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Developmental Aspects of Contemporary Chemistry

Some Philosophical Reflections

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Abstract: The development of contemporary chemistry is surveyed, in an attempt at grasping philosophical consequences: first, chemical research has revealed a potentially endless diversity of matter, and an abysmal complexity of its organization at the molecular level. Second, we may conjecture from reflections on some aspects of chemical reactivity that, owing to the limitations of human investigative means, reality is chemically unfathomable beyond a certain limit. In some instances, this may impede our understanding of the functioning of natural systems in terms of molecular-structural organization. Third, the overall consistency of results obtained by applying different analytical methods in order to establish molecular identity, along with the fact that we are able to interpret a great many different phenomena coherently in terms of molecular structure, indicates that matter – far from being something undifferentiated, easily moldable by the experiment, as anti-realistic views of science presuppose – really possesses a structure at the molecular level; a structure that can be reorganized only according to a formal disposition inherent to matter itself.

Keywords: *development of contemporary chemistry, complexity and inexhaustibility of matter, novelty, by-products, molecular structure, realism.*

Introduction

The development of chemistry is a process that is presently characterized by a great speed. If one assumes that the activity of a scientific discipline, which is denoted by the number of original works produced, is indicative of its growth and evolution, chemistry seems to be developing much more rapidly than the other main scientific disciplines, *i.e.* physics and biology.[1] The impressive number of works written in a language peculiar to chemistry indicates that there is indeed plenty of room to enlarge the body of scientific discoveries through a chemical approach, which is an approach based on formal, observational, and experimental instruments grounded on the basic notion of molecular structure, to which all other fundamental chemical concepts (such as ‘chemical bond’, ‘valence’, ‘reaction’, *etc*.) are related.

Let us try to sketch the developmental features of contemporary chemistry. Apparently, synthetic chemistry, both in its traditional fields, as well as in recent developments (*e.g.* dendrimer chemistry, inclusion compounds chemistry, *etc*.) forms a very big part of current chemical research. (Synthetic chemistry is a unique science in that it produces the objects it is interested in.). However, remarkable advances have taken place also in other branches of chemistry dealing with molecular reactivity (like photochemistry, electrochemistry, and, in a way, mass spectrometry), and in the field of reaction mechanisms. Furthermore, a huge number of analytical and physicochemical studies have appeared in the literature, either aiming at the explication of reaction mechanisms (identification of reaction intermediates, spectroscopic investigation of transition states, kinetic and isotopic labeling studies) or centered on specifically structural aspects (structure determination of complex natural compounds, description of structural features of unusual compounds, *e.g.* fullerenes, strained small ring systems, *etc*.).

Moreover, chemistry has demonstrated a remarkable capacity to describe phenomena in terms of molecular structure, to conceive facts in terms of molecular constitution and spatial arrangement of molecules. In fact, during the second half of this century advances in the understanding of molecular mechanisms of natural systems have been impressive. While one may give examples galore, suffice it to remember the discovery of the double-helix structure of DNA, through which the mechanism of transmission of hereditary characters has been explained, and the identification of the biochemical reactions that constitute the photosynthetic process. Undoubtedly, such an extensive comprehension of natural phenomena [2] has been possible thanks to the isolation and structure elucidation of molecules belonging to a great number of natural systems, molecules which (let us think, for example, of biomolecules) are often complex to a high degree.

Thus, the field of application of contemporary chemistry is wide, comprising different branches of biology, earth sciences, material sciences, and so on.

Naturally, at a given moment of history, the ability to explain facts in chemical terms is not unlimited: when, in very complex molecular aggregates, such as, for example, organelles, properties that are no longer explainable in chemical terms emerge from the whole of molecular interactions, a different scientific approach is needed. Such is possible thanks to the disciplines that are immediately higher than chemistry in the hierarchy of complex systems, *i.e.* cellular biology, pharmacology, genetics, physiology, *etc*.

A complete analysis of the historic, psychological, and methodological elements of the development of chemistry is beyond the scope of this paper. Undoubtedly, such elements are complex and not understandable only in terms of a utilitarian conception of science, according to which the growing need of society for new, useful materials would be the only *raison d'être* for chemical synthesis. As for the factors in the present stage of evolution of chemistry, I would just mention that the interaction with other sciences, *i.e.* physics and mathematics on the one hand, and biology and other natural sciences on the other, has indeed given a substantial boost to modern chemistry.[3]

Several interesting philosophical issues of chemistry emanate from a reflection on developmental aspects of modern chemistry. We have grouped our considerations into three main themes. In Sect. I, we shall point out how unexpected anomalies are the very essence of scientific research. They form the way to get detailed descriptions of phenomena that take into account more and more particulars, and thus lead to a deeper understanding of the physical systems under study, more and more conforming to the inexhaustible, abysmal complexity of the real, with its mysterious, original irreducibility. On this ground, we shall consider from a chemical viewpoint the idea of inexhaustibility, or bottomlessness, of the material being. We shall bear in mind this idea in Sect. II, where the problem of formation of by-products in chemical reactions will give us a clue to speak of the limits of human capacity for scientifically understanding, or describing, certain aspects of the physical world. In Sect. III, we shall propose arguments based on the accomplishments and advances of modern chemistry for a realistic interpretation of molecular structure.

I. The inexhaustibility of matter at the chemical level

1. Premise

In order to place the succeeding argumentation against a background of general epistemological, methodological and ontological assumptions, some principal features of modern sciences are outlined in the present paragraph.

Modern (Galilean) sciences rely on the application of experiments, conceived on the basis of explanatory hypotheses, through which, once he had placed a portion of matter under certain artificial conditions, the researcher 'puts nature some questions'. Thus, he is able to know, as far as quantity and relation are concerned, aspects of reality, thanks to mathematics, which establishes relationships between quantities by means of equalities, inequalities, equations *etc*. Chemistry falls into this scheme, though it makes use of largely non-mathematical formal instruments (pivoted on the fundamental concept of molecular structure) which were conceived through a very long process, which was to a large extent autonomous and independent of physics.[4]

On the basis of the experimental outcomes we note regularities, which we call laws, and elaborate models and theories, through which we are able, at least potentially, to reveal some aspects of the material systems under study. We formulate new explanatory hypotheses, thence devise experiments that can be applied to analogous systems, or even to systems with a higher degree of

complexity. In this way the progress of a scientific discipline is realized, that is we know more and more aspects of the physical world.

We cannot scientifically investigate reality as such. Therefore, as stated above, we examine portions of reality, usually referred to as *systems*, which, as far as possible, we must define in an unambiguous manner, and which we think of as being discrete parts of the universe. In practice they are something much smaller and less complex compared with the objects and phenomena we experience in everyday life.[5] The real is so complex that global scientific representations of too big or too complex portions of it are elusive.

According to the post-Newtonian view, the systems of the physical world belong to hierarchically ordered complexity levels. Upon perceiving reality on a rather fixed level of complexity every scientific discipline marks out a locus, from which the sensible, corporeal being is, at least in part, comprehensible by means of descriptions, models, or laws. That is to say, that the 'sense of matter' – as far as quantitative and relational aspects of a certain complexity level are concerned – is intelligible, its *congruousness*, its *orderliness* being recognized; *i.e.* form, proportion, and structure of this congruousness can be *approximately* determined.

Obviously, neither chemistry (or any of the other natural sciences), nor science as a whole can clarify a phenomenon completely:

> Any event […] is so rich that the words, by which we signify it, are always incapable to comprehend all its value. The event's truth is so thick that it cannot be exhausted by a single description […]. Therefore, the event can be read from different standpoints. There can be metaphysical, or also spiritual, sapiential readings besides a physical reading […] A reading does not exclude the other [Arecchi & Arecchi 1990, p. 35, my translation].

In other words, science is not the only way to understand the real. Thus, scientism is unacceptable:

> Scientism, presuming that an event must be described in one way only, *i.e.* physically, says that the limits of man's capacity for knowing the world coincide with the limits of science […]. Consequently, the world that cannot be scientifically observed is insignificant, in practice it does not exist. [Arecchi & Arecchi 1990, p. 33 and 47, my translation].[6]

2. The growth of synthetic chemistry and the inexhaustible novelty of matter

The advance of science is documented by the works published in many scientifically diversified international journals. 'Novelty of data' is the *sine qua non* in order that the results of an investigation may be published, which means being recognized as an original contribution to the total body of scientific knowledge. The words 'novelty' and 'novel' convey the idea of 'unusual' and 'unforeseeable', they connote something unprecedented, something unexpected. Data that are easily deduced from a methodologically and theoretically consistent set of known experiments do generally not fulfil the criteria of an original publication. Indeed, it is necessary to demonstrate their novelty (*cf.* the expression from the terminology of patent law: 'objection for want of novelty'). In other words, an unexpected event is essential, *i.e.* a response by the system under study one couldn't have foreseen on the basis of literature data.[7] For example, a synthetic chemistry journal would not accept for publication the synthesis carried out by standard procedures – *e.g.* synthesis of ethyl ester analogues ($RCOOCH_2CH_3$) of a series of known methyl esters ($RCOOCH_3$), even if the ethyl esters have never been described –, because the accomplishment of such a synthesis could have been easily predicted.

If we regard the substantial growth of modern synthetic chemistry against the background of such a strict requirement of novelty, we may conclude that, from a chemical-structural viewpoint, reality is extremely rich in novelty. In fact, the prolonged exertion of chemical inquiry has not resulted in the reduction of chances of making new discoveries.[8] On the contrary, the more compounds we prepare, the greater are our synthetic prospects; *i.e.*, a 'virtuous circle' has set up resulting in an exponential growth of chemical synthesis. In consequence, on preparing and analyzing so many molecules, the architectural complexity of which is astonishing sometimes, modern chemistry has shown that matter can be subjected to a huge number of transformations, a process which seems to have unlimited possibilities. In other words, matter has an impressive and potentially infinite structural, hence functional, diversity.

Modern physics perceives the bottomlessness of matter concerning the immensity of the celestial body on the one hand, and concerning the apparently endless possibility of disassembling the structure of the sub-atomic world, on the other. Unlike that, chemistry (and molecular biology) perceives the deepness, the inexhaustibility of matter in terms of the potentially infinite number of substances, which could be prepared, and of the organizational complexity of its microscopic components. Let us think, for example, of the process of protein folding, which results from the complicated, puzzling interplay of intramolecular forces. Let us think, above all, of the astounding complexity of the organization of the cell at the molecular level. Though detailed, inclusive descriptions of the functioning of living organisms in molecular terms are elusive, we are able to know by intuition the marvelous order existing at the biological level of matter:

> One should ponder the fact that life itself is a phenomenon which is strictly dependent upon the play of reaction rates, that is the rates of the innumerable, very complex, and often unknown reactions, on which the existence and the reproduction of every living organism, whether animal or vegetable, is based. [Silvestroni 1984, p. 300, footnote 5, my translation]

Besides being facilitated to perceive the abysmal complexity of the material being – an idea that has not only epistemological, but also metaphysical and religious implications (*cf*. Giussani 1997, pp. 50-51) –, chemists should easily become aware that matter does not lend itself to any kind of transformation. A synthetic scheme is realized only if matter 'consent to' that scheme; matter is not an amorphous bulk, over which we have complete domination.[9] In other words, matter undergoes changes only according to formal propensities, as if it had an intrinsic tendency towards well-defined forms. In a theological perspective, this seems to relate to Grotti's concept of 'formal vocation':

> Stating that things have a 'formal vocation' means excluding the possibility that the world consists only of 'useables', that things reduce to the way man wants to make use of them, that the meaning of things lies only in the practical view which, getting them included in its project, utilizes them. Things possess in themselves this 'formal vocation', independently of the project of the man who will, or will not, make use of them. It would be otherwise impossible to explain the 'resistance' that matter often offers to man's projecting choice, which obliges him to replace that choice sometimes […] Things resist because their being does not lie in their 'usability' alone […] they conceal something more profound, that is the imprint of their Creator, that which we may call their being present for themselves, independently of all references, of all the 'for' by which they can be circumscribed […] matter is not only blind resistance. If it were so, it would be negatively defined with regard to the transforming activity of man, it would be nothingness *per se*, it would be totally manipulable during the production process. Instead, matter 'is' something, it possesses a symbolic consistency of its own, it refers to something beyond itself, this reference being just announced by that resistance to human work, which acts at the same time as a guide and a method during the work by which nature is transformed. [Grotti 1988, my translation; see also Giussani 1997, pp. 100-104]

II. The vanishing points of the development of chemistry

In this section, starting with problems of formation of by-products in chemical reactions, I would like to speculate on some latent aspects of chemical development. At a given moment of history, both for practical reasons and because of the limitations of human means (see Sect. II.1 below), there is a limit beyond which a proper scientific examination of nature is hampered. Hence, the *factual* progress of the scientific understanding of nature is interrupted, though its *potential* evolvement (leading ultimately to a developmental depth, which the bottomlessness, the inexhaustibility of matter implies, and on which it would be interesting to speculate) is not.

1. The importance of individual and historical factors in the development of scientific disciplines

Scientific knowledge results from the interaction of two factors. The models, through which we are able to reveal, at least potentially, some aspects of the material being, are mentally developed on the basis of experimental data originated (*cf*. Sect. I.1) in the *interaction between the material systems under study and human scientific action (research).* Thus, the elements of the 'human factor' may affect our scientific view of nature.[10] Contemporary historiographical research has indeed realized that it is impossible to describe the evolution of sciences without considering the specific historical situations. Therefore, cultural values, practical interests, or even individual elements belonging to the researchers' personality may be significant.[11] Moreover, many important discoveries came from favorable circumstances (serendipity).[12] Lastly, scientific progress depends on materials researchers have at their disposal; *e.g.*, it is hard to imagine chemistry at a comparable state of development without the minerals of which the prisms of the spectrometers are made.

In brief: at one moment of history, science is a magmatic scenery, the irreversible development of which is affected by innumerable factors, among which are cultural, or even social and political factors.

That does not mean that scientific knowledge is totally produced by the social context. For that matter, I agree with Koyré, who, on

the basis of a "sufficiently realistic conception of the scientific knowledge" (Strumia 1992, p. 131, my translation) attributes a certain degree of autonomy from external factors to the scientific enterprise.

On the whole, I think the advance of scientific knowledge may be metaphorically compared to the exploration of an unknown, woody territory following interlacing paths, rather than to a trip on long, straight asphalt roads. In both cases, our possible movements are fixed, for we follow pre-existent routes. However, in the first case we must from time to time choose one of the many possible alternative itineraries, the choices being influenced by several factors.

2. By-products

In general, the isolation and structure determination of a compound is worth being published if the following conditions are met:

i. the description of the product adds a novel piece of information to previous knowledge;[13]
ii. the amount of product formed in the reaction outweighs a conventionally established value (actually, products whose yield is less than 1% are seldom reported in the chemical literature).

It is clear that, from an epistemological viewpoint, only condition i) is well-founded, whereas the range of weight, in which products are to be isolated from a reaction mixture, is just an option grounded in practical and technical considerations that are supported by rightful demands for social utilization of the scientific discoveries: "The main purpose, and the ultimate goal of organic chemistry are to provide society with substances which permit to ameliorate the lives of people, or restore people to health." (Rosini 1997, my translation). That is to say, according to current views, a product should be formed in such a yield that it can be used for practical aims or subjected to chemical transformation, *i.e.* it is regarded as starting material for the synthesis of other compounds. If a compound is formed only with a very low yield, the isolation of a quantity sufficient for analytical characterization would not be reconcilable with such views, as it might require a long time, a scale-up of the reaction being necessary. However, chemical research is motivated not only by utilitarian ends, although in the introductory section of chemical papers we often read a few sentences about actual, or potential applications of the substances studied therein. Most of the synthetic chemistry research originates from an intrinsic interest chemists have in increasing the number of new compounds, which seems to be an end in itself, rather than from the possibility that their discoveries will be applied.[14]

As for the lack of epistemological grounds for condition ii), one may object that products formed in very low yield relate to reaction pathways of minor importance, *precisely because* low amounts of those products were formed. However, a statement like this again rests in part on prevailing cultural values (*e.g.* the idea of profit) and, what is more, there are indeed several strictly chemical arguments against it.

1. If, under certain reaction conditions, a compound A gives, among other products, B in low yield, it may be possible that:

    a. the pathway leading to compound B becomes the main one on changing the reaction conditions (*e.g.* Lee *et al*. 1991);
    b. compound A', structurally related to A, gives under identical reaction conditions the corresponding product B' in high yield (*e.g.*, Lee *et al*. 1991; Wu *et al*. 1991).

    In brief, whether a certain reaction pathway is the principal one or not, may depend on reaction conditions, the use of a particular reagents, or catalysts.

2. Even from a practical viewpoint, a by-product may turn out to be more interesting than the main (and/or formerly desired) product (*e.g.* Mauragis *et al*. 1997).
3. One cannot exclude the possibility that compounds, which are interesting from a structural and mechanistic point of view, are present in complicated mixtures of unidentified products.[15] If formed in very low amounts, a compound may be a complex one, or it might have formed through nontrivial, not yet known mechanisms, some steps of which involve transition states with very high activation energies.[16] Of course, we could also find low amounts of compounds formed by a trivial, though energetically very unfavorable mechanism, as well as uninteresting by-products, whose low concentration can be easily explained by the law of mass action. However, the formation of by-products sometimes gives helpful hints on how to increase the yield of the desired products (see for example Maggini *et al*. 1991).

3. Conclusion

In sum, as concerns by-products, one may speculate that the chemical community, on acting solely according to methodological and procedural conventions or practical interests, which are legitimate of course, discards a huge amount of chemical information which, if it were ordered, might contribute to chemical knowledge.

However, our ability to study products formed in lower and lower yields is limited. To whatever extent reactions may be scaled up in order to isolate by-products, however powerful our analytical instruments may become, there will presumably remain a fathomless depth of reactions due to the myriad of products formed in infinitesimal quantities, which we will not be able to say anything about. This kind of considerations might be cautiously generalized. Apart from cultural customs, prevailing opinions, *etc*., which may prevent us from observations that might improve our scientific understanding of the world, there is an intrinsic limitation of our human nature. For practical reasons we are not able to investigate extremely reduced systems properly at the chemical level, or to study phenomena whose dimensions are too minimal.

What is more, I think one cannot exclude the possibility that minimal unfathomable structural elements generate, modify, or influence properties of systems on a higher level of complexity, *e.g.* the macromolecular or cellular level – provided that variations of these elements are adequately amplified through ordered structures, so that minimal pieces of information can be transmitted to higher levels and eventually turned into macroscopic effects. In fact, organic and medicinal chemists often experience that minor structural changes in molecules cause remarkable effects on chemical reactivity and biological activity, respectively. Reasonings based on classical chemical concepts, such as ‘steric hindrance’, ‘lipophilicity’, ‘bond polarization’, ‘electronegativity’, *etc*., do not always account for these effects. Anyway, this should not be surprising, if we but keep in mind that certain hormones are active, *i.e.* they produce physiological responses, at 10^{-12} M concentrations! In brief, if we are concerned with highly organized, complex systems, such as biological systems, unfathomable structural elements may be no longer negligible.

III. The evolvement of contemporary chemistry and the realistic interpretation of molecular structure

The metaphysics of molecular structure, *i.e.* the question about the objective reality of microscopic entities called ‘molecules’, whose parts are framed in a manner the classical chemical structural representations analogically[18] display, is a problem of central importance for a philosophical understanding of chemistry. The notion of molecular structure, according to which a molecule is made up by a fixed number of atoms of one or more kinds corresponding to a definite composition, which are linked in a well-defined manner, bond lengths and angles being precisely defined as well,[19] has been questioned by some quantum chemists,[20] even though with Born-Oppenheimer approximation quantum mechanics is in fact not in conflict with the classical notion of molecular structure. A recent paper of Del Re (1998) deals at length with this issue, giving sound arguments in favor of the real existence of molecular structure and molecular shape. Along this direction of thought, I would like to point out two arguments that in my opinion seem to be strong evidences in favor of a realistic interpretation of molecular structure: First (Sect. III.1), structure elucidation results from the application of different analytical methods to the same system (the substance to be analyzed). Secondly (Sect. III.2), very different natural phenomena can be interpreted in terms of molecular structure. Both of the two arguments gain support by the growth of contemporary chemistry.

1. Structure elucidation results from the application of different analytical methods to the same system

In order to state that an unknown, pure substance possesses a definite structure (‘to describe a compound’ is the current expression of chemical terminology) an unambiguous convergence of results from different analytical methods is needed. That is why nearly all synthetic chemistry journals require at least an elemental analysis as well as a ^{1}H-NMR spectrum for each new compound prepared, and why additional data sets of IR and mass spectrometry are preferred. Actually, when a compound is subjected to analysis by means of instrumental techniques based on *completely different* principles, it gives results which, in the frame of the classic notion of molecular structure,[19] are consistent with each other. Thus, different techniques are nowadays "most commonly employed *collectively* to establish [molecular] identity" (Hardcastle 1998, my emphasis).

It is worthwhile to pause upon the differences between the analytical procedures most commonly employed to investigate chemical structure. On the one hand, there are spectroscopic methods based on the absorption of radiant energy corresponding to the transition between distinct energy states, such as IR, NMR, and UV spectroscopy. On the other hand, there are mass spectrometry and elemental analysis based on principles which are completely different from those of absorption spectroscopy. Mass spectrometry utilizes the chemical processes, namely the formation of ions and their successive fragmentation (which is indirectly determined by measuring the molecular weight of the gaseous fragments), after the sample has been subjected to vaporization and electron impact (EI).[21] In elemental analysis, which is also a degradative method, the sample is combusted and the resulting amounts of water, carbon dioxide (as well as other compounds, depending on which elements are present in the substance) are determined.

Among further analytical methods, we should at least mention the degradative method of structure deduction by means of reasoning based on chemical behavior. Though it has been supplanted by modern spectroscopy, it is historically significant. This method is exclusively grounded on chemical properties of substances. Chemists used it, not seldom brilliantly, in order to establish the structure of sometimes very complex natural compounds. In supporting the argument of the present Section, the results obtained by means of such degradative procedures have been confirmed by instrumental analysis.[22]

As far as geometrical features and thermodynamic data (such as bond distances and angles, enthalpies of formation, conformational preferences, and so on) are concerned, theoretical calculations[23] and the results coming from experimental approaches, such as NMR and IR spectroscopy, X-ray diffraction, *etc*. are often comparable.[24] In brief, on applying *different* methods to the *same* system we obtain primary results that are unlike in kind or character (*e.g.* the 'external' appearance of a set of numbers from a computer calculation is quite different from, say, an X-ray map, which is in turn different from an NMR, or mass spectrum). Nonetheless, we can interpret these results to give structural representations that, in general, are consistent with each other.[25]

Owing to the growth of synthetic chemistry, the structure of an impressive number of molecules has been determined. The process of structure elucidation takes place every day in the laboratories all over the world where classes of molecules with totally different structural features are studied. Resulting from such a huge analytical effort, there is, as it were, an overall congruity of structural data.

2. The interpretation of natural phenomena in molecular terms

Undoubtedly, the studies aimed at defining the interactions and spatial arrangement of molecules in numerous physical systems, which in most cases are very different from one another in nature and dimensions, have increased our understanding, thanks to the late developments of chemistry. This was particularly in connection with i) the theoretical and technological advances in the field of purification methods, thanks to which the isolation and the identification of a great number of natural compounds have been possible; and ii) the physical and mathematical refinement of chemical notions,[3] which has led to a more profound knowledge of the structural features (*i.e.* geometric, electronic, and energetic properties) of molecules.

As a consequence, today we are able to rationalize a variety of material properties of substances in terms of molecular structure. For example, we can explain how, in a series of homologous hydrocarbons, the melting (or boiling) points vary according to molecular weight, or, in a series of isomers, to the degree of branching; we can give a valid explanation for the color of the sky, the antiknocking properties of globular molecules like tetraethyllead, the difference between the macroscopic characteristics (*i.e.* stretchability, elasticity, tensile strength, and softness to the touch) of wool and silk.[26] We also better and better understand chemical reactivity, both by means of coarse, non-formalized structural concepts, such as 'steric hindrance', 'nucleophilicity', *etc*., and by sophisticated computer modeling of transition states. Moreover, as already mentioned in the Introduction, nowadays we are able to describe and interpret a great many different natural processes consistently in molecular terms, among which photosynthesis, transmission of hereditary characters, aging of documents depending on the type of paper and ink, *etc*.

3. Conclusion

The conspicuous convergence of observations and experiences that we have just outlined is, in my opinion, a fact of philosophical consequence, as it disproves the instrumentalistic conceptions stating that science gets models with which, at the most, one is able to make predictions, while real aspects of the objects under study cannot be known. Indeed, an anti-realistic interpretation of molecular

structure provides no explanation of the fact that we can consistently interpret or explain events of so different nature, and/or dimensions, by means of chemical theories grounded upon the classic concepts of molecular structure and shape.[27]

In addition, the fact that analytical methods depending on totally different physical principles give results that converge at identical descriptions of molecular structure supports the steady consistency that the objects, we call 'molecules', have in responding to dissimilar actions done on them from the outside. In other words, molecules are not provisional appearances originating in the interaction between theory (and the experiments based on it) and matter. If it were so, one may reasonably suppose that experimental methods based on different principles give results not consistent with each other. The phenomenalistic conception of science leads one to believe that every observation is distorted "by a theory of the object that is to be observed, a theory on whose basis the experimental instrumentation is devised. As a consequence, that which one observes is not the real in itself, but the phenomenon resulting from the interaction between theory and fact. Carrying this idea to extremes Feyerabend conceives what we call an *experimental fact* as chiefly determined, in its informational content, by the theory that frames and interprets it. An experimental fact actually is a *theoretical fact*, since it can be conceived only through an *observational language*; if we changed this language, the fact would be no longer interpretable and comprehensible." (Strumia 1992, pp. 169-170, my translation, italics in the text). That is tantamount to saying that, according to the phenomenalistic theory, the material being is something undifferentiated, something easily moldable by the experiment.[28] Accordingly, one could reasonably assume that different methods would give correspondingly different forms to the objects under examination, and this would result in incomparable, or even contradictory results. However, if we but consider the acquirements of contemporary chemical research (see above), it is much sounder to admit that matter possesses a *real* structure at the molecular level, a structure which a suitable chemical investigation, conceiving a veridical image of molecules, describes, albeit *approximately*.

I would like to remark on this last word;[29] stating that matter possesses a real structure at the molecular level does not mean that actual molecules are somehow reducible to any of their structural models, for a model is after all only an abstract, simplified representation conceived mentally. Unavoidably, as H. Belloc once briefly stated, "consciousness [of matter] is not material."[30] The whole truth of the physical objects called molecules is something fathomlessly complex, as is the reality of any physical object – if only owing to the fact that it is a portion of matter assembled in a complex way, the basic units of matter (the famous 'atoms and quanta') being themselves characterized by a remarkable and apparently elusive degree of complexity, as modern physics has indeed shown. As for molecules, they are not something 'stiff', but possess an 'inward dynamism'. A molecule may be characterized as a system consisting of a dynamic equilibrium between a potentially infinite number of conformers, some of which energetically favored. A molecule may be also characterized by a set of distinct energy levels, so that changes in the environmental conditions (*e.g.*, when energy is supplied from the outside) may result in transition from a rotational, vibrational, or electronic ground state to an excited state or even in a change of the energy levels. It is worthwhile remembering that the question of the validity of quantum descriptions of molecules based on Born-Oppenheimer theorem has been raised in connection with the dynamics of molecules.

We also ought to keep in mind that, unless we consider an ideal gas, *i.e.* an imaginary, abstract model, it is not possible to conceive of molecules as being isolated individual entities. Although a highly rarefied gas may be considered practically ideal, the interactions between its molecules being minimized, most of the systems chemical research deals with are in the liquid or solid state. In reality, an extremely rich organizational (hence functional) state at the microscopic level, resulting from the participation of molecules in the formation of quasi-molecular species, *i.e.* molecular aggregates formed through hydrogen bonds, van der Waals forces, *etc*., is characteristic of condensed matter. Hence, the idea of molecules as individual entities leads *de facto* to considerably simplified explanations of phenomena.

Clearly, molecular representations like structure formulas, but also pictographic representations including geometric details about angles and distances do not take into account, do not tell us anything about the aspects we have just surveyed: they only give a rather *approximate* description of a molecule. Nonetheless, as far as relational and quantitative aspects are concerned, they do say something about the ontology of molecules. In this regard, a metaphor, which has also been proposed by Del Re (1988), may be used: a photograph of a man (let us call him, say, Marco Bianchi) cannot define his personality, tell us the vicissitudes of his life, or reveal what percentage of his blood cells are red corpuscles. Yet, it would be absurd to deny that some real features of Mr. Bianchi are reproduced on it. Thus, the photograph is the vehicle for conveying true aspects of the personal reality of Marco Bianchi to our consciousness, the 'amount of reality' carried depending upon the quality of the photograph itself. Even a fuzzy photograph could still provide us information about Mr. Bianchi, for instance making us known of his height, build, *etc*.

This metaphor may also hint at the inconsistency of the claim that scientific ideas are mere instruments of prediction, objective reality being not reflected on them. If a friend of Marco Bianchi saw the Eiffel Tower standing out against the background of our photo, he should infer that his friend had visited Paris one day. Now, such an inference entails an act of identification, that is, Marco Bianchi

must be recognized in the photograph. In other words, the correspondence, the assimilation between a portion of the physical reality and the image obtained when that portion of reality is exposed to the photographic process is granted. Interestingly, the verb 'to recognize' comes from the Latin word '*recognoscere*', a word formed from the root '*gnosco*', '*nosco*' (to come to know, know) by the addition of the prefixes '*re-*' ('back', 'again', 'against') and 'co-' (from '*cum*', 'with'). At least etymologically, recognition means that one comes to know again.

Notes

[1] See Schummer 1997 and references therein.

[2] Of course, the understanding of natural phenomena in chemical terms is a process under constant refinement, for the molecular machinery to be examined is often highly complicated from a molecular-structural viewpoint. This is not surprising, given the complex nature of the overall processes to be achieved especially when biological processes are concerned. As for the chemical understanding of natural photosynthesis, for example, important advances in the comprehension of the two fundamental functions from the viewpoint of energy conversion, namely photo-induced charge separation, and energy migration in the so-called light harvesting antenna system, have been possible thanks to detailed structural information about reaction centers and antenna units. This kind of information has become available only in recent years; see the nice paper by Scandola *et al*. (1995).

[3] This will be the subject of a future paper.

[4] See Del Re 1994. For a general history of chemistry see, for instance, Leicester 1956; for a history of chemical theoretical thought see Solov'ev 1971.

[5] Suffice it to think, for example, of the neurobiological studies on memory (see Battaini and Govoni 1993). The very complex psychological and neuronal phenomena, of which learning and memory consist, are studied in terms of relatively simple synaptic events like long term potentiation (LTP) and depression (LTD). Also, one of the experimental models with which memory is studied is a marine snail called *Aplysia Californica*, whose nervous system consists of 20,000 neurons (human brain contains 1,000 billion neurons!)

[6] These themes are extensively treated in Strumia 1992.

[7] An interesting article by Bersanelli (1997) deals with the part the unforeseen event (*l'imprevisto*) plays in scientific discovery.

[8] This also applies to the other sciences of course.

[9] *Cf*. also Sect. III. 3.

[10] "Let us be aware that, however impossible it is to encounter such a thing as 'raw datum', our constitutive concepts had not emerged *ex nihilo*. They are the product of the active coping of our species with a reality irreducible to itself. Our ideas, at least our saner and more successful ones, bear always the impress both of ourselves and something beyond ourselves." (Sheehan 1981). See also Lorenz 1973 and Giussani 1997, pp. 23-33.

[11] As concerns chemistry, see the biochemical example of the digestion of the proteins in the gut, which is reported in the recent work by Akeroyd (1997). See also Del Re 1997, who has pointed out how the personal element is involved in scientific activity.

[12] As for this point, a telling (and pleasant to read) example is the discovery of radical deoxygenation (the reaction of Barton and McCombie); see Barton 1993, pp. 34-45. For another interesting example concerning benzodiazepines, see Sternbach 1977.

[13] This may also occur indirectly: though trivial *per se*, the preparation of a compound will be in fact published, if it forms part of a synthetic sequence of which some steps imply a novelty; or also, as usually happens in medicinal chemistry, when the novelty does not lie in synthetic aspects, but in the molecular description of the interaction between products and enzymes, receptor proteins, *etc*.

[14] See Schummer 1997. By the way, some chemists seem to guess at the thing: "The collection of reagents and reactions one can make use of, when planning a synthetic strategy, is now huge, and (often without any substantial justification) it continues to be enriched." (Rosini 1997, my translation).

[15] For example the isolation of several products in low yield enabled Moody and co-workers to elucidate reaction pathways of thermolysis of dienyl azides (Moody *et al*. 1985). Products formed in 1 % yield made possible the determination of the structure of a spiro dimer from methyl 2,3-Bis(chloromethy)thiophene-5-carboxylate possible (Takeshita *et al*. 1991). Davies and co-workers were able to rationalize the effect of the solvent on the rhodium(II)-catalyzed decomposition of vinyldiazomethanes in the presence of 1-methoxy-1-[(trimethylsilyl)oxy]buta-1,3 diene, leading to tropone derivatives, thanks to the observation of certain by-products (Davies *et al*. 1991).

[16] For example the palladium-catalyzed carbonylation and coupling of 1,2-dibromocyclopentene and aniline yields, among expected products, a dimer of the desired N-phenylimide derivative, the structure of which is unknown (Perry *et al*. 1991).

[18] For the role of analogy in the scientific knowledge see Del Re 1998, in particular sect. B.4; for a more extensive discussion see Strumia 1992, pp. 229-242.

[19] Here we shall not take into account the distinction, made by Schummer (1998), between structure formulas, to which the first part of our definition corresponds, and pictographic, geometrically detailed representations of molecules; although these two ways of describing molecular structure have a different linguistic significance, we shall assume that the two signs are different modes to look at the same object (*cf*. also the second part of footnote 25). This assumption seems to us a reasonable one, considering that, albeit a piece of information not stored in structure formulas, the geometrical characterization of a molecule *presupposes* an unambiguous spatial ordering of the parts which constitute the molecule itself, and this is precisely what structure formulas tell us. Moreover, on speaking of the possibility of a translation between the two languages, the author of the above paper, among other things, states that "the relative success of such translations […] gives at least some evidence of a common referential basis of the underlying theories of both type of representations."

[20] See for example Woolley 1978.

[21] EI has been the ionization method most commonly employed until now; however, many other ionization techniques are available today.

[22] The story of morphine structure elucidation provides a beautiful example in this regard; *cf.* Butora *et al.* 1998.

[23] Including both molecular orbital calculations (either *ab intitio* or semi-empirical methods) and the so-called molecular mechanics (or force fields calculations): again, methods which are theoretically different from one another, inasmuch as they make use of different mathematical models of molecular structure (though they all rest upon the classic notion of molecular structure, *cf*. the latter part of footnote 24).

[24] See for instance Bock *et al*. 1974 and Buyong Ma 1995. For a more specific example see Tontini *et al*. 1998. One may object, following for example Woolley 1978, that the kinds of quantum chemical calculations I consider here are in fact grounded on the classical theory of molecular structure, inasmuch as they make use of the Born-Oppenheimer separation of electronic and nuclear motion, hence they do not represent a 'pure' quantum mechanical approach to molecules. On the other hand, the above mentioned methods, inasmuch as theoretical, are in essence a kind of procedure different from empirical approaches, even if they all presuppose the classic notion of molecular structure as a common referential base. In fact, on the one hand we need only an algorithm to treat mathematical models of molecules computationally; on the other, a sample of substance is subjected to a physical action (data being subsequently treated according to theory, of course). It is on these grounds that I consider of interest the convergence of results mentioned in the text.

[25] Yet, occasionally, when applied to the same system, different methods, whose validity is unquestioned among the members of the chemical community, give responses apparently not reconcilable with each other. The determination of the microscopic structure of water is an interesting example (Benson & Siebert 1992; see also Bertagnolli 1992). With regard to apparently contradictory results, we might think to a town lying between two hills. Two completely different images of the *same* town will come into view from each of the two hilltops. If we took photographs from each hilltop and showed them to a stranger, he would say, perhaps, that those are views

of two different towns, unless he is clever at finding common elements, which may be hidden through perspective phenomena.

[26] Chemically speaking, both materials are proteinaceous substances.

[27] The latter point may be related to the general 'argument for the best explanation', a type of reasoning used by some contemporary American philosophers of science (for an anthology covering *inter alia* some articles about this kind of argumentation see Leplin 1984). Interestingly, such an argument was first applied by Berzelius to chemistry, in that he reasoned that the law of multiple proportions would be a miracle without accepting Dalton's atomism (J. Schummer, personal communication).

[28] Incidentally, starting from a reflection on the actual possibilities of synthetic chemistry, we have already come to a conclusion disproving such a conception of matter (*cf*. Sect. I.2).

[29] *Cf*. also the latter part of Sect. I.1

[30] *Cf*. Belloc 1992, sect. 3.ii.

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