when these half-molecules combine, they will produce two volumes of nitric oxide). Avogadro also showed that his hypothesis offered the means of easy determination of the relative molecular masses of gases and also the relative number of elementary molecules in a compound: the ratios of the masses of the molecules are the same as the ratios of the densities of the corresponding gases, and the relative number of elementary molecules in a compound corresponds to the ratio of the volumes of the gases which form it.

Figure 37. Amadeo Avogadro (1776–1856). From a drawing by C. Sentier (1856). (*Wikimedia Commons*, 2017c)

The reconciliation of Gay-Lussac's law with Dalton's atomism was also attempted by the famous Swedish chemist Jöns Jacob Berzelius (1779–1848), who proceeded from a different assumption espoused by Dalton (in the same volume, the number of particles of different gases is either equal or in ratios 1:2:3, etc.). He suggested that only gaseous chemical elements have the same number of atoms in the same volume. The number of atoms of a gaseous compound, however, in the same volume no longer necessarily equals the number of simple atoms, but can differ from it by a certain proportion which needs to be determined experimentally with regard to each individual compound. Thus, Berzelius, unlike Dalton whose "rule of greatest simplicity" required the formula of water to be HO and ammonia NH, applied the Gay-Lussac's law and obtained the formulas of gaseous compounds as we know them today: H_2O, NH_3, etc.

It was indeed Berzelius' solution which the chemists adopted. Their choice remains somewhat a mystery, resisting a fully satisfying explanation. In most cases, we are told that Berzelius was a highly respected and influential scientist, the torchbearer of chemistry who prepared and issued annual reports on the progress of physical sciences, while the existence of Avogadro, an unknown physicist, simply went unnoticed by chemists for 50 years, and therefore his hypothesis could not be given due consideration by the scientific community—until the Karlsruhe Congress, the first international chemistry conference held in 1860.

However, a closer inspection reveals that the chemists, if we still consider them scientists and do not expect them to have the divination powers of prophets, indeed had also objectively no better chance of noticing the merit of Avogadro's work, had no opportunity at the time to see Avogadro's hypothesis in the same light as did Avogadro's fellow countryman Stanislao Cannizzaro half a century later in Karlsruhe.

In Avogadro's works we can certainly find the molecules of the four gaseous elements which were known at the time (O_2, H_2, Cl_2, N_2) and their formulas and chemical equations (if we use their modern symbolic representation) as we know them to be today, but at the time they were not justified by better science than Berzelius' counterparts which today appear more outdated and obsolete. For instance, the reaction which forms water vapour can be written down in Avogadro's system in its present-day form: $2H_2 + O_2 = 2H_2O$. For Berzelius, oxygen and hydrogen were monoatomic substances: $2H + O = H_2O$. We must remember, however, that Avogadro had no underlying theory to explain the diatomic nature of the oxygen and hydrogen molecules. It was simply an *ad hoc* hypothesis of his to explain the fact that the reaction produced two volumes of water vapour. If it had been three volumes instead, the oxygen and hydrogen molecules would have been triatomic, etc. In contrast, Berzelius managed to interpret Gay-Lussac's experiment results within the atomic system and yet without resorting to *ad hoc* hypotheses regarding the atomic structure of the gaseous elements. As with all elements, gaseous elements were deemed to be monoatomic and therefore there was no need to presume any splitting or combination of atoms (molecules) of the same element. The only parameter that remained to be determined in an experiment was the number of compound atoms (molecules), the combination product of gases, per unit of volume (although Avogadro had this as a constant, he also could not answer the question of how many volumes of gas would be produced by the reaction in any other way than by experiment). Compared to Berzelius' Daltonian solution, Avogadro's hypothesis could offer no advantages or better explanations or predictions of empirical facts. We must not let our modern knowledge interfere with the assessment of a theory's scientific merit, which should always be considered in its own historical context. If we do that, we will realise that Avogadro's "correct" solution was in its own time less justified than the other "controversial" and "bizarre" conceptions which were favoured by the scientists for "mysterious" reasons. Avogadro's conception at the time contributed virtually nothing to the progress of science, while Berzelius' "wrong" conception achieved quite a lot: the atomic weights of all known elements and the chemical formulas and molecular weights of their compounds. All these three tasks were interrelated: molecular weight was calculated from atomic weights and the determination of atomic weights in most cases depended on the compound's formula (the number of different atoms in a molecule).

Figure 38. Jöns Jacob Berzelius (1779–1848). Engraving by O. J. Södermark (1875). (*Wikimedia Commons*, 2018h)

Berzelius determined the atomic weights relative to the atomic weight of oxygen which he set equal to 100. At the same time, he also often included in his tables the atomic weights relative to hydrogen which, like Dalton, he also set equal to 1. Later, considering that usually two hydrogens combine with the atom of a different element, he set diatomic hydrogen equal to 1 and used ~~H~~ as its symbol. Later, he also developed other similar diatomic formulas: ~~P~~, ~~As,~~ ~~NH$_3$,~~ ~~HCl~~.

Oxygen, in Berzelius' view, was the "pivot" around which the whole of chemistry revolved, i.e., oxygen was a direct or indirect link between all compounds. Admitted, many Berzelian atomic weights (after conversion, of course, setting the oxygen equal to 16) do not match the current ones and also differ across different tables. Berzelius' method was hampered by the difficulties in finding a single objective way for determining the number of different atoms in compounds. Berzelius tried to make use of all known laws and regularities, analysed data, similarities in the properties of compounds, etc. This meant, however, that any new developments in this large body of knowledge also necessitated required updates to formulas and recalculation of atomic weights. In addition to Gay-Lussac's law, whose atomic interpretation he used to determine the atomic weights of the gaseous elements and the number of atoms in their compounds, Berzelius also utilised the empirical Dulong–Petit law (the specific heat capacity of elements is close to a constant value when multiplied by corresponding atomic weights) that had been proposed in 1819 and the law of isomorphism (the same number of atoms which are joined in the same manner yield similar crystals, regardless of the species of atoms), formulated by Eilhard Mitscherlich (1818–1822). He also relied on his own theory of electrochemical dualism, of which we will speak shortly. The modifications of atomic weights due to the corrections in compounds' formulas, of course, did not affect the accuracy of the determination of the atomic weights as certain ratios.

The precise determination of atomic weights was one of the most characteristically "paradigmatic" pursuits of the early nineteenth-century chemistry. More careful measurements were also stimulated by an influential hypothesis postulated in 1815 by the English physician William Prout (1785–1850), proposing that the atom of the lightest element, hydrogen, is the single fundamental particle and all other elements are groupings of different numbers of hydrogen atoms, so therefore their atomic weights are multiples of that of hydrogen and whole numbers if the atomic weight of hydrogen is 1. Many chemists were inclined to think that the discrepancies in the atomic weights must be due to measurement errors. The one-time popularity of Prout's hypothesis is a good example of how easily the scientists may be willing to overlook the inconsistencies between the existing experimental data and the hypothesis, much to the chagrin of inductivists and empiricists. Empirical data (in this case the atomic weights which deviated from the expected whole-number pattern) was simply declared inaccurate and the chemists began to reexamine their results again and again, rounding decimal fractions to integers, etc. The measurements would have required a very firm theoretical basis to prevent the temptation to round them in favour of Prout's hypothesis.

At the same time, Prout's case also shows that the elegant simplicity of a hypothesis is not enough to launch a new working paradigm. A paradigm requires all of its components in place and must have the actual capacity to "produce" science. So Prout's hypothesis did not quite make that qualitative leap and only remained a peculiar catalyst that invigorated the research in the existing (Daltonian-Berzelian) paradigm. It could not have conceived without Dalton's atomic theory, but unlike the former, it permitted the divisibility of atoms and the possibility of their conversion into one another.

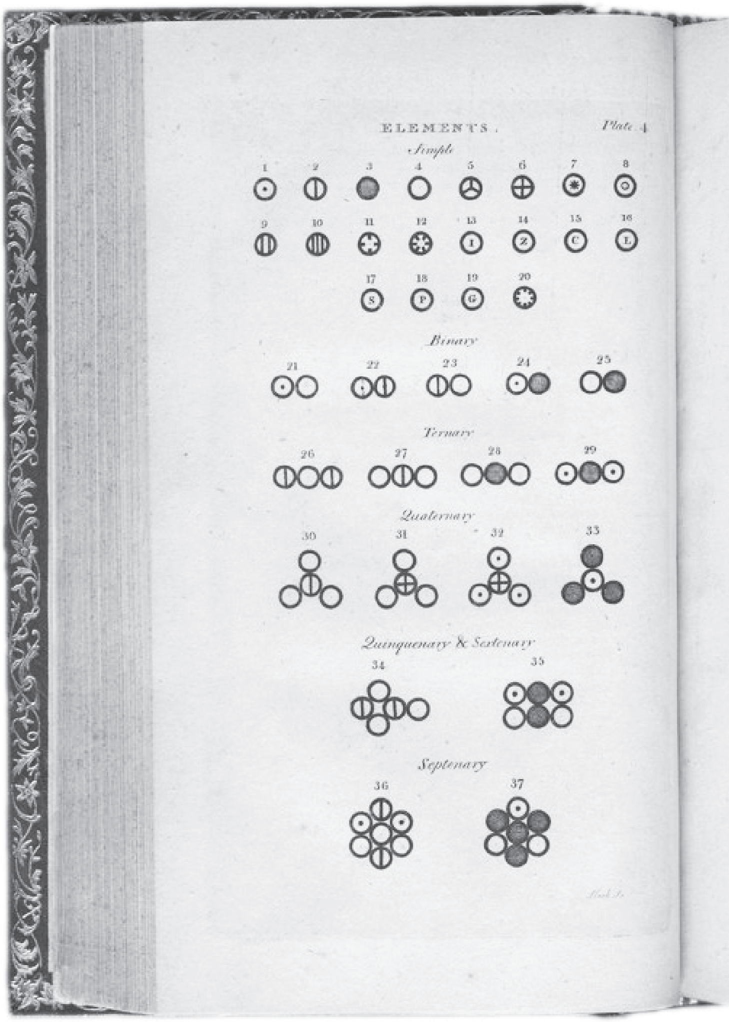


Figure 39. Signs chosen to represent simple and complex chemical elements (Dalton, 1808b, Plate 4). Courtesy of Science History Institute.

One of the successes of the Daltonian chemistry in Berzelian interpretation was the introduction of the system of letter-based symbols for elements and chemical formulas, which continues to be used to this day. By doing this, he had created the alphabet of a special chemistry language. Before that, various graphic symbols had been used in chemistry (particularly consistently by John Dalton). Their replacement with letter symbols in itself was not that much of a revolution, yet made the writing of elements, compounds and reactions so much simpler. The importance of this innovation becomes clear when we consider its rigourous logic and universal applicability in exact correspondence to chemistry's principles and laws. It is interesting to note that one and the same symbol may at the same time denote several objects, both micro and macro entities, which, however, subtracts nothing from the precision and clarity of the language. The letter symbols were introduced to denote chemical elements. Yet a chemical element also meant a certain type of atom. That atom, in its turn, was assigned a unique atomic weight. The atomic weight also led to the concept of gram atomic weight. The symbols of the compounds of elements (hence, of atoms as well) were already self-organising, formed of the corresponding symbols of elements (atoms) and the subscripts designating the number of atoms of each element in the compound. The number of compound atoms (molecules) in a chemical equation was indicated by the coefficient before the symbol. True, Berzelius himself initially linked the element symbols in compound formulas and equations with volumes of gases. For example, $S + 3O$ denoted sulfuric acid, or to be precise, its anhydride: 1 volume of sulfur + 3 volumes of oxygen. This caused the true Daltonists to shun Berzelius' system until he expressly linked it with the atomic theory in the 1820s.

Thereby, a language had been created that guaranteed the denotation of each chemical compound and reaction on a fixed universal basis—the symbols of chemical elements. The new language allowed the formulation of any chemistry problem and verbalisation of its theoretical solution. At the same time, the new language was very adaptable and flexible towards any new situations (with very simple modifications, it was later possible to write down different structural formulas).

Berzelius understood perfectly the need to provide justification for Dalton's "rule of greatest simplicity", i.e., to investigate what laws govern the atoms' chemical combination. He stressed that the atomic structure of matter solely is not sufficient to explain the laws of stoichiometry. What we also need are certain laws to regulate the compounds of atoms and assign them certain limits, because it is clear that, as Berzelius stated, if an indeterminate number of atoms of one element could combine with an indeterminate number of atoms of another element, we would have an infinite number of componds, in which the differences of the relative quantities of their components would be so insignificant that they could not be estimated even in the most precise experiments (Berzelius, 1819, p. 26). (Let us recall here, however, that this is what Berthollet believed, although he did not accept the possibility of infinite number of compounds of the same elements and regarded the combinations of atoms in different ratios one and the same, but of indefinite composition.)

Already in Lavoisier's days, the formation of chemical compounds was associated with certain opposing properties in substances and the existence of certain opposing aspects in substances, i.e., the idea of dualism, especially the dualism of acids and bases, or that of oxygen and radical (the root base of acid). Certain dualist tendencies are also present in Dalton's atomism, which are partially connected to his "rule of greatest simplicity": the atoms of one and the same element do not chemically combine with each other, since they are completely identical; the atoms of two different elements combine according to their difference, by stages and pairs, i.e., first of all, two simple atoms combine into a diatomic compound atom, and only then the formation of triatomic compound atoms of the same elements (two possibilites) can take place, in which, again, only pairs of atoms combine (1 diatomic compound atom + 1 simple atom).

Berzelius provided a certain electrochemical interpretation of the idea of dualism (and therefore also of the "rule of greatest simplicity"). The electrochemical dualism in the structure of matter, in his view, had the following causes:

> If these electrochemical views are correct, it follows that every chemical combination is wholly and solely dependent on two opposing forces, positive and negative electricity, and every chemical compound must be composed of two parts combined by the agency of their electrochemical reaction, since there is no third force. Hence it follows that every compound body, whatever the number of its constituents, can be divided into two part, one of which is positively and the other negatively electrical. Thus, sulfate soda is a compound of sulfuric acid and soda, each of which can be separated into an electropositive and electronegtive constituent, and is not composed of sodium, sulfur, and oxygen. (Translated from Berzelius, 1820, p. 103)

At the same time, the atoms of elements are electropolar, having both negative and positive poles, but since one of them is more dominant, the elements are either electropositive or electronegative. Oxygen is the most electronegative element of all, lacking the positive pole entirely. Here we can see that Avogadro's hypothesis of the gaseous elements occurring as diatomic, triatomic, etc., molecules is in contradiction with Berzelius' electrochemical dualism.

The French chemist Jean-Baptiste Dumas (1800–1884) was one of the first who attempted to apply Avogadro's hypothesis instead of Berzelius' unreliable, as he found, method of determining atomic weights. It followed from Avogadro's hypothesis that the surest, simplest and most direct way of determining the atomic weights of elements is by the measurement of their vapour densities. However, Dumas' measurements did not give him the results he hoped for. The atomic weight of mercury was half of the weight measured by any other method, while the atomic weight of phosphorus was twice and sulfur was thrice the value measured by other methods. Marc Antoine Gaudin (1804–1880) wanted to salvage the work, showing that consistency is achieved if we, like Avogadro, supposed that simple substances are also composed of molecules, not directly of atoms (or simple atoms, using Dalton's and Berzelius' preferred term). The molecule of phosphorus would be composed of four atoms and sulfur would have six atoms. Such a supposition, at the time, however, amounted to an *ad hoc* hypothesis, undeserving any consideration. At any rate, it was soon also discovered that the vapour density of sulfur, for example, depending on temperature, is within a certain range constantly changing. Therefore, Dumas finally admitted (in 1836) that Avogadro's hypothesis had to be wrong, "It must be clearly stated that gases, even when they are simple, do not contain in equal volumes the same number of atoms, or at least of chemical atoms." (Dumas, 1878, p. 291) Further measurements of vapour densities contributed to the increasing pile of inconsistencies and contradictions speaking against Avogadro's hypothesis (the fluctuating vapour density was also noted with several other elements and compounds).

Figure 40. Jean Baptiste André Dumas (1800–1884). Stipple engraving by S. Freeman after E. Desmaisons. (*Wikimedia Commons*, 2014b)

Berzelius also drew attention to the fact that, if we presume the molecular composition (of groupings of atoms) of simple substances, Avogadro's hypothesis will provide us the simplest of explanations in the case the compound is formed of the equal number of atoms of the corresponding elements (e.g., $H_2 + Cl_2 = 2HCl$—*R. V.*), but it will lead us to incorrect proportions with different ratios of atoms, such as when a grouping of atoms has to lose more atoms than it gains via replacement, i.e., when 1 atom of one element combines with 2 or 3 atoms of another element (such as the formation of H_2O or NH_3—*R. V.*) or when 2 atoms of one element combine with 3 or 5 atoms of another element (such as the formation of N_2O_3 or N_2O_5—*R. V.*). (Berzelius, 1814). Thus, Berzelius found the theory of simple atoms more preferrable over the theory of groupings of atoms. Here we can see that the introduction of the concept of molecule was also resisted due to the lack of the units of chemical affinity—the chemical bond and the number of such bonds. Before the concept of atom was developed in chemistry, the quantity of a substance was simply measured by measuring its mass (it was the default assumption that the particles of different substances do not have a specific weight). In a similar way, before the concepts of chemical bond and valence had come to existence, the combining power of an atom with other atoms was simply measured as the number of combined atoms. That is, it was essentially assumed that the character of the relationship of one and the same atom, such as the number of its bonds with other atoms, does not depend on the type of that atom, thus rendering inconceivable such exchange of atoms whereby a single atom from the first compound where it is only connected to one other atom would replace three atoms in the second compound and the three from the second would replace the single one in the first.

4. How was the concept of molecule arrived at?

On the route of scientific investigations, which led from the concept of atom to the concept of molecule, numerous roadblocks began to appear. There were gaps in the knowledge which would have made possible the "assembly" of atoms into a molecule or simple atoms into a compound atom. In the language of categories, they followed the principle that the whole is the sum of its parts, but by regarding atoms as parts, no whole could be formed, since the properties of atoms which would bind them into a whole were not known.

The properties of things are naturally revealed in their relations with other things. As we saw, Dalton's atomic theory appeared as a means to make the distinction between the chemical change of a pure substance and the physical diffusion in a mixture of substances. What Dalton's atomism explained was the dependence of the chemical properties or chemical quality of a substance on the substance's atomic composition. Such properties which would characterise the atoms' relations in compounds, in the structure of compound atoms, Dalton's atoms could not possibly have. For that reason, in organic chemistry where the structure of molecules (compound atoms) became an issue of central importance, where the elementary composition of a substance was not enough to account for its chemical properties, theories were posed which envisioned compounds as composed of fragments (called 'radicals') which were larger than atoms. This path had already been taken by Berzelius' electrochemical dualism (as well as by earlier dualist conceptions). Radicals were deemed to be such fragments which are transferred unchanged from one compound to another during the chemical change of the compounds. For example, according to Berzelius, sodium sulfate consisted of two radicals—NaO and SO_3.

The radical theory was initially very successful, since it permitted to mount an attack from old positions against a new field—organic compounds. Namely, it was found (originally by Lavoisier, later by Berzelius and Liebig) that organic compounds differ from inorganic ones due to the much more complicated composition of their radicals; radicals contain numerous atoms, yet the entire grouping of atoms still behaves as a single "piece" and is comparable to an element in an inorganic compound. The radical theory necessarily entailed the problem of extracting radicals from organic compounds to prove their existence. Such attempts were met with initial success, although it was soon realised that the produced "fragments" were not exactly the expected radicals.

The radical theory was replaced by a new theory which was based on the opposing idea whereby the molecule of a chemical compound was seen as a whole structure which qualitatively differs from the parts it is made of. As it opposed dualism, it was called the unitary theory (which, in fact, comprised several theories). From the point of view of the logic of categories, it was no longer the principle that the whole is the sum of its parts, but the opposite: the character of the parts is determined by the whole. So once again we can see very clearly how the "single whole" is "split" into opposing or contradictory conceptions, which is logically expected to eventually culminate in a synthesis of these one-sided conceptions, which will be transcended. However, it is important to understand that before the synthesis could take place, both one-sided conceptions necessarily had to be fully developed. Otherwise, we cannot know where exactly these conceptions fail and would not know how to overcome their shortcomings. Following the logic of categories, we will also see that the radical theory necessarily had to precede the unitary theory. Namely, before we can study change, we must observe things in their unchanged state at first. At the level of categories, the definition of radicals implies emphasis on stability, immutability (as the radical is the unchanged part of the compound, a grouping of atoms that are permanently connected and are transferred unchanged from one compound to another). The unitary theory, however, denies stable radicals and stresses the opposite: the atoms of different elements can replace each other in compounds, the character of the element changes depending on the type of the compound and the place of the element in the corresponding structure, while these types of compounds do not describe the actual placement of atoms in particular chemical compounds, but represent the types of certain reactions.

Figure 41. Charles Frédéric Gerhardt (1816–1856). (Moore, 1918)

Already during the domination of the radical theory, anomalies appeared. Polyprotic acids were discovered, which led Liebig to conclude that acids and bases do not always react in 1:1 ratio and that “equivalent” and “atom” (simple or compound) are not always one and the same, and that acids, as Sir Humphry Davy (1815) had already explained, were certain hydrogen (not oxygen) compounds which are capable of forming salts by reacting with metals, which replaced the hydrogen, equivalent for equivalent (i.e., salts are not compounds of oxygen-containing radicals—acids and bases) (Davy, 1840). At the same time, it was also discovered that an electronegative element could replace an electropositive one and take over its role in a compound. The most “intractable” fact was that in acetic acid three hydrogen atoms could be replaced with those of chlorine and the resulting trichloroacetic acid still retained the essential chemical properties of acetic acid. This phenomenon of exchange was named ‘metalepsy’. Organic compounds began to be characterised by their “nucleus” or “type” which is preserved when hydrogen is replaced with equivalents of other elements (the theories of the French chemists Auguste Laurent, Jean-Baptiste Dumas and Charles Frédéric Gerhardt). The molecule of an organic compound began to be compared to a geometric body or building which, for it to exist, only needed to have all its walls in place, irrespective of the material used. If the building is to survive when a wall of one particular material is removed, it must be replaced with a wall made of a different material. Charles Frédéric Gerhardt (1816–1856), who often collaborated with his friend Auguste Laurent (1808–1853), was the most prominent advocate of the unitary chemistry.

In order to determine the molecular formula and weight of a compound, Gerhardt returned to the method which had been abandoned by Dumas—the measurement of the vapour densities. He did not directly refer to Avogadro’s hypothesis, but accepted the position that the molecular weights of most compounds are proportional to their densities, i.e., given constant pressure and temperature, equal volumes of gas contain an equal number of molecules. The formulas of organic compounds which had been determined following this principle were found to be in better conformity with their chemical properties. He also started to distinguish between the concepts of atom, molecule and equivalent and came to the conclusion that the molecules of all elements must consist of two atoms. Let us observe how Gerhardt reached these views.

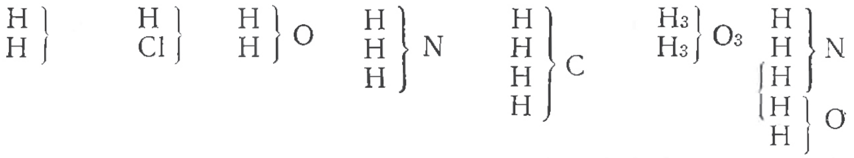
While investigating the decomposition reactions of organic compounds—while attempting to create a classification of organic compounds, Gerhardt considered it important to have a gradual decomposition—it was discovered that carbon dioxide, ammonia or water vapour was always released in such an amount that corresponded to four volumes (or its multiples) of a gaseous element (for example, hydrogen or oxygen). At the same time, the number of atoms in the formulas of these compounds was twice (in the case of carbon, four times) of that in the formulas previously determined in inorganic chemistry, i.e., C_4O_4, N_2H_6, H_4O_2. The reason was to be found in Berzelius' system which was used for obtaining the molecular weights and formulas of organic compounds. It was based on the neutralisation reaction of organic acids with silver oxide whose formula was presumed to be AgO. Therefore, the molecular weights and formulas were doubled. Carbon was even quadrupled, since an equivalent weight that was half of the actual value was used as its atomic weight.

Gerhardt, as most chemists at the time, did not distinguish between the concepts of molecule, atom and equivalent. He identified the four volumes of vapour and the corresponding double formulas (C_4O_4, N_2H_6, H_4O_2) as equivalents. In order to eliminate the discrepancy with the formulas found in inorganic chemistry, there were two choices: either double the atomic weights of the elements (in the case of carbon, its original atomic weight had to be adopted), or halve the number of atoms in the organic formulas (again, the number of carbon had to be halved twice). Gerhardt initially tried to realise the first option, but then went for the second. This also meant switching from the four-volume to the two-volume convention for formulas. Gerhardt then stated that atoms, equivalents and volumes are synonymous—but only in the case of gaseous elements, while for the gaseous compounds, the equivalent (molecule) corresponded to two volumes (i.e., density was the half-sum of the densities of the elements). (Gerhardt, 1838, pp. 17–54)

Here, Laurent drew Gerhardt's attention to his inconsistency regarding the elements and compounds and recommended that they should receive equal treatment. In order to do this, one needed to assume that gaseous elements consist of two parts (two "half-molecules"). It was thanks to Laurent's influence that Gerhardt eventually started making distinctions between molecules, atoms and equivalents. Simple substances also began to be viewed as consisting of molecules (and not directly of atoms). A chemical reaction was seen as an exchange of atoms between different molecules. In the case of equivalent, it was stressed that it was an amount of substance that can replace another amount of substance, while one and the same element may have several equivalents, depending on the nature of the compound (molecule).

Thus, Gerhardt obtained the molecular formulas of H_2, O_2, Cl_2, I_2, etc. However, due to the experimentally proven exceptions, he did not regard the equality of equivalent volume and molecular weight as a universal law, but rather as a helpful regularity that is additional to chemical considerations, and therefore also applied it inconsistently. He also decided to ignore it in his general formula of metal oxides (Me_2O) which he justified by the equivalence of hydrogen and metals (this formula corresponded in his "theory of types" to the so-called "water type"). Berzelius had been using MeO instead. As a result, Gerhardt managed to generate the correct formula, for instance, of silver oxide (its incorrect version, as we saw, was responsible for the "doubled" organic formulas, but the atomic weights of most other metals, i.e., multivalent metals, and the formulas of their oxides turned out to be wrong (Berzelius had produced the correct atomic weights of bivalent metals and formulas of their oxides). Here, Gerhardt's system came into contradiction with most inorganic formulas which had been obtained on the basis of atomic weights determined on the basis of the Dulong–Petit law and the law of isomorphism. A rift began to appear between organic and inorganic chemistry. Organic chemistry was facing specific problems of its own. At least initially, Gerhardt's method for the determination of the molecular weights and empirical formulas appeared to work.

Gerhardt found that an organic compound cannot be given a single rational formula which would characterise the compound's structure, encapsulate all its properties and reactions, show its possible precursors and possible derivatives. The compound's empirical formula only characterises the proportions of different elements in its molecule. According to Gerhardt, chemical reactions in organic chemistry can be classified on the basis of the four types of inorganic compounds—the types of hydrogen, hydrogen chloride, water and ammonia (and of methane, the fifth that was added later):



$\left.\begin{matrix}H\\H\end{matrix}\right\}$	$\left.\begin{matrix}H\\Cl\end{matrix}\right\}$	$\left.\begin{matrix}H\\H\end{matrix}\right\}O$	$\left.\begin{matrix}H\\H\\H\end{matrix}\right\}N$	$\left.\begin{matrix}H\\H\\H\\H\end{matrix}\right\}C$	$\left.\begin{matrix}H_3\\H_3\end{matrix}\right\}O_3$	$\left.\begin{matrix}H\\H\\H\end{matrix}\right\}N$ $\left.\begin{matrix}H\\H\end{matrix}\right\}O$
hydrogen type	hydrogen chloride type	water type	ammonia type	methane type	triple water type	water and ammonia mixed type

The formation of organic compounds was regarded as the substitution of hydrogen in these types with certain atom groupings (which began to be called radicals, as in radicals theory). It was emphasised that one and the same organic compound can behave according to several different types. For instance, methanol can behave according to both hydrogen and water types:

$$\left.\begin{matrix}CH_3O\\H\end{matrix}\right\} \qquad \left.\begin{matrix}CH_3\\H\end{matrix}\right\}O$$

The development of the theory of types led to the emergence of the concept of valence (initially, the terms 'atomicity' or 'basicity' were used. The type diagrams show that oxygen, nitrogen and carbon (but in a sense also hydrogen or chlorine) atoms combine with a different number of hydrogen atoms which can be substituted by other elements or radicals. This number of hydrogens that can be substituted or combined became the basis for the concept of the atomicity or basicity (later 'valence') of an element or radical. We already mentioned that polyprotic acids had been discovered earlier. August Kekulé (1829–1896) interpreted Gerhardt's three principal types and his own additional methane type in the light of the notion of atomicity (valence). He observed that atoms can be classified as monoatomic (for example, H, Cl, Br, K), diatomic (for example, O, S), triatomic (for example, N, As) and tetraatomic (for example, C), while their simplest of compounds would be HH (1+1), OH_2 (II + 2I), NH_3 (III + 3I), CH_4 (IV + 4I). Kekulé also provided another important generalisation, the formulation of the concept of interatomic bond (1858, these bonds could also form between the atoms of one and the same element). Kekulé found the inspiration for developing the concept of interatomic bond in the homologous series of carbon compounds (this was a phenomenon which had already been discovered a while ago and had been studied extensively by Gerhardt). Assuming the tetravalence of carbon and monovalence of hydrogen, Kekulé reasoned as follows: the general formula of the homologous series of alkanes (C_nH_{2n+2}) shows that for two carbon atoms, we have 3 hydrogen atoms, while the remaining $n - 2$ carbon atoms are left 2 hydrogens each; therefore, of the $4n$ chemical affinity units of carbon atoms, $2n - 2$ must be spent between the carbon atoms themselves.

Figure 42. August Kekulé (1826–1910), c. 1880. (*Wikimedia Commons*, 2018i)

This way, the chemists had arrived at the concepts of valence and interatomic bond, which now provided the necessary tools for describing the structure of molecules. Yet neither Gerhardt nor Kekulé initially thought it possible to speak of unique fixed rational formulas of compounds, of the real molecular structure. The compound's rational formula was seen as its scheme of chemical transformation. Yet, since a single compound can be chemically transformed in so many ways, then it turned out to be impossible to express them all in a single formula. New types of chemical reactions were also constantly being discovered and schemes, especially in connection with the introduction of mixed types, became very complicated and not very informative. The compound's bare empirical formula was often all that was practically sensible. In his textbook on organic chemistry (1859–1861), Kekulé (1861) wrote that no established theories, even such fundamental concepts as atomic and molecular weights, not to speak of the molecular structures and formulas, existed in organic chemistry and remain the subject of speculation and hypotheses only.

Thus, Dalton's chemical atomism which had its roots in physics, as we recall, had by the middle of the 19th century in the course of (organic) chemical research evolved to such a point where substances and their chemical transformation were no longer viewed as a process involving atoms directly, but as a process involving atoms as components of molecules. In addition to chemical investigation of substances, the need for their physical investigation also became apparent, i.e., the physical atomism—the study of a substance under such conditions where the structure of molecules remains unchanged, where the substance is essentially just a body whose properties depend on the movement and relations of a different kind of bodies—molecules. Thus, the evolution of the chemical atomism made a full circle and returned to its origin—the physical atomism. How did Dalton's physical atomism actually became chemical? How did he distinguish a physical atom from a chemical one?

The last question must be probably answered thus—by means of the atmosphere of caloric! Indeed, Dalton had envisioned the atmosphere of caloric into which the atoms were inserted as blocking the chemical affinity forces between them and being the cause of repulsion between atoms, which he used to explain the structure of a gas mixture. According to Dalton, physical atoms would be the physically indivisible and immutable caloric-shelled particles, since their division or union, which would entail the destruction of their caloric shell and the subsequent formation of a new particle surrounded by a new atmosphere of caloric, would no longer be a physical, but already a chemical phenomenon. The investigations of the physical structure of a gaseous substance revealed the relativity of the atom as a concept characterising the structure of substance: the atom as the indivisible particle of matter, the limit of divisibility, was shown to be open to the opposite meaning—the indivisible particle is still divisible, the limit of divisibility can be breached, but this means the qualitative change of the substance, which as such is no longer a physical but a chemical phenomenon. The relativity of the concept of atom is probably most apparent in Dalton's concept of 'compound atom', which we discussed on pages 125–129.

Thus, in physical atomism, molecule acquired the meaning of the limit of divisibility of a body as the object of physical investigations, the meaning of the smallest body which was indivisible and immutable only in the physical sense, but divisible and mutable in the chemical sense. The original concept of atom, however, sank one level deeper: an atom became a particle which remains indivisible and immutable in chemical processes, i.e., in the division and transformation of molecules. (As a term, atom has been preserved in chemistry, although the descent of the concept of an 'indivisible particle' has continued. At the same time, more and more evidence has been found to support the relativity of indivisibility, also driving the ascent of the atom into upper levels. This can be seen, for example, in the concept of genes which are described as the "atoms of heredity".)

Although Dalton's atomism began with physical atomism, he laid the foundation for chemical atomism. Moreover, we even need to resort to a paradox: Dalton's chemical atomism indeed began as physical atomism, but was still founded upon chemical atomism! As we recall, to prove the difference of the diameters of gaseous particles—this was how he explained the diffusion phenomena—he needed to know the relative weights (masses) of the gas particles (molecules). Dalton, however, presumed that chemical elements occur in gaseous state as (simple) atoms which are only surrounded by the atmosphere of caloric, and instead of molecular weights, he determined the atomic weights. Because of the identity of the physical atoms to chemical atoms, he also did not consider possible the divisibility of the element's physical atom. Was it justified? At any rate, he had no grounds to believe that the physical oxygen atom (molecule) would consist of two "simple atoms". The idea of atom as a scientific concept originated in the indivisibility of a chemical element, after all. Later, however, as we saw, several chemical considerations came to light which did not favour the viewing of simple substances as built of multiatomic molecules, although this was the conclusion that was eventually reached.

The progress in physical atomism only commenced after the concept of caloric was made obsolete by the molecular-kinetic theory.

In 1857 and 1858, Rudolf Julius Emmanuel Clausius (1822–1888) published his work on the kinetic theory of gases (Clausius, 1857; 1864). Clausius proclaimed Avogadro's hypothesis as a law, since it now had a foundation in the kinetic theory of gases. He also came to the conclusion that the molecules of gaseous elements must be diatomic.

As we recall, Avogadro's hypothesis had been struggling with substantial experimental evidence against it, in the form of irregular vapour densities of numerous substances. However, as it later transpired, these were the substances which dissociated at the temperature of the experiment. In 1857, before the works of Clausius, Henri Étienne Sainte-Claire Deville (1818–1881) had published an article containing the proof regarding the thermal dissociation of compounds. The author himself nevertheless deemed it necessary to stress that he did not endorse Avogadro's law, and the notion of atoms and molecules, since he could not believe in what he could not see or imagine (quoted in Lalanne, 1996, p. 119).

Now it is appropriate to devote a few paragraphs to Stanislao Cannizzaro (1826–1910). In 1857, Cannizzaro published a short article in response to Sainte-Claire Deville, where he emphasised that Avogadro's hypothesis should be regarded as a universal law of *physics*: equal volumes of gases at the same temperature and pressure contain equal numbers of molecules. This law was

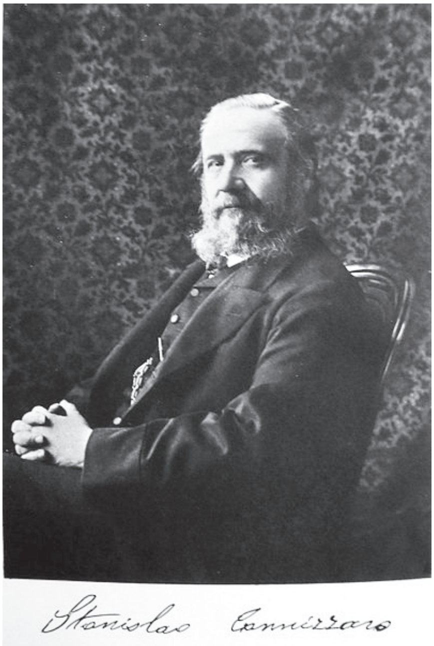


Figure 43. Stanislao Cannizzaro (1826–1910). Printed in *Zeitschrift für Physikalische Chemie*, 1906, vol. 56. (Wikimedia Commons, 2015b)

made by Cannizzaro the foundation for the calculation of molecular weights. We should pay heed to the fact that Cannizzaro's premise was the opposite of that of the earlier methods of determining molecular weights: Cannizzaro specifically proceeded from the molecular weights (i.e., from the physical atomism which only now had been formulated as a scientific theory!), whereas earlier the molecular weights had been determined via atomic weights (on the basis of chemical atomism). On the basis of molecular weights, Cannizzaro determined the compound's formula and the atomic weights.

The method created in 1858 was the following: the experiment was to be conducted with as many compounds of the given element as possible, their molecular weight was to be calculated from their measured vapour densities, the weight percent composition of elements was to be determined in the compounds, the relative weights of the elements were to be calculated on the basis of molecular weights and the weight percent composition of elements in compounds, and finally, by comparing the relative weights of the elements in different compounds, the atomic weights were calculated and the number of atoms determined in the molecules. For instance, Cannizzaro initially set the molecular weight of hydrogen equal to 1 and found the relative weight of hydrogen in different volatile compounds. It turned out that, for instance, in hydrogen chloride, hydrogen bromide and hydrogen cyanide, the relative weight of hydrogen was ½; in water vapour and hydrogen sulfide 1; in ammonia and phosphane 1½; in acetic acid and ethylene 2; in ethanol 3; in diethyl ether 5. These measurement results revealed that the smallest relative weight of hydrogen was ½, all other values were multiples of ½. Hence the conclusion that ½ is, in fact, the atomic weight of hydrogen and, in order to obtain the number of atoms, the values of relative weights should be divided by this figure. It is also possible to set the atomic weight of hydrogen equal to 1, as it had been done before, i.e., by multiplying all other obtained values by 2. In that case, the molecular weight of hydrogen turned out to be 2 and the hydrogen molecule turned out to be a diatomic molecule.

In a similar way, Cannizzaro also found the atomic weights of other elements and the number of atoms in their compounds. It was also determined that, in addition to hydrogen, diatomic molecules are also formed by chlorine, oxygen and nitrogen, that at a temperature below 1,000° C, sulfur forms six-atomic molecules, but mercury is monoatomic, etc. Thus, on the basis of physical atomism, Cannizzaro solved all anomalies which had earlier required *ad hoc* hypotheses or had no solutions at all. He also managed to bridge the gap that had appeared between the inorganic and organic chemistry. Cannizzaro corrected the metal oxide formulas which had been determined on the basis of Gerhardt's system and obtained the atomic weights of metals and formulas of inorganic compounds which were in conformity with the Dulong–Petit and isomorphism laws. Cannizzaro's method was presented to the wider audience at the Karslruhe Congress of 1860 (Hartley, 1866).

Cannizzaro's objective method for the determination of molecular weights, formulas and atomic weights created a fertile ground for the continued progress in chemistry on the basis of atomism. The next two pinnacle achievements in

Figure 44. Alexander Mikhaylovich Butlerov (1828–1886) (Aksakov, 1889, frontpiece)

Figure 45. Dmitri Ivanovich Mendeleev (1834–1907) (*Wikimedia Commons*, 2017d)

chemical theory were Alexander Mikhaylovich Butlerov's (1828–1886) theory of chemical structure and Dmitri Ivanovich Mendeleev's (1834–1907) law and system of periodicity of chemical elements.

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Here we end our overview of atomism as the foundation of chemistry. Chemistry today indeed has remained a science which, on the basis of different chemical elements, studies the change of substances caused by breaking, formation and transformation of interatomic bonds. What is important, however, is the "migration of bonds" between atoms, not necessarily the formation, dissolution or transformation of molecules, since, strictly speaking, a substance can occur as molecules only under ideal gas conditions. Atoms can form compounds of widely differing structure and size. There is no point in saying that a piece of metal of salt crystal consists of molecules. We need to consider the structure of different types of crystal lattices, alloys, adsorption compounds, etc. The structure of a substance should not be identified at all in the structure of a molecule only. This, by the way, also gives a new lease on life, in a way, to Berthollet's ideas: the laws of stoichiometry cannot be regarded as absolute. Of course, due to the limited space of these pages, we cannot analyse the subsequent developments in chemistry in such an extent and detail as we have done so far. But we will try to speak of the chemistry's more recent "fate" in a more general language—the language of categories.

By way of conclusion. How did chemistry's development continue and how might it develop in the future?

Further development of chemistry was broadly characterised by two trends: firstly, continuing physicalisation and mathematisation, and secondly, the fact of shifting the focus of its research to processes. The first trend is evidenced by the fact that physical chemistry, whose theoretical part has practically become synonymous with theoretical chemistry, has acquired the status of an independent discipline. The second trend is expressed by the categories of element and structure having lost their central place, becoming subordinated to, dependent on, derivative of the categories that characterise processes. The structural approach examines "ready-made things", permanence, non-continuity, the states of substances that are not undergoing a reaction (reactants and products), states independent of time. We know that such an approach is the precondition for any successful investigation of processes. The investigation of processes itself starts not by investigating the operation of the process in time, but rather by establishing its equilibrium conditions. This was what permitted chemistry's further physicalisation and mathematisation.

Characteristic of the above is the idea expressed in 1867 in a joint research paper by the Norwegian scientists (the mathematician Cato M. Guldberg (1836–1902) and the chemist Peter Waage (1833–1900)), who formulated the theory of chemical equilibria (1864–1879):

> In chemistry like in mechanics the most natural method will be to determine forces in their equilibrium state. This means that we need to study these chemical reactions in which forces which generate new compounds will be balanced against other forces. This is what happens in chemical reactions which are not complete but take place partly. (Translated from Guldberg & Waage, 1867, p. 6)

They subsequently provided an interpretation of these forces that is clearly based on molecular and kinetic understanding, showing that the equilibrium of forces in question is not a static one but changes continuously: the rates of forward or reverse reactions are equal—they depend on the frequency of collisions between the reactants' molecules, and are therefore correlated to their unit volume molecule counts, i.e., to concentrations.

Guldberg and Waage's approach clearly shows that they were looking for a way to model, or construct, chemical processes in a manner that would allow them to apply already known principles of (mechanical) physics. Let us consider, again, how the researchers expressed this. They wrote,

> Chemical affinity only occurs at very small distances. As the distance increases, the affinity is discontinued. The sphere in the limits of which the chemical affinity still occurs could be called *the sphere of affinity* or *the sphere of action*. The absolute extent of the sphere cannot be determined. Fortunately, it suffices to know its relative volume and we may take a random volume, e.g., one cubic centimetre. The amount of substance in the cubic centimetre is called the active mass. (Translated from Guldberg & Waage, 1867, p. 5)

Guldberg and Waage's research results are expressed by the equation:

$$K = \frac{C_Q^{\,q}\ C_R^{\,r}\ldots}{C_L^{\,l}\ C_M^{\,m}\ldots} = \frac{k_1}{k_2}\ ,$$

where K is the equilibrium constant of the reaction; C_Q and C_R—concentrations of the products Q and R; C_L and C_M—concentrations of reactants L and M; q, r, l and m—stoichiometric factors, i.e., the number of molecules (or moles) in the reaction equation; k_1 and k_2—the rate constants of forward and reverse reactions.

It is instructive to compare Guldberg and Waage's approach with Berthollet's. As you will recall, Berthollet, too, spoke of the mass action, stressing that in addition to chemical affinity, the result of the process depends also on the ratio of quantities of the substances participating in the reaction. Berthollet, however, had no chemical units to determine the quantity of a substance and his attempts to model the equilibrium of empirically noted reversible chemical reactions as a measurable physico-mechanical process—as did Guldberg and Waage—remained unsuccessful.

The next important step was the development of chemical thermodynamics on the basis of general thermodynamics (in the work of August Horstmann, Hermann von Helmholtz, Jacobus Henricus van't Hoff, Josiah Willard Gibbs and others during 1860–1880), which allowed chemical reactions to be modelled in terms of energetic equilibria. Thermodynamics states the energetic conditions required for a reaction to proceed but does not tell us how much time it takes for the end point (equilibrium) to be achieved. It is chemical kinetics that studies the rates of chemical reactions and the mechanisms involved (the ways in which substances are transformed in the course of the reaction).

The concept of reaction rate was formulated and was shown to be practically investigable already in 1850 (Ludwig Wilhelmy); attempts were made, also during the 1850s, to understand the mechanisms of certain reactions (by Alexander William Williamson, Auguste Laurent, Auguste Kekulé and others), yet chemical kinetics only became a paradigmatic discipline after the elaboration of the theory of chemical equilibria and chemical thermodynamics. As we saw, chemical equilibrium came to be understood as a point at which the speed of forward reaction equals that of reverse reaction. Further development of chemical thermodynamics is related to proving the validity of general thermodynamics on the basis of statistical mechanics—macroscopic thermodynamical values were related to the movement of microscopic particles, which in turn were attributed chemical characteristics and, through that, the thermodynamic approach was brought to bear on reaction mechanisms.

An exposition of chemical kinetics together with chemical thermodynamics is provided in J. H. van't Hoff's (1852–1911) monograph *Études de dynamique chimique* (1884). The book undoubtedly played a major part in the development of the process-based paradigm in chemistry. The next important step was Svante Arrhenius's (1859–1927) theory of collisions (1889), which explained the impact of temperature on reaction rate, introducing the notion of activation energy[10] in chemistry. It was shown that the formation of new molecules is not caused by any random molecular collisions but rather only by the collision of certain active molecules. Activation energy was supposed to show the difference in energy between active and non-active molecules. The interpretation of activation energy was elaborated after the formulation of the quantum mechanical theory of chemical bonds (initial proponents Walter Heinrich Heitler and Fritz London, 1927) and of the theory of the activated complex (initial proponents Henry Eyring and Michael Polanyi, 1930–1935).

The theory of the activated complex regards reactants as a unified system whose energy is constantly changing as a function of the changes in interatomic

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[10] The Arrhenius equation is as follows:

$$k = Ae^{-\frac{E}{RT}}$$

where k is the reaction rate constant, A—the collision frequency constant, E—the activation energy (e, R and T are widely known symbols—respectively, the base of natural logarithms, the universal gas constant and absolute temperature).

distances and redistribution of chemical bonds between the atoms of reactants. If one monitors closely the manner in which a reaction proceeds, one sees that the system's minimum values of potential energy (the "black holes" of potential energy) correspond to its initial and final states, yet in order to move from one minimum value to the other, an intermediate state—the activation barrier that corresponds to a maximum potential energy value—must be overcome. This maximum energy is what characterises an activated complex, i.e., a configuration of atoms whose chemical bonds, at a given time, are distributed in a such manner that the 'compound' corresponds as much, or as little, to the product as it does to the reactant. If we were to consider the activated complex to be a certain chemical compound and to assume that the compound was in thermodynamic equilibrium with the molecules of the reactants, we could derive an equation that relates the reaction rate constant to the equilibrium constant of the reaction that produces the activated complex. The latter value can be calculated on the basis of the spectral properties of molecules using the methods of statistical thermodynamics.

The reaction mechanism depends on the manner in which the activation barrier is overcome. Broadly speaking, reactions can be divided into catalytic and non-catalytic ones. In the latter case, the activation barrier is overcome by additional external energy fed to the reaction mixture. In catalytic reactions, the activation barrier is considerably reduced due to the presence of the catalyser substance, which participates in producing (or produces on its surface) activated complexes characterised by lower activation energy. The activated complex subsequently transforms into reaction products, while the catalyst is restored and can form new activated complexes with the reactants. (The mechanism of a reaction may, of course, be highly complex and involve multiple stages, and the catalyst may, instead of forming the activated complex, form an intermediate substance of a different type. Yet, the principle of catalysis remains the same.) It was research into catalytic reactions which showed that in order to understand a chemical process it is not enough to know the structure of its reactants and products, but that other, at first glance seemingly insignificant details such as even the shape, size, body material of and negligible additives in the reaction vessel, let alone the characteristics of the reaction environment (for instance, the solvent used) needed to be taken into consideration as well. This allows us to learn more and more about kinetic systems in living nature whose complexity of organisation, dependability and economy make them a wonder to behold.

As we can see, the transition from classical structural chemistry to contemporary process chemistry relates to the transition from classical physics (primarily, the mechanical world picture) to quantum physics as the basis of scientific chemistry. Classical structural chemistry regards the chemistry of any phenomenon as an edifice constructed out of specific permanent elements—atoms, molecules, valence bonds. The classical approach is therefore characterised by thinking in integer terms, by operating with discrete values (the laws of stoichiometry, the approach to a chemical compound as consisting of a certain number of atoms combining into molecules in which single, double or triple bonds are formed between atoms). In contrast, contemporary process chemistry approaches the elements of classical structural chemistry in terms of their creation and transformation, seeing a specific structure simply as a state of the system of reciprocal effects between nuclei and electrons. Chemical bonds are formed to the extent and of the type that is determined by the electrons in the outer electron shell of an atom ceasing to belong to that atom exclusively and being shared by several atoms. The continuity and non-continuity ('granularity') of the properties and structure of chemical compounds are revealed to be in unity similarly to the wave and particle properties of the electron. From the point of view of quantum chemistry there is, in principle, no difference whether the system that is being examined is an atom, a molecule, a radical, an ion, a coordination complex, a micelle, a high molecular compound, a crystal of any type, an adsorption compound, or even a kinetic system with all of its intermediates and activated complexes. It becomes clear that not all chemical compounds are governed by the laws of stoichiometry—that apart from daltonide compounds (which have a discrete composition) there are also berthollide ones (whose composition varies).

One often hears the claim that chemistry has become a branch of physics. This claim is meant to convey that theories of chemistry are ultimately based on theories of physics—on thermodynamics, statistical physics and quantum mechanics. This is, indeed, true. Built on the basis of atomism, the edifice of theories of chemistry with its classical structural theory of chemical compounds and the theory of chemical elements needed a new foundation. That new foundation was provided to it by the theories of physics mentioned. Yet theories of chemistry also contain aspects that theories of physics lack. This ultimately results from the fact which we have already pointed out, i.e., that chemical phenomena cannot be construed as purely physical ones. One may also say that, to the extent that contemporary chemistry is founded on rigorous scientific theory, it is also founded on physics, yet it goes further than physics, further than "rigorous" scientific theory can reach. This should not be seen as chemistry's weakness, immaturity or other such defect. Chemistry simply is not (and why should it be?) strictly speaking an exact science, of the type that, in its pure form, is best represented by physics. These assertions require an explanation. We will try to provide a brief one below.

First of all, about the relative independence of theories of chemistry. Although the branches of contemporary theoretical chemistry—such as chemical thermodynamics and quantum chemistry—have arisen by extending the corresponding physics theories to chemical phenomena, the physical theories thus applied have not remained the same. Chemical thermodynamics is not simply thermodynamics, nor is quantum chemistry simply quantum mechanics. Why? Because chemical phenomena are not derived from physical theories. Physics can be used to model chemical phenomena, to conceptualise them in physical terms, yet this presupposes that such phenomena are known to us as chemical phenomena prior to the modelling exercise. Physical modelling of chemical phenomena is not possible exclusively within the framework of the relevant theory of physics—that theory needs to be integrated into the paradigm of chemistry. A theory of physics only becomes a theory of chemistry after it becomes possible for it to be presented as an idealisation of chemistry experiments. The development of chemical thermodynamics, quantum chemistry and others was a process that in principle—as examined in the previous chapters of this volume—resembled the development of chemical theories during the time of Lavoisier, Dalton and others.

It is far from haphazard that the mathematically and physically rigorous thermodynamics theory (proposed already during the 1870s) of Josiah Willard Gibbs (1839–1903), which also referred to chemistry as a field to which it would apply, was at first completely ignored by chemists. The real foundation of chemical thermodynamics was laid only when van't Hoff formulated his less rigorous theory (1884–1885) which, however, was fully integrated into the paradigm of chemistry. For instance, van't Hoff discovered, by conducting the corresponding hypothetical experiment (which is known as "van't Hoff Equilibrium Box"), a way of modelling chemical reactions as the operation of a heat engine (as is well known, thermodynamics was initially formulated as a theory of heat engines). When applying quantum mechanics to chemistry—in quantum chemistry theories—it is impossible to skirt around experimentally proved classical chemistry idealisations. These idealisations (an example of which is the chemical bond) are not derived from quantum mechanics, yet may be modelled in its terms, represented by the approximations of quantum mechanics equations. The modelling in question allows an explanation, and further elaboration in physical terms, of the physical content of such idealisations.

And now to the reason why chemistry is not strictly speaking an exact science. This conclusion is dictated by a fact which has already been pointed out—that the aim of chemistry research is determined by the task dictated to the discipline in sociohistorical practice—to obtain substances with required sets of properties. Ultimately, this task boils down to developing a technology for transforming one substance into another. For this reason, chemistry cannot itself determine its research object exclusively by reference to what it construes as idealised objects (construction of idealised objects, of course, does not mean simply hypothesising, imagining them, but represents a specific experimental procedure). The object of chemistry is inevitably (and independently of the capability of chemistry as a discipline) the entire actual diversity of substances. *The Feynman Lectures on Physics* aptly note, "Physicists always have a habit of taking the simplest example of any phenomenon and calling it "physics," leaving the more complicated examples to become the concern of other fields—say of applied mathematics, electrical engineering, chemistry, or crystallography" (Feynman, Leighton & Sands, 1963, ch. 13–1). In other words, chemistry is required to also account for what lies beyond discrete, idealised situations, what cannot be reduced to a task of pure mathematics.

Chemistry as a science appears to hold a fundamental contradiction (let us also recall previous references to that fact on p. 125): on the one hand (as an exact science) it needs to construe its research object through an experimental (i.e., artificial) setup as an idealised object, on the other hand (as a natural discipline, a part of natural history) it sees now and again—as is shown by important achievements in its construction work—that the most skilful constructor of substances is still nature itself. Nowadays, chemistry is nearing "real" nature through its path along "artificial", second nature. Let us see what this means and how this takes place.

During different stages of history, chemistry has fulfilled its task—of obtaining substances required by humans—in different manner. Theoretically-minded historians of chemistry have found that these stages may be characterised in terms of four conceptual systems.

The first conceptual system spans the period from the development of chemistry as a science to approximately mid-nineteenth century and can be expressed as the categorical correlate 'composition–properties', meaning that the properties of a substance are determined by, or arise from, its composition (the notion of 'composition' more or less coincides categorically with the notions of 'material', 'substrate', 'substance', 'elements'). Experimental chemistry was predominantly characterised by analysis: in the beginning, qualitative analysis of the composition of substances (Stahl), then quantitative analysis (Lavoisier) and, finally, the determination of atomic composition (Dalton) which brings together qualitative and quantitative analysis.

The second conceptual system arose when the category of structure was added to the first—with the development of structural chemistry (Kekulé, Butlerov and others). The chemical industry of that time was called upon to provide organic compounds with widely different properties. Until the compounds that were needed were mostly inorganic, the schematic 'composition–properties' appeared to "function" reasonably well. In the case of organic compounds, what strikes the eye, however, is the monotony in their elemental composition. It was primarily in the investigation of organic compounds—substances of plant or animal origin—that chemists discovered that knowing the composition of a substance is not enough to distinguish it from other substances that have different properties: the molecules of different substances may even have identical atomic composition (isomerism). Thus, the understanding was reached that the properties of a substance are determined by the spatial arrangement of atoms in its molecule—i.e., by its structure. (In traditional philosophical terminology, the category that corresponds to 'structure' is that of 'inner form'.) In experimental chemistry and in chemical industry, research focused on synthesising organic compounds with predetermined structure and properties. In practical work on chemical synthesis, among the properties determined by the substance's structure, particular attention was drawn to reactivity: the scope of reactions that a substance with a particular structure is capable of (i.e., the scope of synthesising reactions in which the substance could be used as a reactant). The notion of chemical synthesis, as a matter of fact, developed through that of reactivity. As discussed above, structural theories were preceded by unitary theory. Instead of predicating substance properties on substance composition, that theory characterised the reactivity types of substances by showing that a particular reactivity type need not be determined by the composition of the substance. Subsequently, it was discovered, however, that the types of reactions in which a substance could participate have a specific basis. It is that invariant aspect of chemical transformations of substances (that permits one to show what transformations a substance is, in principle, capable of) which is expressed by the notion of chemical structure.

The third conceptual system arose because of the fact that structural chemistry, too, proved inadequate for solving the tasks chemistry was faced with. Further examination of the mutual relationship of chemical structure and reactivity (in categorical terms—of structure and function) showed that the information available by examining the structure of a substance is insufficient to specifically characterise its reactivity—the function of a structure also depends on the processes or external relationships that the structure is part of. It was discovered that the structure of a substance alone does not determine its reactivity type. A substance with a particular structure may give widely different reactions depending on what other substance it reacts with and on what are the parameters of the reaction (temperature, pressure, concentration, environment, reaction vessel material, additives, catalysts, etc.). The reactions evidenced by the same substance may even extend to polar extremes of various chemical continua—it may behave as an acid or as a base, as an oxidiser or as a reducer, as a catalyst or as an inhibitor. It was understood that specific research was needed to establish the factors on which changes in the chemical structure and reactivity of a substance turn.

Structural chemistry in principle allowed one to synthesise substances with any desired level of complexity. Yet, in practical chemistry, a new requirement arose—substances with a specific set of properties were needed in vast amounts and at as cheap a cost as possible—i.e., from inexpensive precursors, with little energy expenditure, over a short period of time, at a high process yield, etc. This required the formulation of kinetic theories.

As was seen above, research into the rates and mechanisms of chemical reactions showed that, in addition to the structure of the reactants, the desired results of a reaction depended on the combined effect and coordination of many other factors and various intermediate processes. A kinetic system encompassing them may be referred to as an ‘organisation’ (a close-match category would be one of ‘organic whole’ or, also, of ‘organic system’). The word ‘organisation’ itself descends from the original Greek word *organon* meaning a ‘tool’ or ‘implement’. Unlike ‘structure’—a pattern of parts that characterises a system from the point of view of stability or permanence—‘organisation’ refers to a pattern that allows the system to achieve a specific objective (aim) through the effect of various changes, acts, actions, functions or tools (as tools used to a purpose or as organs operating in a functioning organism). ‘Organisation’ includes structures that have a permanent function as well as the transformation, formation or reformation of such structures. The permanence of an organisation lies not in the permanence of its “pattern of parts” (although it may, for a certain time, manifest as such) but rather in the fact of consistently achieving a certain purpose (or aim) through various (transitory) processes. Organisation, as it were, encompasses structure in the same way that structure encompasses composition.

Research into chemical processes, as well as the formulation and practical application of kinetic theories are showing, with increasing clarity, that in order to achieve a desired result it is necessary to coordinate the effects of a multiplicity of factors, to account for the impact of circumstances which at a first glance might appear negligible, to approach the problem in a systematic manner, as a complex affair. The need for such an approach has, among other things, brought fundamental chemistry and applied chemistry (chemical technology) significantly closer. Whilst in structural chemistry, as well as during the beginning stages of process chemistry, it was thought that the problem of obtaining a desired substance would be solved when a schematic process for synthesising the substance in a laboratory was successfully formulated (and, of course, tested in practice), it is now understood that a chemical process may, when it “simply” shifts to a different scale (from the laboratory to an industrial facility) take a substantively different course. Theoretical research into industrial processes and their cost-efficient organisation has, in a sense, compelled chemists to completely rethink the classical principles of conducting chemical reactions. This concerns, primarily, the classical principle of direct approach according to which conditions should be created for the reaction to take place in a manner that maximises the chemical transformation, towards the intended target, of the reactants introduced in the reactor, for the reactants to react with one another to the maximum extent possible and to provide the maximum (thermodynamically possible) yield in terms of the end product. Nowadays, however, it is found that a significantly more cost-effective approach is to organise the process according to the principle of re-circulation. This means that the full amount of the end product is not harvested at once but rather in stages, constantly feeding the reactant mixture that has not yet reacted back into the reactor. At the same time, the desired end product is constantly removed from the reactor, as well as the substances that, for the purposes of the given reaction, constitute a side product (if any). By means of such an organisation of the process, what is intended is—contrary to the corresponding classical principle—a minimum chemical transformation of the reactants and the formation of a minimum amount of desired end product in a single cycle through the reactor (this makes it easier to implement the catalysis effect and eliminates the need to conduct the reaction under extreme conditions such as very high or very low pressure, temperature, etc.).

The fourth conceptual system evolves from the third as the third from the second and the second from the first. In logical terms, the formation of a new conceptual system is caused by the fact that organisation presumes an “organiser”: the purposefulness of the system—the purpose itself and the complex of tools to achieve it—must originate somewhere. In chemistry’s third conceptual system, the organiser was the human being itself. The human being established the objective and, quite literally, organised the objective process such that its result corresponded to the aim that he set. In the fourth conceptual system, however, we are looking at a kinetic system that organises itself, i.e., we are dealing with a self-organising system whose mechanisms have developed in the course of the process of chemical evolution and are characteristic of living nature.

From the point of view of the development of economic production, the formulation of the new conceptual system is caused by the problem of pollution of our environment which, in chemical industry, is becoming increasingly serious. The task now is not simply to find a cost-efficient way to obtain substances with desired properties, but to obtain them in a way that does not generate harmful waste products. This requires us to model natural processes, to find ways of conducting chemical processes such that they are in harmony with the circulation of matter in nature.

This was also the direction of development in the third conceptual system, because catalytic and recirculation-based kinetic systems characteristic of living nature proved the most cost-efficient. Thus, the development of chemistry is characterised by its ever closer mirroring of nature. In the future, chemistry, in all probability, will not concern itself with constructing substances from nuclei and—which would be a realisation of the developmental path that is, in principle, possible and that would mean simply chemistry becoming physics—will rather seek to master self-organising kinetic systems.

Thus, we have four conceptual systems in chemistry: (I) composition theories, (II) structural theories, (III) kinetic theories, and (IV) theories of chemical evolution. Their gradual development may be depicted in the following categorical schematic[11]:

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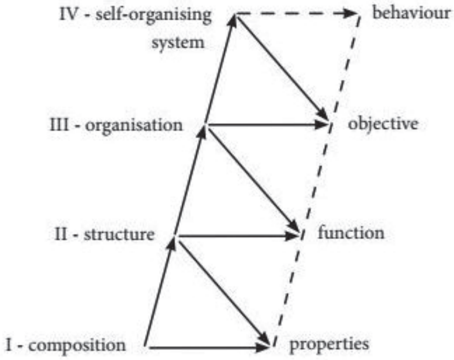
[11] The idea of the schematic originally belongs to Kuznetsov and Pechenkin (1971), but is presented here in supplemented form.



Each subsequent conceptual system encompasses the preceding ones while adding to them, supplementing them with new features. Analogously, in the homologous series of chemical compounds, the higher homologue encompasses the lower ones, yet being a new compound. Categories, too, are homologues: composition—structure—organisation—self-organising system; also: properties—function—objective—behaviour.

Completing the circle of moving through "artefactual" to "natural" is not only characteristic of chemistry—we can see this happening everywhere in natural sciences. Science makes it possible for the humanity to realise its aims in nature. Yet, the humanity's aims depend on nature. Human perception and activity are dialectical, paradoxical. In the case at hand, the paradox is the following: a scientific view of the world must be objective and thus has no place for human purpose. Yet, this objective view is obtained through subjective activity, through human being's purposeful actions. The scientific world picture, as you will recall, was formed on the basis of "mechanical arts"—technology—in which scientific objectivity was related to a specific purposeful activity—the scientific experiment.

In the work at hand, we have stressed from the beginning that man sees the world through the prism of his actions. It would be completely surreal to imagine that objective reality is somehow "provided" for us independently of our practical activity. For instance, the opinion that the way that nature is can manifest in some other way apart from our everyday actions in that nature is illusory. Yet scientists, because of the nature of their work, are prone to overlook the fact that their representation of nature is subjective and biased in that it does not include a subject with regard to whom the indefinable, inexhaustible, boundless nature has been perceived, by whose actions it has been characterised, whose activity has made nature's manifold possibilities manifest. Nature would not have anything to do with human objectives only if those objectives were completely independent of nature, i.e., if humans would not realise their purposeful activity in nature and were not themselves part of nature. “Pure” science, however, presumes to draw from nature knowledge that has no relation to human aims. This is what generates the above paradox—the objectivity of science is based on subjectivity (or, vice versa, the subjectivity of science is expressed in its “pure” objectivity).

This paradox cannot be resolved in theoretical terms, for instance, by modifying the definitions of ‘objectivity’, ‘subjectivity’, ‘scientific’, etc., to make them more precise or give them a better fit. (Of course, it is clear that “pure” objectivity and “pure” subjectivity are one-sided notions. Their one-sidedness will be overcome in sociohistorical practice over time.) The resolution of the paradox should probably be the ceasing, over time, of human activity which causes opposition and subjugation of human subjectivity to the world of things constructed by us as “pure” objectivity, an inexorable fact of nature.

The dialectic of the world of things, however, is such that sooner or later, the subjectivity of such an objectivity is revealed, i.e., although the world of things has been constructed by applying the laws of nature, these laws are applied to trigger certain processes—those that serve the ends of humankind—at the expense of others. It becomes more and more difficult for the humankind to achieve its aims through such one-sided objectivity (the technology required becomes ever more complex, requires more and more energy, etc.) and, moreover, the ultimate consequences of realising those aims are such that they reduce all humanity’s achievements to naught and lead to an outcome that is the complete opposite of the one sought (one could give a host of examples here of pollution of the living environment). Thus, it is through an ecological crisis that humans come to the understanding that the world of things is not an independent one but has been constructed by them in nature and is subject to nature as are the humans themselves.

Reaching this understanding means that the humanity’s aim is no longer to work for the world of things, no longer to turn nature into such a world and to realise the humanity’s aims through it, but rather to bring the world of things and his aims into harmony with nature. Nature, which, as a matter of fact, is absent from technology and natural sciences (which only know the laws of nature as knowledge of what is and what is not possible in nature, but have no knowledge of what nature is actually like), now becomes a reality that can no longer be circumvented.

If we were to recall Aristotle's teaching that the world is a whole organism, we could only concede that, in a certain sense, we are returning to his view. The victory of the scientific world picture over Aristotelian teachings no longer seems so convincing. In terms of the logic of categories, this is expressed by the law of negating a negation. Naturally, we cannot simply return to the views that were held by Aristotle. The aforementioned law of dialectics also states that returning takes place on a new basis and at a higher level of understanding. In fact, Aristotle's description of nature was complete because nature had not been scientifically investigated, the laws of nature remained obscure, nature was conceptualised through the cycle of human activity. Nowadays, however, we understand nature as a whole organism through our knowledge of the laws of nature and—through extensive interference with nature by means of the technology created on the basis of those laws—because of the "push back" from nature. The problem lies in how to ecologise a technologised civilisation. The required reassessment of values should take place through the development of science and technology. The problems of today cannot be resolved by turning our back on developments in science and technology and immersing ourselves in Aristotle's teachings. Yet, against the backdrop of contemporary ecological problems, the general thrust of Aristotle's thinking is very much to the point—the world is seen as a living organism, one that also includes human beings.

It is interesting to compare chemistry's four conceptual systems with Aristotle's teaching of the four causes. The first conceptual system (composition theories) corresponds to Aristotle's material cause—matter; the second (structural theories) corresponds to form; the third (kinetic theories) to efficient cause (one that realises what is possible); the fourth (theories of self-organising systems) corresponds to the purpose or final cause (to predetermination flowing from the aggregate of world phenomena).

How can one explain such a coincidence? Is it by attributing prophetic powers to Aristotle? In fact, the matter seems quite straightforward. In both cases, we are ultimately dealing with a description of the general scheme of human activity in terms of categories. Aristotle was able to provide such a complete description of human activity also as a description of the causes of things because at the time human activity was still organic and human world and Nature were not yet at odds. The development of chemistry's conceptual systems shows how humanity's actions that seek to reshape nature lead us to comprehend the organic reality of nature by reaching the limits of attempts to reshape it.

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