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Research Article

An Investigation into the Role and Importance of Three-Dimensional Representations through an Analysis of Late 19th and Early 20th Century Chemistry Textbooks

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Abstract. Graphic representations of three-dimensional structures play a pivotal role both in academic research and chemical education. Nevertheless, their deceptive simplicity can lead school and even university students to an incorrect understanding of these representations that are central for both organic and inorganic chemistry. A deep knowledge of their symbolic meaning is, indeed, essential to avoid a meaningless learning of the discipline. Two important historical examples, the three-dimensional representations of tetrahedral carbon and the geometry of metal complexes, are discussed in this paper. More in detail, this work investigates the way in which these three-dimensional formulae were received and presented in school and university textbooks published in the late 19th and early 20th centuries, before the introduction of techniques of structural investigation such as X-ray crystallography. Given the difficulty of finding all textbooks published in that period worldwide, the creation of a freely accessible database is also encouraged. Generally underestimated in historical investigations, old chemistry manuals are, in fact, essential to understand how the discipline has been taught in the past.

Keywords: three-dimensional representations, symbolic level, chemistry manuals, tetrahedral carbon, metal complexes.

As soon as humans started using signs and symbols
to represent the natural world,
they pushed beyond the limits of that world.
Elizabeth Kolbert, The Sixth Extinction: An Unnatural History, 2024.

INTRODUCTION

A fundamental problem in the field of teaching and learning chemistry is well exemplified by the so-called Johnstone's triangle, an influential content model in chemistry education (Figure 1).[1, 2, 3, 4]

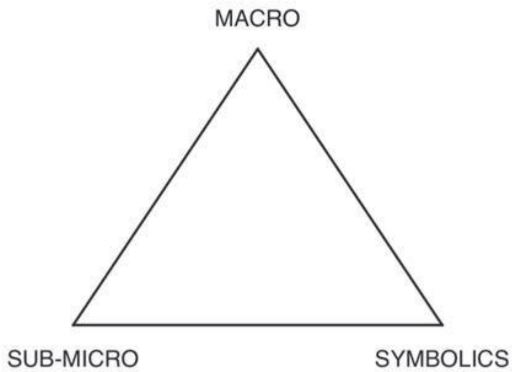

Figure 1. The Johnstone's model, also referred to as *Chemistry triangle*.

Alex Johnstone (1930-2017), one of the most highly regarded chemistry educators[5], highlighted that the difficulty of achieving a meaningful understanding of chemistry often arises from the non-clear distinction between the three levels on which chemical knowledge is based: the macroscopic level, the sub-microscopic level and the symbolic level.[*] As he pointed out: «It is psychological folly to introduce learners to ideas [of chemistry] at all three levels simultaneously. Herein lies the origins of many misconceptions».[6] Johnstone's triangle remains at the core of chemical education. However, other authors, such as Peter Mahaffy, Jesper Sjöström and Ingo Eilks, have expanded this model over the years, by pointing out that it lies at the basis of a more complex tetrahedral structure of chemical knowledge. According to these more recent didactic models, such a tetrahedron highlights other important aspects that should be taken into consideration in chemistry education, such as human and social aspects.[7, 8, 9, 10, 11]

Three-dimensional graphic representations of chemical structures are especially relevant to chemical education, due to their contextual reference to both the symbolic and sub-microscopic vertices of Johnstone's triangle.

The symbolic is the level at which chemists use graphs and drawings to convey their mental image of the structure of a chemical compound, while the sub-microscopic level refers to the actual spatial arrangement of atoms, molecules, electrons etc. and their behaviour. The third level, the macroscopic one, is related to observable properties of substances. A distinctive feature of this area of research is the fact that graphic illustrations, relating to the symbolic level, were introduced by chemists long before the advent of experimental techniques that enabled a deep understanding of the submicroscopic level of matter.

Chemistry has an intensely visual character[12] and Nobel laureates Roald Hoffmann and Pierre Laszlo pointed out that chemical structures are in some ways trademarks of a chemist's profession, even if their deceptive simplicity can be misleading.[13] In general, students find it difficult to understand the correct meaning of these graphic representations and the connection they have with the microscopic level.[14]

In this paper, I focus my attention on the symbolic meaning of three-dimensional representations, trying to understand when they first appeared in chemistry manuals and what sense was attributed to them. I have analysed both graphic representations of tetrahedral carbon, an important topic in the field of organic chemistry, and those of metal complexes, a central aspect in inorganic chemistry. The first step of this work was to find old chemistry manuals from the late 19th and early 20th centuries; this was done by exploring public and private libraries, as well as digital sources.[15, 16, 17, 18, 19] Subsequently, some of the most well-known and widespread manuals of that period were selected and analyzed (see Appendix), on the basis of the presence in the text of a reference to the subjects discussed in this paper, following a chronological approach. Special attention was also devoted to Italian manuals. Thirdly, conclusions were drawn relative to four main issues:

- the speed with which textbooks have incorporated the findings of chemical research;
- the educational role of graphic representations of chemical structures;
- the meaning attributed to these drawings and their relationships with the reality of matter;
- the usefulness of graphic representations as means for reasoning and interpreting empirical evidence.

This work does not claim to be truly exhaustive, given the vastness of the subject and the difficulty of exploring all the manuals published internationally in that period. In addition to this, sometimes the same edition of a manual was published in several languages, with the addition of new contents.

TETRAHEDRAL CARBON

van't Hoff and Le Bel's Independent Proposals

At first, I focus my attention on the first graphic representations of tetrahedral carbon. In 1874 the Dutch chemist, Jacobus Henricus van't Hoff (1852-1911) and the

[*] Johnstone defined the nature of chemistry as follows: «I believe that it exists in three forms which can be thought of as corners of a triangle. No one form is superior to another, but each one complements the other. These forms of the subject are (a) the macro and tangible: what can be seen, touched and smelt; (b) the sub-micro: atoms, molecules, ions and structures; and (c) the representational: symbols, formulae, equations, molarity, mathematical manipulation and graphs».[6]

French chemist, Joseph Achille Le Bel (1847-1930), while working independently, made a proposal for the structure of the tetrahedral carbon that was decisive in enabling the rationalization of optical activity, meaning the rotation of the plane of polarised light, in organic compounds.[20, 21, 22] The two young scientists, in a way, had the ability to imagine a three-dimensional microscopic world, before the advent of any instrument that permitted the exploration of the ultimate structure of matter.

In his doctoral dissertation, summarized in a pamphlet printed in Dutch in September 1874[20], van't Hoff introduced three-dimensional representations of tetrahedral carbon, referred to as asymmetric carbon atom. The text was later translated into French and published in the *Archives Néerlandaises des Sciences Exactes et Naturelles*.[21] An abridged version of this work was published in March 1875 in the *Bulletin de la Société Chimique de Paris*.[23] The first edition of van't Hoff's most famous volume, in which his hypothesis of asymmetric carbon was treated in greater detail, was first published in French in May 1875 under the title of *La Chimie dans l'espace*[24], later translated into German in 1877 with some additions.[25] In the German edition there is a preface by the German chemist Johannes Wislicenus (1835-1902), one of the earliest and strongest supporters of van't Hoff's hypothesis. On the other hand, Wislicenus himself in 1873 had reached very similar conclusions[26] and his ideas seem to have inspired van't Hoff's theory. After this book, van't Hoff's ideas were more widely disseminated.[27] This text went through several editions and about 10 years later, in 1887, it was republished in French under the title *Dix années dans l'histoire d'une théorie*[28] and in 1891 in an English version, under the title *Chemistry in Space*.[29] In this new edition of the text, van't Hoff himself underlines that the presence of his hypothesis in the most popular chemistry textbooks of the time is the most tangible proof of the fact that the theory of asymmetric carbon is spreading rapidly. The English edition says (p. 19): «A more conclusive sign of approval still, it appears to me, is to be found in the fact that the theory in question now forms part of elementary chemical teaching, and is to be found enunciated in the most widely used textbooks». van't Hoff made extensive use of perspective drawings of asymmetric carbons in his publications and prepared even cardboard tetrahedral models which were sent to well-known chemists to help them visualise the relationships between various *physical isomers*, the chemical compounds which are now known as *stereoisomers*.

Le Bel proposed, independently, a tetrahedral structure for carbon atoms in compounds showing optical activity, but as a result of purely geometrical considerations on molecular symmetry and following a more abstract reasoning. His aim was to find a general rule that enabled predictions of the existence of optical activity in chemical compounds on a structural basis. Le Bel's paper was published in French in November 1874[22], but unlike van't Hoff he didn't use three-dimensional drawings or models to illustrate his ideas.

At first, the idea of a tetrahedral carbon didn't meet with a cordial reception amongst chemists. [30] As time went on, however, van't Hoff's proposal of asymmetric carbon atom has become widespread in chemistry and had the greater impact on the subsequent development of stereochemistry, in comparison with Le Bel's. It has been argued by Grossman[31] that it could be due to different reasons. First of all, it was much easier to understand and assimilate and van't Hoff was a well-known chemist who made significant contributions to other fields of chemistry, while Le Bel was not so famous in the scientific community. In addition to this, van't Hoff's structural ideas were much more useful for determining the number of isomers of a particular compound, an important endeavour at that time.

Chemistry Textbooks and First Graphic Representations of Tetrahedral Carbon

Starting with the quotation above from the 1891 van't Hoff *Chemistry in Space*[29], I have found that in some manuals of that period, that have been examined (see Appendix), only a reference to the theory of asymmetric carbon appears in the text but no three-dimensional representations are present. I have focused my research on textbooks where, in addition to a textual reference, there are graphic representations of tetrahedral carbon.

In chronological order, among the first textbooks with three-dimensional representations, there is one written by Carl Schorlemmer (1834-1892), a German chemist nicknamed *the red chemist*[**], who from 1874 was Professor of Organic Chemistry in Manchester.[32] The first edition of *The Rise and Development of Organic Chemistry* was published in 1879.[33] Schorlemmer was very interested in the history of chemistry and his manual is a masterpiece on the history of organic chemistry. In this textbook, he refers to the Le Bel and van't Hoff hypothesis of atoms in space (p. 96) and uses three-dimensional representations of tetrahedral carbons.

As far as chemical representations are concerned, in the text the author uses the expression *graphic formulae,* with reference to bidimensional graphs representing the position of the atoms in one plane, and *glyptic formulae* to describe three-dimensional drawings and solid models.

[**] Schorlemmer was known as the red chemist because of the close friendship that bound him to both Karl Marx and Friedrich Engels.

He explains that (p. 67): «For lecture and class illustration, solid diagrams are often used, consisting of wooden balls of various colours, to represent the atoms, having holes for the insertion of connecting rods, which Kekulè first proposed. These representations are called *glyptic formulae*». These *glyptic formulae* are employed in the manual to show the structure of the succinic acid, where carbon atoms are linked via single connections, and to provide a possible explanation for the isomerism between fumaric acid and maleic acid, two organic compounds containing double linked carbon atoms (Figure 2). This is the kind of isomerism we refer to as geometric isomerism or *cis-trans isomerism*; using a modern terminology, the fumaric acid is the *trans* isomer, while the maleic acid is the *cis* one (Figure 3). The author underlines that these formulae in space, containing one or more asymmetric carbon atoms, have been introduced by van't Hoff. In these three-dimensional drawings, a carbon atom is represented as a tetrahedron, its four combining units being represented by the angles. Hydrogen atoms (H) and carboxyls (CO_2H) are the units linked to the carbon atoms via single linkages. A single connection between carbon atoms is represented by a common vertex, while double connections are represented by two tetrahedrons with one edge in common.

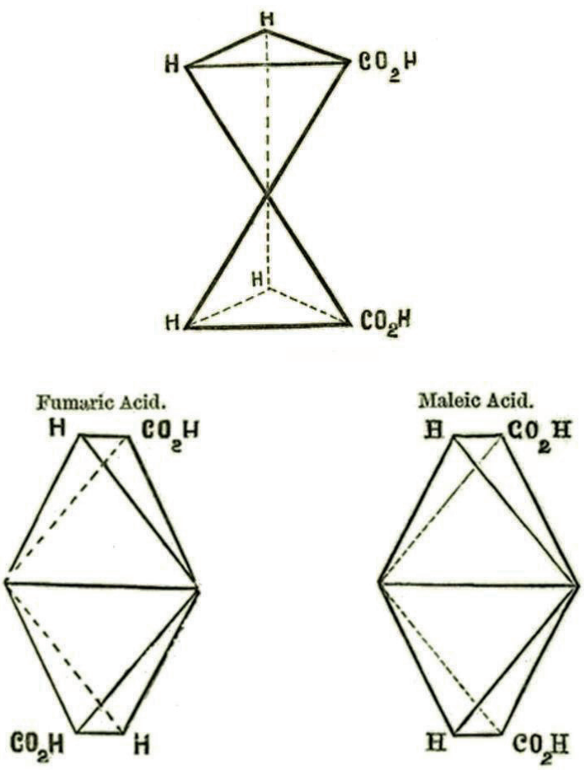

Figure 2. Three-dimensional representations of succinic acid (above) and fumaric acid and maleic acid (below) as found in Schorlemmer's manual (p. 97).

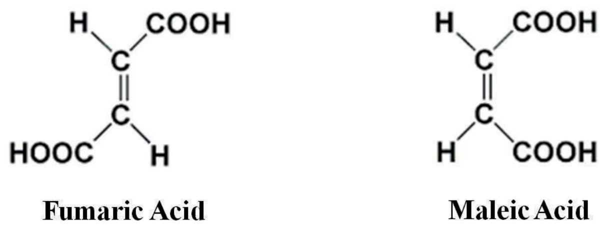

Figure 3. Representations of the two geometric isomers, fumaric acid and maleic acid, according to modern conventions.

The solution of the structural enigma concerning maleic and fumaric acid could be an interesting example of what has been previously mentioned in relation to the Johnstone triangle and the pre-existence of the symbolic level in the field of three-dimensional representations. In fact, van't Hoff's structural hypothesis, exemplified by the graphic structures present in Schorlemmer's manual (Figure 2) referred to a purely theoretical and symbolic level and had been proposed to account for unexplained relations existing between maleic and fumaric acids. It predated the work of Wislicenus, published in 1887[34], where the German chemist presented some experimental observations that could be taken as strong proof of the correctness of the geometrical formulae assumed for maleic and fumaric acids. With this publication, in a way, Wislicenus gave the final impetus on the acceptance of the theory of tetrahedral carbon.[30] In the Schorlemmer manual (p. 98), there are also two-dimensional formulae where asymmetric carbons are marked with a circle (Figure 4) and not with an asterisk as we are used to seeing them nowadays.

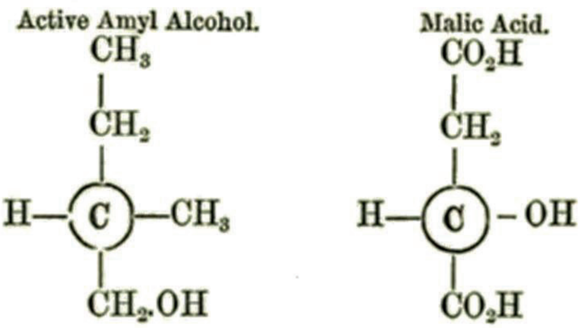

Figure 4. Asymmetric carbons as highlighted in Schorlemmer's manual.

A few years later, another fundamental textbook was published in English by Henry Enfield Roscoe (1833-1915) together with Schorlemmer. Roscoe was a British chemist and had worked under the supervision of Robert Bunsen (1811-1899) at Heidelberg.[35] He was Professor of Chemistry at Owens College in Manchester and Schorlemmer was his assistant there. *A Treatise on Chemistry* was a textbook for tertiary students and for a long time was considered a standard for teaching chemistry. Four different volumes of this text have been published over the years. Volume III is on *The Chemistry of the Hydrocarbons and their Derivatives, or Organic Chemistry*; Part I of this volume was published in 1881[36] while Part II was published in 1884.[37] The two authors use a historical approach both in presenting organic compounds and their discoveries as well as chemical theories and their evolution, adding interesting citations even from Pliny the Elder. In Part I, there is a reference in the text to the hypothesis of the *assymetric* [sic] *carbon atoms* (p. 127) and there are two examples (amyl alcohol and malic acid) where these carbon atoms are circled, as previously said referring to the manual of Schorlemmer. In Part II of this volume we can find the same graphic representations already present in Schorlemmer's manual. After presenting van't Hoff's hypothesis *of considerable probability*, these spatial formulae are used for representing succinic acid and to explain the isomerism between fumaric and maleic acid (p. 216). A reference to tetrahedral structures is also made in the text for the tartaric acid isomers (p. 237).

Two similar manuals with three-dimensional representations of asymmetric carbons appeared in the United States. Ira Remsen (1846-1927), the author, was an American chemist, professor at John Hopkins University and the founder of the American Chemical Journal.*** Remsen is also remembered for the fact that in his lab, the Russian chemist Constantin Fahlberg (1850-1910) produced the chemical compound that was later known as the artificial sweetener saccharin. The first manual was published in 1885 and is about organic chemistry[38], while the second is perhaps Remsen's most famous text, entitled *The Principles of Theoretical Chemistry.*[39] The textbook published in 1885, *An Introduction to the Study of the Compounds of Carbon; or, Organic Chemistry,* presents (p. 164) graphic structures for two tetrahedrons, mirror images of each other (Figure 5). In the text, the author explains these drawings by saying: «Let us suppose that in a carbon compound one carbon atom is situated at the centre of a tetrahedron, and that the four atoms or groups which it holds in combination are at the angles of the tetrahedron as represented in figure».

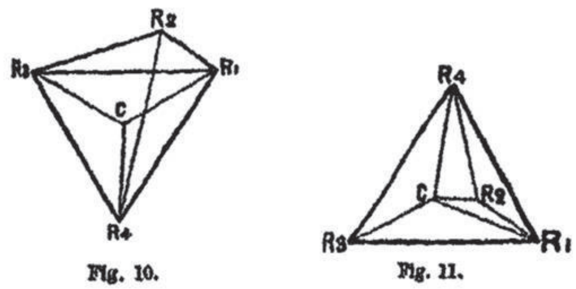

Figure 5. Graphical representations of tetrahedral carbon as found in Remsen's manual published in 1885.

The first edition of the other Remsen manual, *The Principles of Theoretical Chemistry,* was published in 1877, but in this volume there is no reference to van't Hoff's hypothesis. The second edition of the manual was published in 1883. In this second edition there is a reference in the text to the hypothesis of the asymmetric carbon atom, referred to as *a suggestion*, but there is no graphic representation. The first three-dimensional representations of tetrahedral carbon appear in the third edition, published in 1887[39], for the *physical isomers* of lactic acid and tartaric acid (p. 284).

Moving on to an analysis of the manuals published in Italian, a reference textbook for the first three-dimensional representations of tetrahedral carbon is the Sestini-Funaro. The two authors are the Italian chemists Fausto Sestini (1839-1904), Professor at the University of Pisa, and Angelo Funaro (?-1927). This text was very popular in Italian secondary schools and was published in numerous editions between the late 19th and early 20th centuries, the last one being in 1921.[40] In fact, this manual is known outside Italy because Primo Levi (1919-1987) cites it as the school text he used during high school, in the *Hydrogen* chapter of his book *The Periodic Table.*[41] The edition of interest is the sixth edition, published in 1901, where, in a note added to the main text, there are two mirror images of a tetrahedron (Figure 6) used to show the *physical isomers* of lactic acid (p. 321).[40]

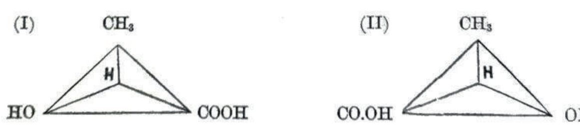

Figure 6. Representations of the two *physical isomers* of lactic acid as found in Sestini-Funaro's manual (1901).

*** This journal ran until 1913 and then was absorbed by the Journal of the American Chemical Society.

Meaning of graphic representations in these manuals

These textbooks, analysed in the present work, are very interesting from an epistemological point of view because authors tend to reflect on the meaning and usefulness of these representations.

In his 1879 manual[33], Schorlemmer points to the objection made by some eminent chemists to the possibly misleading use of these solid diagrams, named *glyptic formulae* (p. 67). Students, in fact, could take these representations as real objects, while they are not, and «it might lead the pupils to believe that atoms had that shape, or were thus arranged in space, and connected by material bonds». In order to support this statement, he adds: «In fact a dunce, when asked to explain the atomic theory, answered, "Atoms are square blocks of wood, invented by Dr. Dalton."» At the same time, the author underlines the usefulness of these three-dimensional representations in explaining experimental features of chemical compounds; in fact, he underlines that: «*Graphic* and *glyptic formulae* [...] are of value for illustrating the different constitution of numerous compounds having the same percentage compositions, but very different properties». In this context, he is referring to different types of *isomers*. It is important to emphasise that both these aspects, meaning the symbolic value of these representations and their usefulness in an educational perspective, should be taken into consideration even today when using three-dimensional models in a classroom to avoid erroneous learning.

Roscoe and Schorlemmer, in part I of the Volume III of their manual published in 1881[36], emphasise the same aspect, that is to say the usefulness of these representations that have only a hypothetical meaning. The authors, in fact, caution readers against a structural interpretation of these three-dimensional formulae (p. 128): «graphical formulae cannot represent the arrangement of the atoms in space, about which, in fact, nothing is known. These rational formulae possess a somewhat similar meaning to the parallelogram of forces in mechanics. They simply serve to give us a notion of the attraction which the single atoms in the molecule exert upon one another».

In the 1885 manual on organic chemistry[38], Remsen adds a reference to the purely speculative and theoretical value that was attributed at the time to the van't Hoff hypothesis and, more generally, to the spatial representations of chemical compounds. It says, in fact, that (p. 164): «At present, it is hazardous to indulge in speculations regarding the relations of the parts in space, and, while the hypothesis which is to be explained briefly is ingenious and interesting, the student should be careful not to be carried away by it. He should remember that it is only a thought». On the other hand, in the absence of data obtained with experimental techniques, these three-dimensional representations are actually only conjectures and hypotheses that move on a purely symbolic plane and useful tools for interpreting empirical evidence.

A further reflection on the value to be attributed at that time to the Le Bel and van't Hoff hypothesis and to its application to cyclic compounds (made by the German chemist Adolf von Baeyer (1835-1917) in 1885[42]), is made by Remsen in the third edition of its *The Principles of Theoretical Chemistry*.[39] He draws readers' attention to the absolute uncertainty that existed at that time; in fact, the text says: «What value to attach to such considerations at present it is difficult to say. In this, as in so many other cases in which our knowledge is imperfect, we can only wait until further work shall have furnished us with more facts» (p. 285). In any case, he underlines that this hypothesis was extremely useful to «account for some cases of isomerism which cannot otherwise be explained».

METAL COMPLEXES

Werner's Hypothesis

Another field that was investigated in the present work is that of three-dimensional geometries of inorganic complexes, initially proposed by the Swiss chemist Alfred Werner (1866-1919), Professor at Zurich, in his original paper of 1893[43], and their first appearance in chemistry manuals. The two cornerstones of Werner's theory are the introduction of the *coordination number*, i.e. the maximum number of chemical species that can bind to the central metallic element, and the spatial geometry of inorganic complexes. In the 1893 paper, Werner proposed the *octahedral* geometry (he himself used the term *Oktaeders*) for complexes with coordination number 6 and, for those with coordination number 4, a kind of geometrical arrangement with four bonds in a single plane which now is referred to as *square planar*. Initially, Werner's ideas were accepted with scepticism in the scientific community, but they began to circulate quickly in textbooks. Werner himself wrote in 1905 a fundamental book on inorganic chemistry where he explained the basis of his coordination theory: *Neuere Anschauungen auf dem Gebiete der Anorganischen Chemie*.[44] This book had a great influence on teaching inorganic chemistry and on the theory of coordination in the early 20th century.[45]

Chemistry Textbooks and First Graphic Representations of Metal Complexes

All the same, it is important to point out that a reference to Werner's work on the ammonia complexes of cobalt and platinum, albeit in footnotes, can already be found in the first edition of a manual written by George Samuel Newth (1851-1936), a British chemist and lecturer at the then Royal College of Science in London.[46] This volume was published in 1894, only a year after Werner's initial proposal. However, no edition of this manual, among the eleven I have consulted, reports a representation of the three-dimensional structures of metal complexes.

The first three-dimensional representations of metal complexes can be found in a series of books where Werner himself had been asked to write or revise sections dedicated to these types of compounds. One of these manuals is *The Elements of Stereochemistry* by the German chemist, Arthur Rudolf Hantzsch (1857-1935). Hantzsch graduated in Chemistry from the University of Würzburg under the supervision of Johannes Wislicenus. He was a Professor at Zurich Polytechnic (now ETH Zurich) and he had a great influence on Werner during his studies there. There were three first editions of this manual in as many languages: a German edition published in 1893[47] and the two editions of interest, the 1896 French edition[48] and the 1901 English edition.[49] In these latter two editions of the manual, there is a section on the stereochemistry of metal complexes by Werner himself, *The Stereochemical Isomerism of Inorganic Compounds*. Here, it is possible to find graphic representations of both octahedral and planar square geometries (Figure 7). It is worth pointing out that these two figures are taken directly from Werner's original paper of 1893.[43]

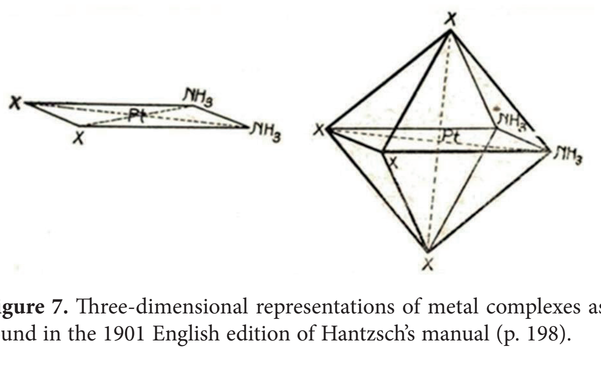

Figure 7. Three-dimensional representations of metal complexes as found in the 1901 English edition of Hantzsch's manual (p. 198).

Another text of this series is the above-mentioned manual by van't Hoff on stereochemistry. In 1898 a second English edition of *Chemistry in Space* was published under the title *The Arrangement of Atoms in Space*, with an appendix on *Stereochemistry among Inorganic Substances* by Werner.[50] This book is much more extensive than the previous 1891 English edition and, in addition to Werner's appendix, contains a section on the stereochemistry of nitrogen compounds. In the section on metal complexes there are numerous three-dimensional representations both for octahedral and planar square geometries. There is also a reference to an article published by Werner and the Italian chemist Arturo Miolati (1869-1956) in 1893, with experimental data relating to the measurement of the *molecular conductivity* of solutions of metal complexes, which helped to confirm the theory of coordination.[51] This kind of experiment, performed in aqueous solution, is now called *ionic conductivity* and relates to the number of ions in solution.

A third manual of this group is Holleman's textbook, *Textbook of Inorganic Chemistry*, which has been a reference manual for teaching inorganic chemistry for a very long time, as proved by the various editions of the text translated into different European languages. Arnold Frederick Holleman (1859-1953) was Professor of Chemistry in Groningen, in the Netherlands. The first edition of this textbook was published in Dutch and dates back to 1898.[52] Other editions of the volume were published in German, the first in 1900[53], in English in 1902[54], and in other languages.

The first three editions of this manual have been consulted, both in German and in English. From the very first edition of the text, there is a paragraph dedicated to the ammonia complexes of the metals of the eighth group. In this section, a mention is made to Werner's work and his hypothesis, but without any reference to the three-dimensional geometry of these complexes. The third English edition, partly rewritten and approved directly by Werner himself with regard to the ammonia complexes of metals, was published in 1908. In this edition there are graphic representations of octahedral complexes (p. 487). These structures are reported as support for the only structural hypothesis that would explain the existence of stereoisomerism for metal-ammonia compounds. In the third German edition published in 1905 there are no graphic representations.

Another interesting manual on stereochemistry, with no contribution from Werner, but where there are three-dimensional representations of metal complexes, was written by Alfred Walter Stewart (1880-1947), a British chemist and writer of several chemistry textbooks and detective novels. The first English edition of this manual was published in 1907.[55] In this edition, at the beginning of the chapter on the stereochemistry of cobalt complexes (p. 270), there is a reference to Werner's work and the author underlines that: «It seems possible only to sketch the outlines of his work, as up to the present there does not appear to be sufficient accumulation of material to allow more than this to be done». This statement by Stewart sounds a bit odd, as Werner had published at least 5 papers on metal complexes by 1906. The author continues by underlying the hypothesis of two sets of valences, designated as *principal valencies* and *auxiliary valencies*, and the text reports images of three-dimensional structures of both octahedral complexes of cobalt and planar square complexes of platinum. In the manual we can also find a reference (p. 274) to the geometrical motives underpinning the idea of the octahedron as the only possible arrangement of ammonia complexes of cobalt. It says, in fact: « Now six points can be thus symmetrically arranged in space if they are placed at the corners of a regular octohedron [sic]».

Among Italian manuals published in the early 20th century, even for metal complexes the reference manual is the Sestini-Funaro.[40] From the seventh edition on, this text is edited by Quirino Sestini (1872-1942), Fausto's son. Until the ninth edition of this text in 1909, no reference is made to Werner's complexes. From the tenth edition of the manual, published in 1912, graphic representations of metal complexes with octahedral and planar square geometries appear in the text for the first time. These graphic representations are present in the chapter *Complex Compounds of the Metals of the VIII Group* and represent the first that have been so far found in Italian manuals.

CONCLUSIONS

Several conclusions can be drawn from the present research. First of all, it is possible to conclude that the period of time between the original proposals by van't Hoff, Le Bel and Werner and the first appearance of three-dimensional representations in textbooks, is relatively short. This is despite the fact that the means of communication used at the time were not as fast and efficient as those today.

Secondly, from a didactic point of view, it is important to stress that these three-dimensional structures, as presented in the manuals studied, are useful and essential tools for visualising the differences between distinct types of isomers. This property, in a way, evokes the importance of visual aspects in enhancing learning of complex chemical concepts. However, while underlining the usefulness of graphic formulae, some authors warn against a structural interpretation of three-dimensional representations, i.e. they caution against an excess of realism applied to the sub-microscopic level.

This statement leads directly to a third conclusion about the epistemic value of these drawings, which are described in these textbooks as hypothesis, ideas and conjectures. These structures are useful attempts to construct scientific explanations referred to a level of reality, such as the microscopic one, that at the time was not accessible experimentally. On the whole, it is necessary to point out that, with reference to Johnstone's triangle, the clear distinction between the symbolic and the microscopic level should be kept in mind in today's teaching of chemistry if we want to pursue the goal of a truly meaningful learning of the discipline. In fact, even if today we have access to accurate data on the microscopic world, the representations remain purely symbolic, because they refer to a world which cannot be represented in a realistic way, by virtue of its dynamic and quantum mechanical nature.

Finally, it is important to remember the crucial role played by these graphic structures as useful tools for explaining empirical evidence which could not otherwise be explained. One of the most relevant examples was the application of the structural hypothesis put forward by van't Hoff to the solution of the enigma concerning the then unexplained relationships between maleic and fumaric acid.

To sum up, given the difficulty of exploring all manuals published in that period worldwide, the creation of a freely accessible database where everyone could add references to chemistry textbooks with three-dimensional structures would be very interesting. This could help the construction of a sort of map showing how rapidly these fundamental concepts of chemistry spread in different languages and therefore were accessible to secondary school and university students.

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APPENDIX: TEXTBOOKS EXAMINED IN ALPHABETICAL ORDER

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