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Mechanistic Trends in Chemistry

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Abstract. During the twentieth century, the mechanistic worldview came under attack mainly because of the rise of quantum mechanics but some of its basic characteristics survived and are still evident within current science in some form or other. Many scholars have produced interesting studies of such significant mechanistic trends within current physics and biology but very few have bothered to explore the effects of this worldview on current chemistry. This paper makes a contribution to fill this gap. It presents first a brief historical overview of the mechanistic worldview and then examines the present situation within chemistry by referring to current studies in the philosophy of chemistry and determining which trends are still mechanistic in spirit and which are not.

Keywords. Mechanism, Descartes, atomism, substance, teleology.

Chemistry can be described as the study of how matter adopts different forms and of how it changes from one form to another. Within this discipline, various conceptual issues arise. They are of interest to philosophers, to historians and sometimes to chemists themselves, especially to those chemists who seek greater clarity about the deeper assumptions of their work. One of the most interesting conceptual issues has to do with mechanism. To account for the way matter changes from one form to another, chemists often use mechanistic explanations. For instance, they may explain a chemical reaction in terms of a small number of steps from the initial reactants to the final products, the intermediates being conceived of as somewhat stable molecular combinations. The mechanistic explanation in these cases is like a set of snapshots taken at different stages of the transformation. The basic assumption is that the world functions like a complex machine and that every process can be analysed into definite steps that involve simple reconfiguration of parts and transfer of energy. Chemists tend to see a chemical reaction as a kind of sub-device within the larger machine of nature and tend to see their task as a kind of reverse engineering.[1]

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[1] The clearest example of this method is probably E. J. Corey's retrosynthetic analysis. "*Retrosynthetic* (or *antithetic*) analysis is a problem-solving technique for transforming the structure of a synthetic target (TGT) molecule to a sequence of progressively simpler structures along a pathway which ultimately leads to simple or commercially available starting materials for chemical synthesis." E. J. Corey and Xue-Min Cheng, *The Logic of Chemical Analysis* (New York: John Wiley & Sons, 1989), p. 6.

The fascination with mechanisms has an interesting history. The origin of the so-called mechanistic worldview is often associated with Galileo Galilei and with the beginning of the scientific revolution. Even before his time, however, the proliferation of machines had been a distinctive feature of the intellectual milieu of the Renaissance. About a hundred years before Galileo, Leonardo da Vinci had filled notebook after notebook with designs of various contraptions intended to satisfy all kinds of human needs. Leonardo's contraptions qualify as machines because he proposed them as artefacts made up of components that function together for an overall positive effect. The most rudimentary machines, like levers and pulleys, have been with us since the dawn of civilization but, in the course of European history, from the Renaissance onwards, we see the importance of machines increasing at an accelerating rate, with human society becoming progressively dependent upon them. The rise of mechanistic thinking left a significant mark on the wider cultural, philosophical, and religious contexts. It affected the way people understood the world and their place within it, and it gave rise to a distinctive worldview, a cosmology in which God became increasing seen as the chief engineer responsible for the greatest and most intricate machine of them all, the entire universe. The specific philosophical features and assumptions of this worldview were not completely clear from the start. It took philosophers and scientists of the early modern period many generations to explore and articulate such assumptions often after lengthy disputes with theologians.

During the twentieth century, the major features of this worldview came under attack mainly through the rise of quantum mechanics but some of the basic characteristics still survive today in some form or other. For example, it is arguable that the research programme of reductive physicalism within the brain sciences is a direct descendant of the mechanistic materialism of the late seventeenth century. Many scholars have produced interesting studies of such significant mechanistic trends within current physics and biology but very few have bothered to explore the effects of this worldview on current chemistry. In this paper, I intend to make a contribution precisely in this neglected area, primarily by seeking an answer to the question, "How mechanistic is current chemistry?" In the first section, I will present a brief historical overview of the mechanistic worldview with the aim of extracting its main philosophical characteristics. In the second section then, I will examine the present situation by referring to current studies in the philosophy of chemistry and determining which trends are still mechanistic in spirit and which are not.

1. THE MECHANISTIC VIEW IN HISTORY

The rise of a distinctively mechanistic worldview would not have been possible without the position often called corpuscularianism, according to which macroscopic bodies should be described, and their behaviour explained, in terms of microscopic corpuscles — a view not very different from traditional atomism.[2] The novelty of corpuscularianism arose from the conviction of fifteenth and sixteenth century thinkers that the Aristotelianism of the Middle Ages needed urgent revision. These thinkers were convinced moreover that a revision could only come about by using mathematics to quantify in some way the various attributes of the ultimate constituents of the world. Such insights pointed towards something that would be definitely new. In spite of this novelty, however, some affinity between the emerging, new mechanistic paradigm and the old scholastic Aristotelianism remained. Elements of continuity were especially evident in the way major proponents of the new paradigm justified their project. They adopted an attitude that corresponds exactly to what one would expect from an Aristotelian Scholastic thinker: they referred to an underlying essence. Aristotle had constructed his entire edifice of natural philosophy on the idea of substance. Descartes, one of the paradigmatic mechanistic philosophers, adopted a similar approach: he constructed the entire edifice of his mechanistic view upon the idea that the essence of matter was extension. It is clear therefore that, since the change from the old to the new paradigm included elements of both discontinuity and continuity, a responsible historiography needs to be sensitive to both.[3] To determine those features of the new worldview that affected chemistry, we need to investigate such complex conceptual transformations and legacies with special attention. Let us start by considering the contribution of three prominent protagonists of the mechanistic worldview.

Pierre Gassendi (1592-1655) left his mark on the history of philosophy because he not only endorsed and developed the atomistic philosophy of Epicurus but also attempted to produce a Christianized version of it. With his competence in both philosophy and theology, he managed to produce a sophisticated natural philosophy that was on a par with the Cartesian proposal.

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[2] Ancient Greek philosophers used to assume that atoms were indivisible; corpuscles however were assumed microscopic building blocks of everyday objects, just like atoms, but without the condition of indivisibility.

[3] See R. Ariew, "Descartes and Scholasticism: the intellectual background to Descartes' thought," in *The Cambridge Companion to Descartes*, edited by J. Cottingham, Cambridge University Press, 1992, pp. 58–90.

Now, many features of Epicureanism seem, at first sight, completely irreconcilable with religious belief, especially Christianity. For instance, the kind of atomism defended by Epicurus denies creation and divine providence, assumes the infinity and eternity of atoms, rejects final causes, and gives a central role to chance. Gassendi knew this well. Nevertheless, he engaged in reconciliatory work by launching a critical evaluation of Aristotle's objections to this kind of natural philosophy. Gassendi was convinced that what Aristotle had attacked was not the genuine version of atomism but a caricature of it. The genuine Epicurean philosophy was indeed reconcilable with religious belief primarily because it included an element of wisdom. Like many other Ancient Greek philosophers, Epicurus had produced his theoretical proposal ultimately as an ethical way of life, his main aim being that of grasping the correct structure of the world so as to do away with imaginary fears arising from animistic cosmology. This element was certainly reconcilable with Christianity. Gassendi was aware of this point but did not limit his defence of Epicurus to these considerations. He turned his attention to other aspects as well. According to Gassendi, Epicurus and Christianity were opposed primarily as regards materialism and divine providence. Unlike Democritus, Epicurus had accepted as real not only the atoms themselves, but also the complex compounds that these atoms constitute when combined in various configurations. Epicurus had not insisted however that, by perceiving the macroscopic object, in other words, the combination of atoms, we have access to that object's essence, as Aristotle was to do after him. For Epicurus, in cognition we do not grasp the hidden essence of things but merely their appearances. Gassendi's first move was therefore to try to retrieve and defend this pre-Aristotelian Epicurean position.

Epicurus had also insisted that all physical processes, including those of perceivable macroscopic objects, are nothing more than interaction between atoms. He had complicated his picture however by assuming that all atomic motion was downwards, if not disturbed by swerving. In this somewhat strange assumption, Gassendi found his opportunity to introduce the element of divine providence. He argued that God provides atoms with different initial attributes: different motions and different sizes. Thus God gives the atoms the ability "to disentangle themselves, to leap away, to knock against other atoms, to turn them away, to move away from them, and similarly the capacity to take hold of each other, to attach themselves to each other, to join together, to bind each other fast, and the like, all this to the degree that he [God] foresaw would be necessary for every purpose and effect that he destined them for".[4] With such a proposal, Gassendi seemed to distort Epicurean thinking considerably. He was effectively replacing the fundamental idea of chance with goal-directed atomic behaviour. In this move, we see why Gassendi represents a radical departure from both Epicureanism and Aristotelianism. He brought God's action into Epicurean atomism and he also removed Aristotelian final causes from within nature. He ceased seeing goal-directed behaviours or final causes as intrinsic to the nature of things. Instead, he started to treat goal-directedness as an extrinsic factor, deriving not from nature but from God. With such an idea of providence, Gassendi had to respond to the problem of personal freedom. How could an externally goal-directed universe leave space for freewill? The answer for him involved the idea of flexibility: he argued that the intellect is precisely that kind of complex combination of atoms that produces a flexible nature, one that can judge various aspects of the same object, and can evaluate different future possibilities. This proposal does account for what we observe but seems *ad hoc*. Overall, we can say that Gassendi's attempt to arrive at a synthesis of Epicureanism and religious belief was brave but not without its own problems.

We move on now to another defender of the mechanistic worldview, Thomas Hobbes (1588-1689) who proceeded in Gassendi's steps but was not concerned as much as Gassendi with retaining consistency with religious belief. Hobbes embraced materialism and determinism, and consequently expressed an overall view that nowadays we would call a materialist theory of the mind. He developed a comprehensive version of mechanistic philosophy that aspires to explain the entire universe in terms of matter and motion only, without reference to other features or forces, not even space and time. Within this picture, there is place neither for spiritual substance nor for religious belief in the traditional sense. In his book *De Corpore*, which contains most of his ideas on the workings of nature, he adopts an overall reductive approach. For him, any object's capacity to produce motion is nothing more than the motion of the constituent corpuscles. Space for him is neither substantial, enjoying a separate existence, nor a container, as Plato had suggested. It is merely a subjective frame of refer-

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[4] P. Gassendi, *Opera Omnia*, Lugduni: 1658 (sumpt. Laurentii Anisson, & Ioan B. Bapt. Devenet), volume I, page 280: "congruam sese movendi, ciendi, evolvendi; et consequenter sese extricandi, emergendi, prosiliendi, impingendi, retundendi, regrediendi; itemque ses invicem apprehendendi, complectendi, continendi, revinciendi, et cetera quasenus ad omneis fineis effectusque quos tum destinabat necessarium providit." Such anthropomorphic language seems inevitable and is still present in chemistry today. In current literature, molecules attack each other, nuclear spins "flip," and electrons push other electrons.

ence, a mental abstraction. To explain an object's tendency to move, Hobbes developed the notion of *conatus*, which roughly refers to the object's inherent directionality or vectorial aspect. He developed also the correlative notion of *impetus*, which roughly refers to the measured conatus of any given object.[5] He used these two notions to describe not only any given object's motion but also its capacity to produce sensation in rational creatures. Overall, his worldview was clearly materialistic, but most commentators agree that the arguments he put forward to defend his materialism were never very strong. It seems likely that what convinced him of materialism was not sustained reflection or a knockdown argument but confidence in the new method of empirical inquiry, which was making fast progress during his time. There is no doubt that religious belief played a significant role in his philosophy, especially in his political philosophy, but this does not mean that he was an orthodox believer. Some surprising ideas that he expressed, for instance that God could be material, suggest that he was an outright atheist. The issue however remains unclear. The best way of seeing him is probably as a heavy-handed, revisionist, religious believer, a sceptic about much that organized religion proposed; in other words, a very critical theist.[6]

Compared to Gassendi and Hobbes, René Descartes (1596-1650) stands out as the one who produced the most characteristic expression of the mechanistic worldview of the modern period, influencing nearly all areas of culture. He presented his views for the first time in the book *Principia Philosophiae* of 1644, where he focused on the nature of human cognition. For him, the very nature of natural philosophy obliges us to see the characteristics of mind, and of God, as essentially distinct from the physical world. This affirmation for him was a typical "clear and distinct idea", something that can offer guidance to inquiry because we perceive it with the mind rather than with the senses. A non-deceiving God who is responsible for all existence will ensure that what we perceive by the mind clearly and distinctly is in general true rather than systematically misleading. This principle throws light also on the essential features of substances that make up the world. The two basic attributes of substances are extension and thought. Extension can show variations, for instance when an object is now in one position and later in another. Similarly, thought can show variations, for instance when the mind remembers one thing and then another. Such variations constitute what he calls modes. For him therefore, motion is a mode; and so is the lack of it, the state of rest.

We notice here some fundamental novelties with respect to Aristotelian thinking. For Aristotle, there was an asymmetry between motion and rest, at least when the motion is not heavenly. For non-celestial objects, all motion showed a natural tendency to come to rest. The motion of such non-celestial objects therefore needed an explanation, while their state of rest did not. As opposed to this, Descartes sees a symmetry between uniform motion and rest. Both are modes. For him therefore, uniform motion does not need an explanation in terms of a force. He follows Aristotle and says that God is the primary cause of motion but adds that God maintains a constant quantity of motion within the entire universe. What may change is the distribution of motion and of rest within the universe. The overall amount of motion, however, remains the same. This is a law of conservation, justified just like all genuine laws of nature, by God's immutability. Descartes concludes that "in general, we evidently cannot see this otherwise than as follows: that God himself, who set the parts of matter in motion or at rest when he first created them, now, through his sole ordinary attention, preserves in all of it the same quantity of both motion and rest".[7] Another important novelty with respect to Aristotelian physics concerns the laws of nature. For Descartes, laws are causes: "From God's immutability, we can also know certain rules or laws of nature, which are the secondary and particular causes of the various motions we observe in individual bodies."[8] Consequently, the natural regularities we discover and formulate in mathematical form are not, as Aristotelians had assumed, descriptions of the intrinsic activity of the various substances. They are rather extrinsic causes affecting extended substance that, on its own, is inert. A third innovation worth mentioning here deals with the idea of a vacuum. For Descartes, the idea of a vacuum is mistaken. Motion is not movement across empty space but displacement of one part of the universe by another.

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[5] For further details, see H. Bernstein, "Conatus, Hobbes, and the Young Leibniz", *Studies in History and Philosophy of Science*, 11 (1980): 25–37.

[6] For a specific study of Hobbes's mechanistic philosophy, see F. Brandt, *Thomas Hobbes' Mechanical Conception of Nature* (Copenhagen; London, 1928); C. Leijenhorst, *The Mechanisation of Aristotelianism: The Late Aristotelian Setting of Thomas Hobbes' Natural Philosophy* (Leiden: Brill, 2002).

[7] R. Descartes, *Principia Philosophiae*, Part II, sec. 36: "Et generalem quod attinet, manifestum mihi videtur illam non aliam esse, quam Deum ipsum, qui materiam simul cum motu & quiete in principio creavit, jamque, per solum suum concursum ordinarium, tantundem motus & quietis in ea tota quantum tunc posuit conservat." See *Oeuvres de Descartes*, ed. C. Adam and P. Tannery, Paris: Vrin, 1996, volume VIII, p. 61, my translation.

[8] *Ibid*., sec. 37: "Atque ex hac eadem immutabilitate Dei, regulae quaedam sive leges naturae cognosci possunt, quae sunt causae secundarae ac particulares diversorum motuum, quos in singulis corporibus advertimus." *Oeuvres de Descartes*, ed. C. Adam and P. Tannery, Paris: Vrin, 1996, volume VIII, p. 62, my translation.

For any part of the universe to move, other parts need to squeeze out of the way accordingly. This is the direct consequence of Descartes's idea that the entire cosmos is a *plenum*. This means that, at any point, there is either a body or the fluid medium that fills up the space between bodies. This fluid medium causes bodies to move or come to rest. It reconfigures the overall distribution of motion and rest within the universe, which, on the large scale, is therefore a system of adjacent whirlpools carrying planets around their respective centres that are occupied by a central star. The Sun is just one of these central stars. This Cartesian cosmology is often referred to as a vortex theory, because it is modelled on what we see when a liquid moves round in a whirlpool. He argues that "the matter of the heavens, in which the planets are situated, revolves unceasingly, like a vortex having the sun as its centre, and that those of its parts that are close to the sun move more quickly than those further away."[9] Descartes thus offers a serious contender to Aristotle's cosmological system, which had assumed that the sub-lunar region is essentially different from the supra-lunar regions. Some historians highlight the fact that Descartes was not conceptually innovative on all counts. As I mentioned briefly before, he remained committed to giving explanatory priority to deductive arguments and essentialist thinking. Nevertheless, his original cosmological system had an enormous impact and remained the major point of reference for many generations of thinkers, even after the publication of Newton's *Principia Mathematica*.

The three philosophers mentioned up to now are by no means the only defenders of the mechanistic worldview. For a full list of philosophers who contributed to the detailed articulation of this worldview, we need to include people who were more directly associated with the new methods of empirical inquiry, figures like Galileo Galilei, Isaac Newton, and Pierre-Simon de Laplace.[10] It may be interesting to note that, even if we add all these, the list will not contain the name of anyone who was definitely against religious belief. In some form or other, religion was never completely absent in the work and life of these mechanistic thinkers.[11]

With the hindsight we enjoy today, after about four centuries since the emergence of the mechanistic worldview, what can we say about its basic conceptual ingredients? To answer this question, some scholars adopt the method of first identifying an ideal type of mechanistic philosophy, and then seeing the major sixteenth and seventeenth century thinkers as expressing some specific aspect or aspects of this ideal type. For instance, according to Stephen Gaukroger, the ideal mechanistic philosophy is one that reduces all physical processes to the motion of inert particles, fully describable in mechanistic and geometric terms.[12] The ideal mechanistic worldview assumes that we can fully explain any macroscopic object and its behaviour in terms of such particle motion only. The solid corpuscles are all of the same shape and size, while causation occurs between them only on contact. What we call matter is space that is full to capacity with such solid corpuscles. All macroscopic features of matter, such as observable variations in density, arise because of variations in the distribution of the constitutive corpuscles in space. The universe is causally closed, with no possibility of processes beginning or ending spontaneously. Given this basic picture, the main research programme of a mechanistic natural philosopher is to determine the laws of nature that allow a mathematical explanation of all observable changes. Of course, within such an explanation, corpuscles have passive attributes only. They are driven around according to the laws of nature. This modest list of assumptions is all we need to produce an exhaustive account of all kinds of motion and change, whether organic or inorganic. An important consequence here is that such a worldview has no place for Aristotelian final causes. It involves no intrinsic goals or purposes: neither within the corpuscles themselves nor within the complex composites.

This last point may give the impression that the mechanistic worldview represents a clear breach from ancient and medieval cosmology, but this is not completely true. Some important features of the old style of explanation did remain, as manifested by the example already mentioned, namely the recourse to first principles within the explanation. Descartes resorted to precisely this kind of explanatory strategy when *deriving*

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[9] *Ibid*., Part III, sec. 30. The fuller explanation is as follows. "Sic itaque sublato omni serupulo de Terrae motu, putemus totam materiam coeli in qua Planetae versantur, in modum cuiusdam vortices, in cuius centro est Sol, assidue gyrare, ac eius partes Soli viciniores celerius moveri quam remotiores, Planetasque omnes (e quorum numero est Terra) inter easdem istius coelestis materiae partes semper versari. Ex quo solo, fine ullis machinamentis, omnia ipsorum phaenomena facillime intelligentur."

[10] For a fuller historical treatment of the mechanistic worldview, see E.J. Dijksterhuis, *The mechanization of the world picture,* Oxford 1961.

[11] Admittedly, some historians today present Laplace as a champion of religious unbelief. He showed mathematically that the solar system is stable on its own, without the need of the occasional Divine readjustment as Newton had proposed, and he famously affirmed that he had no use of the "divine hypothesis". He thus produced the complete mechanistic worldview and allegedly pushed God out of a causally closed universe. This interpretation however neglects the fact that even Laplace retained a form of Deism and endorsed the idea that we should consider God the Supreme Being responsible for the laws of nature.

[12] S. Gaukroger, *The Emergence of a Scientific Culture: Science and the Shaping of Modernity 1210-1685*, Oxford University Press, 2006. I am drawing especially from chapters 8 and 9.

observations from his basic principle of matter as *res extensa*. Is this strong element of deduction an essential ingredient of the mechanistic worldview? Some historians distinguish between a mechanistic philosophy that is highly dependent on deduction from another kind that is less dependent. This second kind of mechanistic philosophy highlights observation and experiment, and minimizes the role of speculation about what might lie hidden. Gaukroger argues that these two kinds of methods of approaching nature depend on whether one gives explanatory priority to the formal element of the explanation or to the observations themselves. The mechanistic style of natural philosophy described so far puts the emphasis on first principles, which it then considers the building blocks of the new worldview. It then interprets the phenomena to fit that logical structure. As opposed to this, the experimental style of natural philosophy gives the priority to the observations and experiments, highlighting the importance of empirical evidence and reliability. In this latter style, first principles are not the engine of inquiry. They do not play the role they had within the Cartesian mechanistic philosophy, the role of ensuring the organization and unity of knowledge. In the experimental style of mechanistic explanation, what drives the inquiry is rather the effort to arrive at piecemeal, local explanations of the phenomena at hand.

An interesting example is the explanation of colour. Descartes, as a typical mechanistic philosopher of the deductive style, produced a theory rationally grounded on his geometrical optics and microscopic corpuscles, whereby he explained white light as a homogenous collection of corpuscles whose spin could be differentially affected by passing through a prism. This explains our sensation of seeing different colours. Isaac Newton, on the contrary, did not feel constrained to start his explanation from an alleged underlying hidden principle, from which the observations could be derived. He concentrated exclusively on the relations between observable aspects at the phenomenal level. He thereby arrived at the idea that white light is indeed heterogeneous, composed of different colours that can be separated by passing through a prism. Descartes therefore had looked for underlying causal links while Newton looked for manifest causal links at the phenomenal level without the need for foundational assumptions regarding the hidden dimension of reality. Newton realized that, if he focused on the phenomenal relations only, he had to suspend judgment as regards the correctness of the theory of corpuscles. This introduced a new attitude within the mechanistic philosophy, an attitude that Newton excellently summarized in his famous comment regarding the origin of gravity:

> *I have not as yet been able to discover the reason for these properties of gravity from phenomena, and I do not feign hypotheses. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction.*[13]

We note here how Newton distinguishes his views from mainstream mechanistic ideas by calling his own philosophy experimental.[14] In spite of this new terminology, however, there is much that keeps all mechanistic natural philosophers together. The Cartesian style and the Newtonian style are therefore better seen as two versions of the same worldview rather than as two different worldviews. It may be interesting to add here that, as regards consistency with religious belief, there was no significant difference between Descartes' deductive style and Newton's experimental style. Both versions were open to belief in God more or less in line with the standard Western religious tradition.[15]

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[13] Newton wrote this in the General Scholium, which was an appendix to his book *Philosophae Naturalis Principia Mathematica*. The final version of this Scholium appeared in the 1726 edition of the *Principia*. "Rationem vero harum gravitatis proprietatum ex phaenomenis nondum potui deducere, et hypotheses non fingo. Quicquid enim ex phaenomenis non deducitur, hypothesis vocanda est; et hypotheses seu metaphysicae, seu physicae, seu qualitatum occultarum, seu mechanicae, in philosophia experimentali locum non habent. In hac philosophia propositiones deducuntur ex phaenomenis, et redduntur generales per inductionem." The translation used here is from I. Newton, *The Principia: mathematical principles of natural philosophy*, trans. I. B. Cohen and A. Whitman, Berkeley: University of California Press, 1999, p. 943.

[14] M. Ben-Chaim, "The Discovery of Natural Goods: Newton's Vocation as an 'Experimental Philosopher'" *The British Journal for the History of Science* 34 (2001): 395-416.

[15] Descartes presented and justified his most famous work, the *Meditations*, as a way of defending the Catholic Faith: "I have always considered the two questions, the one regarding God and the other the Soul, to be the main ones that ought to be answered by the help of Philosophy rather than of Theology. For, although to us, the faithful, faith is enough to believe that the human soul does not cease to exist with the body, and that God exists, it surely seems impossible ever to convince infidels of the reality of any religion, or almost even any moral virtue, unless, first of all, those two things be proved to them by natural reason." (Semper existimavi duas quaestiones, de Deo et de Anima, praecipuas esse ex iis quae Philosophiae potius quam Theologiae ope sunt demonstrandae: Nam quamvis nobis fidelibus animam humanam cum corpore non interire, Deumque existere, fide credere sufficiat; certe infidelibus nulla religio, nec fere etiam ulla moralis virtus, videtur posse persuaderi, nisi prius illis ista duo ratione naturali probentur.) R. Descartes, "Sapientissimis Clarissimisque Viris Sacrae Facultatis Theologiae Parisiensis Decano & Doctoribus" (Letter of Dedication to the very sage and illustrious, the Dean and Doctors of the sacred faculty of theology of Paris), in *Oeuvres de Descartes*, ed. C. Adam and P. Tannery, Paris: Vrin, 1996, vol. VII, pp. 1-2, my translation. Newton justified his major work just as Descartes had done before him, by referring to its

So far, I have tried to show how the mechanistic worldview emerged slowly, how it remained in step with the new empirical methods of the natural sciences, and how it then eventually took definite shape towards the end of the seventeenth and early eighteenth centuries. Most of its fundamental tenets enjoyed considerable popularity during the nineteenth century but started to experience serious setbacks during the twentieth century. Scientific advances, especially in the area of quantum mechanics, obliged physicists to abandon the idea of elementary particles as tiny blobs of matter. The new paradigm in physics became incompatible with most of the features of classical mechanistic thinking. One of the most surprising novelties was the way in which the new physics undermined the materialistic basis of the mechanistic worldview. It brought about what N. R. Hanson called the "dematerialization of matter".[16] This expression does not mean that we should now reject the word "matter" as useless. It means rather that we need to retrieve its original philosophical sense: matter as a principle of individuation. The new paradigm obliges us to refrain from assuming that "matter" refers to some elemental stuff situated in space and time. This and other relevant shifts of meaning regarding fundamental terms show that, in the course of the twentieth century, the support that the mechanistic worldview used to receive from physics decreased considerably. It seems fair to say that, compared to what this support used to be in the seventeenth and eighteenth centuries, it is at present of minor importance.[17]

2. THE MECHANISTIC VIEW WITHIN CHEMISTRY

How has this mechanistic worldview affected chemistry? Does the present state of this discipline still show traces of mechanistic thinking? To answer these questions, we can first prepare the ground by considering the two fundamental concepts at work here, namely the concept of nature and the concept of mechanism, as they appear in chemistry.

For many centuries before the rise of natural science, the concept of nature was determined by Aristotelian philosophy and included a strong element of teleology or finality. Moreover, the distinction between natural and artificial, between *physis* and *technē*, was clear and important for the understanding of the world and of our place within it. With the Christian assimilation of these Aristotelian ideas, "natural" started to mean "in line with God's will", but, when the mechanistic view took over, final causes lost much of their importance, God was sidelined, and nature itself started being seen as the ultimate basis of explanation. These shifts caused some prominent thinkers to examine carefully how God should be referred to by the new science. The first book-length study of the concept of nature, written by Robert Boyle in 1682 and entitled *A free inquiry into the received notion of nature*, argued against the replacement of God by nature. For Boyle, it was a mistake to see nature as an agent. What scientists call the laws of nature should really be called the laws of God.[18] In line with this understanding, going against the laws of nature, or doing the unnatural, becomes sinful. When chemists create substances that are not found in nature, they therefore seem to transgress God's will, because, if God had wanted such substances to exist, He would have included them in creation. This kind of argument is obviously simplistic. Chemists could indeed be held responsible for going against God's will but their transgression would not lie in their having added something new, which God had not created before. It would lie rather in their intention to cause harm via the use of that new substance. Since humans are themselves part of nature, created by God like the rest of creation, their chemical ingenuity is not in itself something that goes against God's will. The chemists' endeavor to bring out, to actualize, the hidden potentialities of creation is perfectly natural. These considerations show how the dis-

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value as an apology for religion: "When I wrote my treatise about our [solar] system, I had an eye upon such principles as might work with considering men, for the belief of a Deity, and nothing can rejoice me more than to find it useful for that purpose. […] To make this system therefore, with all its motions, required a Cause which understood and compared together the quantities of matter in the several bodies of the sun and planets, and the gravitating powers resulting from thence; the several distances of the primary planets from the sun, and of the secondary ones from Saturn, Jupiter, and the earth; and the velocities with which these planets could revolve about those quantities of matter in the central bodies; and to compare and adjust all these things together in so great a variety of bodies, argues that Cause to be not blind and fortuitous but very well skilled in mechanics and geometry." I. Newton, *Four letters from Sir Isaac Newton to doctor Bentley, containing some arguments in proof of a Deity*, London: R. & J. Dodsley, 1756, digitized 2007, Letter I, p. 1; p. 7-8.

[16] N. R. Hanson, "The Dematerialization of Matter," *Philosophy of Science* 29 (1962): 27-38.

[17] As regards the fundamental constituents of nature, the present majority-view seems to involve a version of structural realism according to which what scientific theories ultimately refer to are not objects in space and time but patterns of relations expressed in the form of mathematical equations. See for instance Anjan Chakravartty, *A Metaphysics for Scientific Realism: knowing the unobservable* (Cambridge University Press, 2007).

[18] See Joachim Schummer, "The notion of nature in chemistry," *Studies in the History and Philosophy of Science* 34 (2003): 705–736. This paper presents a good overview of how chemistry resisted some of the fundamental assumptions of the mechanistic worldview. It is important to add however that the way the author identifies the Christian worldview with an odd narrative that he extracts from the non-canonical *Book of Enoch* shows considerable ignorance in this area.

tinction between natural and artificial can be misleading. In fact, we can observe that, from Newton onwards, the distinction starts losing its significance in philosophical and theological works about science and technology.

If we can say that the Aristotelian heritage regarding the pair *physis-technē* loses its importance, we cannot say the same thing as regards final causes. The literature about modern chemistry, especially during the interesting period of the artificial production of organic substances (roughly between the 1840s and the 1870s) shows that chemists increasingly assumed a teleological notion of nature and thereby distanced themselves more and more from physicists. Chemists readily made use of expressions like "imitating nature" and "learning from nature". Of course, the meaning of such expressions can oscillate between two extremes. The meaning may be that chemists see themselves as apprentices of nature or as its rivals. In spite of this possible semantic ambiguity however, we can safely conclude that, especially with the discovery of how to produce organic compounds artificially, chemists started seeing nature as active, as *doing* something. They thus reinstated some elements of teleology within the notion of nature, liberating themselves from the strictures of the classical mechanistic worldview. In this respect therefore, the chemists' idea of nature lies apparently midway between the finality-free mechanistic worldview and the teleologically rich, biological worldview. Current chemical literature confirms this point. A recent study affirms that, "the fact that we can so easily attribute the old metaphors to each of the branches [of current drug research] – learning from Nature, imitating Nature, improving Nature, competing with Nature, and controlling Nature – is hardly pure chance. It is more likely that these metaphors have actually been effective in shaping research traditions until today."[19]

Like the concept of nature, that of mechanism has had significant recent developments, some of which are relevant for chemistry. For lack of space, I will highlight two main features only. The first one deals with the idea of mechanism as corresponding to the form of acceptable explanations. Basically, a mechanism is an explanation that has the form of "nested hierarchies".[20] In line with the classic mechanistic worldview, the explanatory style I am referring to here assumes that objects are complex arrangements of smaller units, which are themselves made up of even smaller units, and so on. For current chemists, this should sound familiar. The explanation of a given phenomenon consists in supplying a description of a lower-level set of objects together with the push-pull relations between them and then supplying another even-lower-level set of smaller objects and their relations, and so on until we bottom out at the level of fundamental non-reducible elements. We support the entire explanatory ladder by assuming that the fundamental elements have some dispositions that do not need any further explanation. We affirm, for instance, that the electron has a negative charge, period. In such an explanatory process, the challenge is to reduce the number of inexplicable dispositions to a minimum. Of course, to arrive at a satisfactory set of nested hierarchies in this sense, we are entitled to use all the knowledge at our disposal. We can use previous knowledge of other systems and subsystems. We can use also knowledge that we may have acquired from situations that have nothing to do with the phenomenon that we are trying to explain. Moreover, the particularity of the phenomenon we are studying could be a stepping-stone for broader understanding. If we manage to extract the abstract form of the mechanism, if we manage to extract it out of the particularity of the one phenomenon we are studying, we could then use it for understanding other similar phenomena.[21]

This is one feature of mechanism within current chemistry. Another important feature is the mechanism's inherent directionality. The Hempel-inspired discussions on the structure of explanation of the late 1960s and 70s supported the idea that to explain a phenomenon is to provide some information about general laws and about its causal history. Given this background, we can conceive of a mechanism simply as a particular subset of causal relations that contribute to the appearance of the phenomenon. For any given phenomenon, the entire causal history is a vast network of mutually interacting cause-effect relations. The subset of this network that deserves to be called a mechanism is, according to this view, that subset that researchers consider relevant for their discipline. This understanding of mechanism, however, remains unsatisfactory. It seems too subjective. Different researchers would carve up the causal history in different ways. Some philosophers therefore have defended the claim that a mechanism is not just any sub-

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[19] Schummer, "The notion of nature in chemistry", p. 726.

[20] Peter Machamer, Lindley Darden and Carl F. Craver, "Thinking about Mechanisms," *Philosophy of Science* 67/1 (2000): 1-25; the quote is from p. 13.

[21] The abstract version of a mechanism, usually in a diagrammatic form, is sometimes called a mechanism schema. Such schemas help in the effort to unify the knowledge that we derive from different situations, regarding both macroscopic properties and microstructure. "Higher level entities and activities are thus essential to the intelligibility of those at lower levels, just as much as those at lower levels are essential for understanding those at higher levels. It is the integration of different levels into productive relations that renders the phenomenon intelligible and thereby explains its." Machamer et al., p. 23. See also James A. Overton, "Mechanisms, Types, and Abstractions," *Philosophy of Science*, 78/5 (2011): 941-954.

set of the causal history. Something more is needed. A causal subset deserves to be called a mechanism when it is clearly directional, when it is clearly productive of the specific effect that we are investigating. The causal subset needs to be a complex system consisting of mutually interacting sub-systems that *function together* to produce the specific effect. The specific effect, in this case, would be what the mechanism is for.[22] On this view therefore, we are not entitled to call a set of nested hierarchies of systems a mechanism if we do not know what it is for.

We notice immediately here the affinity with the biological concept of function. These developments therefore are suggesting that the concept of mechanism in chemistry should depend on that of function, just as in biology.[23] When explaining living organisms, we can talk about the mechanism involved in a specific organ only when we know the function of that organ within that living thing. The simple causal-role view of mechanism therefore is not enough. We do not pick any set of events that have a causal role within the production of an effect. To refer to a biological mechanism, we first determine the specific task that the effect represents, in other words, we determine its function, and then spell out, step by step, how that function is realized. Not every change in a living organism is associated with a function. Changes can be accidental or even pathological. We do not take a pathology to be a mechanism. We take it to be a mechanism that has broken down. A malfunction is, as the word implies, a mechanism that went wrong. This shows how intimately related is the idea of mechanism to that of function. Now, the functional view of mechanism is typical of biology. In physics, the situation is different. Here, final causes have no significant role and the causal-role view of mechanism is therefore the only one available. What about chemistry? As one would expect, chemistry lies somewhere between these two positions. In the course of the seventeenth and eighteenth centuries, the mechanistic worldview gave priority to physics over the other sciences, it emphasized the causal-role view of mechanism, and it convinced many scientists to apply the causal-role view without alterations to chemistry and even to biology. The indispensable role of functional explanations within biology however, together with the onset of organic chemistry, has persuaded recent philosophers of science that the functional view of mechanism is indispensable not only for biology but for chemistry as well. The present situation therefore is interesting because, within the one discipline of chemistry, we find features that are definitely mechanistic and others that are not.[24]

Let us consider one current feature that is definitely mechanistic in character, namely the way chemists espouse atomism in some form or other. Just as the early mechanistic philosophers had their version of atomism, according to which all things were made up of small corpuscles, so nowadays chemists have their own version. They think of substances as combinations of smaller units and these units as combinations of even smaller units, and so on. The basic idea of postulating building blocks or elements to explain the great variety of things in the world has a long history going back to the Ancient Greek philosophers for whom there were only four elements: earth, water, fire and air.[25] In the course of history, alchemists adopted this assumption of the four elements and used it extensively in their somewhat confused talk about the transformation of substances. Subsequent studies became more systematic and started to involve the categorization of substances and the study of controlled changes, especially through the invention and betterment of the distillation apparatus. No doubt, technological advances continued to increase our knowledge of how substances react but the deeper mechanisms behind the observed changes remained indefinite. Sometimes, alchemists referred to animistic powers or occult forces to explain the hidden mechanisms, but such explanations were never a substitute for the basic idea of the four elements. As innovation progressed, interest in uncovering what lay hidden waned. Metallurgical manuals of the mid 1500s adopted an instrumentalist view, concentrating on how-to-do rather than on the underlying mechanisms that might explain the production of useful materials like glass, acids and gunpowder.[26] When natural philosophers started formulating the mechanistic worldview in terms of corpuscles, early chemists tended to combine the doctrine of the four elements with the new atomism, postulating the existence of four kinds of atoms, one for each element. On this view, the transformation of substances became a reconfigura-

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[22] Stuart Glennan, "Rethinking Mechanistic Explanation," *Philosophy of Science* 69/S3 (2002): S342-S353.

[23] Justin Garson, "The Functional Sense of Mechanism," *Philosophy of Science* 80/3 (2013): 317-333.

[24] The functional view of mechanism and the idea of "nested hierarchies" are not the only important features of current philosophical research concerning mechanism. For other features, see for instance Stuart Glennan, *The New Mechanical Philosophy* (Oxford University Press, 2017); Carl Craver and James Tabery, "Mechanisms in Science", *The Stanford Encyclopedia of Philosophy* (Spring 2017 online edition), Edward N. Zalta (ed.). These studies deal with the broad picture including all the sciences. In my paper, I focus on chemistry.

[25] For more on how Ancient Greek philosophy paved the way for modern theories about atoms, see Andrew G. van Melsen, *From atomos to atom: the history of the concept Atom*, trans. H. J. Koren (Pittsburg: Duquesne University Press, 1952).

[26] Aaron J. Ihde, *The Development of Modern Chemistry* (New York; Evanston; London: Harper and Row, 1964), p. 24.

tion of these four types of atoms.[27] The fact that the atomic theory continued to develop, to receive empirical confirmation and to arrive finally at the remarkable achievement of the Periodic Table did not change the basic explanatory strategy. The idea that chemists should reduce every process to a mechanistic picture that involves nothing more than motion of electrons, atoms or molecules, together with energy-transfer between states, continued well into the twentieth century and is still dominant today, even as regards organic chemistry. This explanatory strategy gained considerable support within organic chemistry through the discovery of the DNA structure in 1953, a discovery that refreshed hopes that chemists would soon be able to explain the reproduction of cells via a mechanism in the classical sense.[28] The twentieth century formulation of quantum mechanics did affected research strategies in chemistry but it did not eliminate all traces of the mechanistic and reductive style that this discipline had inherited from atomism.

At this point, we need to consider an important conceptual issue that lies behind the entire approach, an issue that arises whenever we seek to explain a phenomenon by referring to some lower-level microstructure. The problem arises because of the relation between parts and wholes. In general, we can say that there are different ways for parts to be together to form a whole. We can have loosely associated agglomerations, likes heaps. We can have mixtures. We can have compounds. And we can have strongly associated agglomerations like living cells. We can even have very intricately associated agglomerations that reiterate themselves, forming a whole of wholes, as in the case of the human body made up of organs, each of which is constituted of living tissue. What is the difference between these degrees of unity? Philosophers have discussed this question since ancient times. It is certainly not a new question resulting from the mechanistic worldview or from modern chemistry.[29] In nature, we find examples of all these kinds of combinations. As regards chemical thinking, a strictly mechanistic attitude would imply that the behavior of a chemical compound is exhaustively explainable in terms of our knowledge of the constituent atoms. Current knowledge however does not seem to support this view. Obviously, a compound like H_2O is not just a mixture of hydrogen and oxygen. It represents a specific state of togetherness that is different from that of mixtures. It is also different from that of organisms. Its state lies somewhere between these two grades of constitution. The individual elements, hydrogen and oxygen, can indeed exist separately, and, when combined, they are not destroyed. In philosophical terms, we can say that their ontological identity is not annihilated by the identity of the whole of which they are now part. We need to add however that they do not have any longer all of the attributes that they had before the formation of the compound. We do not seem capable of explaining all of the properties of the compound in terms of those of the constituents. Some philosophers argue that, with the formation of the compound, the individual elements undergo a kind of ontological promotion. The hydrogen atom in its combined state is not *primarily* a hydrogen atom any longer; it is now *primarily* a part of the water molecule. These last decades, philosophers have been exploring these issues in terms of emergent properties but we need not stray too far away from our main argument in this paper.[30] Suffice it to say that current explanatory strategies within chemistry include some persistent conceptual issues but, in spite of this, still show some traces of the classic mechanistic philosophy especially as regards the trend to explain marco-properties in terms of micro-properties.[31]

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[27] This was defended especially by the seventeenth century Wittenberg professor of medicine, Daniel Sennert (1572-1637).

[28] For a useful historical study of how the mechanistic worldview had a role in the emergence of molecular biology, especially in the contrasting explanatory strategies of microbiologist Oswald T. Avery and theoretical physicist Max Delbrück, see Ute Deichmann, "Different Methods and Metaphysics in Early Molecular Genetics — A Case of Disparity of Research?" *History and Philosophy of the Life Sciences* 30/1 (2008): 53-78.

[29] See, for instance, Aristotle, *Metaphysics* 1040 b, 5-10; *On generation and corruption*, Book I, chapter 10. A more recent study worth mentioning is Pierre Duhem, *Le mixte et la combinaison chimique. Essai sur l'évolution d'une idée* (Paris, 1902). See also Paul A. Bogaard, "After Substance: How Aristotle's question still bears on the philosophy of chemistry," *Philosophy of Science* 73/5 (2006): 853-863.

[30] The philosophical literature on emergent properties is considerable. I offer a short overview with special attention to the concept of nature in chapter 7 of *Nature: its conceptual architecture* (Peter Lang, 2014). What I am calling ontological promotion is more evident in the case of a biological whole. When I eat a loaf of bread, I am not adding bread as such to myself. Nevertheless, some parts of the bread do indeed became part of me. What used to be part of an inanimate thing becomes part of a living thing. If we accept the idea of higher and lower forms of unity, higher and lower kinds of wholes, then we should take the chemical example of H and O combining into H_2O as analogous to the organic example. For the specific question of how major biologists Ernst Mayr, Theodosius Dobzhansky, and George Gaylord Simpson defended biology from the encroachment of the physics-inspired mechanistic approach, see Erika Lorraine Milam, "The Equally Wonderful Field: Ernst Mayr and Organismic Biology," *Historical Studies in the Natural Sciences*, 40/3 (2010): 279-317.

[31] My insistence on persistent atomistic assumptions within chemical thinking might suggest that the way chemists resort to explanations in terms of micro-attributes is diametrically opposed to the way physicists do so. When chemistry resorts to the microscopic, it reveals itself as mechanistic while, when physics resorts to the microscopic, it reveals itself as non-mechanistic, especially because of its indeterminism, nonlocality and wave-particle duality. It is good to recall however that this is correct only to the extent that chemistry focuses mainly on what happens from the level of electrons, protons and neutrons upwards, and

What about other features that seem diametrically opposed to the mechanistic worldview? I will focus on three points only. Consider first the way chemistry as a discipline is related to physics. There is, of course, the trend to see chemistry as part of the far-reaching physicalist research program that seeks to reduce all objects and all motion to the fundamental interactions now acknowledged in physics, namely the electromagnetic, strong, weak and gravitational interactions.[32] In current chemistry, some reduction of this kind is always present, as is most evident in the sub-discipline of computational quantum chemistry. The results of using computers instead of chemicals have been important but we cannot take these methods to be a substitute for practical, experimental work. Computational chemistry is the theoretical counterpart of concrete practice, accounting for what is already known and exploring new possibilities, but always in need of calibration with reference to experimentally observed data. For the theory to be useful, approximations are inevitable. As the complexity of the system increases, so also the need to make approximations. For heuristic reasons therefore, it seems better not to limit chemistry to strictly reductionist explanatory methods but to assume that chemical explanation enjoys a certain degree of autonomy with respect to physics. The forms of explanation in both camps show similarities but remain distinct. For instance, a theory in physics may include theoretical entities whose existence is justified because of the theory's explanatory success. This occurs also in chemistry. Chemical theories have their own theoretical entities, entities like atomic and molecular orbitals, but these entities are different from anything that physics deals with.[33] We have here, therefore, a feature of current chemistry that is opposed to the classical mechanistic worldview. The point can be summarized as follows. If we take the classical mechanistic worldview as equivalent to today's physicalism and if we take physicalism as the idea that all scientific disciplines are reducible to physics, then chemistry today, even in its computational form, is not straightforwardly mechanistic. It is no wonder that some current philosophers working in this area are convinced that we "must abandon the *a priori* assumptions and ontological commitments of traditional mechanistic epistemology and go beyond the physicalistic reference frame […]. Mechanistic doctrine is even a barrier for understanding the epistemology of chemistry."[34]

A second novel feature worth mentioning here is the shift of interest from the internal microstructure of substances to relations. The classical mechanistic worldview suggests that we should see chemistry as the study of substances and their constitution. The interest of current chemists however is not primary in substances as such but in relations between them. The emphasis is on the rules that govern the combinatorial possibilities of substances. These rules are comparable to the rules of grammar that determine how language can function properly. Some philosophers of chemistry call them "semiotic rules" and equate them to reaction mechanisms.[35] On this view, chemistry is "the science of the rules of possible chemical substances".[36] The term "mechanism" therefore is changing its meaning. According to these philosophers, a mechanism for chemistry is not a physical system of particles in motion but the set of signs and their rules of combination. For instance, the valence of an element, as the measure of its combining power, serves as a rule within the writing of a chemical equation. Revising the meaning of mechanism in this way implies a major shift from the classical stance. Previously, we used to assume that the highest form of understanding of a given phenomenon was the determination of the primary qualities of the entities involved and, when possible, the determination of its accurate pictorial representation. This attitude apparently implies that a direct photograph of a molecule, as we can sometimes obtain via X-ray crystallography, would be the best that chemistry could achieve. Such a photograph however would be useless for modern chemistry because what constitutes the important focus of chemical mechanisms is the set of rules of combination. A significant transformation is happening here within the very concept

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rarely considers elementary particles. Physics, on the contrary, had to abandon its mechanistic foundations precisely because of its tackling phenomena at the level of elementary particles. The relatively recent sub-discipline of quantum chemistry reduces this opposition to some extent because it uncovers quantum effects at the atomic and sometimes even at the molecular level. The overall point is that there are areas of chemistry that are not influenced by quantum mechanics. These retains a mechanistic character.

[32] The way physics dominates other disciplines, and the reasons behind this phenomenon, constitute an interesting area of study; for more about this effect on chemistry in the early 1900s, see Kostas Gavroglu, "Philosophical Issues in the History of Chemistry," *Synthese* 111/3 (1997): 283-304.

[33] In philosophy of science, the term "theoretical entity" refers to an unobservable thing that scientists assume to exist so that their theory predicts observations successfully. For further discussion on this point as regards chemistry, see Eric R. Scerri and Lee McIntyre, "The Case for the Philosophy of Chemistry," *Synthese* 111/3 (1997): 213-232. A typical theoretical entity in current physics is the electron. In chemistry, molecular orbitals were first stipulated as a mathematical construct to help solve a particular set of quantum mechanical problems. They were then co-opted by organic chemists as an explanatory framework, and are now said to have been "observed" via the visualization of electron density.

[34] Joachim Schummer, "Towards a Philosophy of Chemistry," *Journal for General Philosophy of Science / Zeitschrift für allgemeine Wissenschaftstheorie* 28/2 (1997): 307-336; the quoted text is from pp.308-309.

[35] E.g. J. Schummer. See *Ibid.* p. 324.

[36] *Ibid.* p. 327.

of mechanism. From the idea of a faithful pictorial representation of material elemental objects and the push-pull relations between them, mechanism has become the abstract idea of a set of rules. Although we use the same term "mechanism", the way chemists today use this word would hardly be recognizable by the mechanistic natural scientists of the modern period.

The third point of departure of modern chemistry from the mechanistic worldview concerns the persistent importance of macro-properties with respect to microstructural explanation. The classical mechanistic view, as has been shown in the first part of this paper, emphasized the importance of microstructure. It emphasized the way the corpuscles were configured in a specific way. It deconstructed the idea of substance inherited from ancient and medieval philosophy, substances as persistent macro-objects, and substituted it with that of a combination of elemental units. This is what the classic mechanistic philosophers defended. Does modern chemistry still depend upon this kind of deconstruction? It seems not. Modern chemistry, of course, still considers atomic structure of capital importance. Nevertheless, we have some clear indications that it does not make the idea of substance redundant. It does not substitute the idea of substance by a discourse about atoms. Philosopher Jaap Van Brakel argues persuasively that at least two chemical definitions of pure substance remain fully operational within current chemistry. They are in fact independent of one's convictions regarding atoms or quantum mechanics. First, "a pure substance is a substance of which the macro-properties (of one of its phases), such as temperature, density and electric conductivity, do not change during a phase-conversion (as in boiling a liquid or melting a solid)". Second, "pure chemical substances are the relatively stable products of chemical analysis and synthesis: nodes in a network of chemical reactions".[37] The plausibility of such definitions shows that, for chemistry, the way we quantify and understand the macroscopic world remains indispensable. We need not resort always to the microscopic world. The macroscopic world, in fact, remains indispensable for calibrating the microscopic. The macroscopic world guides the explanation in terms of microstructure and not the other way round, as reductionists sometimes assume. This point recalls the crucial distinction between what philosophers call the manifest image of the world, which refers to what I am here calling the macroscopic world, and the scientific image of the world, which refers to microstructure. For chemistry, the manifest image remains indispensable. We are entitled to say this because, as Van Brakel puts it, "if quantum mechanics turns out to be wrong, it would not affect all chemical knowledge […] What there is, are chemical and physical descriptions of macroscopic entities, whose identity conditions are grounded in the end in the manifest image".[38]

CONCLUSION

My original aim was to determine the extent to which current chemistry is still mechanistic in spirit. Through my initial historical overview, I illustrated that the mechanistic worldview involved some basic ingredients, such as the assumption that we can fully explain any macroscopic object and its behaviour in terms of corpuscular motion only, that the scientist's task is to determine the laws of nature, that the universe is causally closed, and that there are no final causes. This set of assumptions experienced some setbacks during the twentieth century but some of its explanatory maxims remained. In the second part of my paper, I focused on chemistry, analysed the notion of nature and that of mechanism within this discipline and determined which trends in current chemistry are still mechanistic in spirit and which are not. The results show that, as regards the urge to explain phenomena by resorting to lower-level ontological units, chemistry is still in line with some of the major tenets of the mechanistic worldview. It is not mechanistic, however, as regards its acceptance of higher-level properties that are not fully reducible to lower-level properties, as regards its assumption of some form of finality within nature, as regards its heightened focus on rules of combination, and as regards its notion of substance that is primarily associated with macroscopic attributes. Of course, much more can be said about many of the points I discuss in this paper. Moreover, my evaluation of the current situation has probably not considered all the significant trends in current chemical thinking. I hope however that what I did present here is enough to support the conclusion that current chemistry still involves some traces of mechanistic thinking but it does so without adopting the entire philosophical baggage of the seventeenth and eighteenth centuries. Today, chemists seem to use mechanistic explanatory strategies just like any other instrument. In their overall project of studying substances and their properties, they use this instrument when it helps and reject it when it hinders.[39]

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[37] J. Van Brakel, "Chemistry as the Science of the Transformation of Substances," *Synthese* 111/3, (1997): 253-282; the quote is from p. 253.

[38] *Ibid.* p. 273. The distinction between manifest and scientific images of the world is, and has been, the object of sustained philosophical study. The most prominent philosophers in this area are probably Edmund Husserl and Wilfred Sellars.

[39] Thanks to Prof. Michelle Francl-Donnay and to an anonymous reviewer for *Substantia* for helpful comments to a previous version of this paper.