A PICTURE PROVOKES A THOUSAND THOUGHTS. ARE THEY ALL RIGHT?

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Abstract

Cave illustrations from the prehistoric period used to tell stories of hunting and of rituals and even today provide us with a satisfactory view of how our ancestors lived many centuries ago. In this sense, illustrations in books help to make the content more easily understood whether the content is a fiction story or a scientific textbook. In scientific textbooks especially, pictorial representations are used widely in order to clarify relationships between measurable quantities and even between observables and more abstract ideas. However, pictures and diagrams are not free from misinterpretations and/or oversimplifications, therefore provoking a series of thoughts which can create or maintain logical deductions not strictly true within the scientific realm studied. It is therefore, not straightforward and always true that a picture has an equivalent of thousand words and may be used accordingly. In Chemistry textbooks we have identified several cases where pictorial representations may give rise to misconceptions which could and should be avoided. In most of the cases discussed there is a way to overcome such effects with low cost and high applicability amendments, a few of which are proposed in the text.

Keywords: *chemistry textbook, diagrams, pictorial representations, misconceptions*

1. INTRODUCTION

Among the numerous topics covered by those interested in the didactics of Chemistry, one which receives an ever-lasting and ever-growing attention is related to the misconceptions delivered, promoted or even created throughout the primary, secondary and higher education levels. Misconceptions tend to be formed since the pre-school age and young students usually tend to carry on living with them during their education process (Katsikis et al, 2015). In fact, it is not uncommon that new knowledge provided by the education programs is rather attempted to be incorporated into the pre-existing background of beliefs and personally constructed models rather than used to establish a solid foundation for the incorporation of further knowledge provided within the same educational program. It is therefore, of key importance for the teacher to be able to recognize, identify and circumvent misconceptions in order to achieve the maximum result of his teaching efforts (Kind 2004, Horton 2007).

Several factors other than pre-existing interpretations are accused for influencing misconception retention and/or promotion. Among them, central role plays the multitude and the extent of misconceptions possessed by the teachers themselves as well as the influence of cultural and/or religious background of the students (Diesing 1991). Lifelong education and training can be a cure for the former as for the latter special care in the construction of the corresponding educational programs has to be applied.

In today's world with the abundance of information sources, among which numerous internet sites and information platforms (Aldrich 2005) there exists a vast arsenal of material available to obtain, evaluate and utilize in order to confront and counter misconceptions.

Human and monster drawings, figures of saints and sinners, kings and peasants are found alongside artistically formulated representations of flora and even geometrical schemes in texts dated back to the Roman period and they kept being used in the printing era of the history of human communication. Draws and graphs have been used since the early days of printing in order to both decorate and to give life to the bare text. In more recent periods, there exists an abundance of scientific publications all of which are accompanied by large numbers of graphs and figures presenting the experimental results, besides photographs or elaborate drawings of laboratory equipment. In this respect, it is not

uncommon for scientific textbooks to be full of all of the above pictorial representations, providing in this way aid to the reader for the better understanding of the printed text. Electronic equipment, initially in the form of overhead projectors and more recently screen projections of computer files of various "presentation" software are used extensively in all kinds of teacher-student interactions, with the same as above scope. By drawing attention to a simple graph of the Boyle law of ideal gases, the understanding of the relation between the two observables discussed is much easier and more straightforward than the presentation of a page full of the related recordings. Attention can be directed by pointing at the graph on the screen where it is projected in the classroom or by suitably placing it within the pages of the corresponding textbook (Kasiara et al 2019).

It is reported that at least as early as 1911, it has been stated that a picture is worth a thousand words (Wikipedia). Of course, the original thought was related to using pictures in newspaper and journal editions to enhance their impact on the readers but it can be readily transferred to any text or modern presentation and especially in textbooks which are by definition aiming at the promotion of scientific knowledge to young students. In the case of scientific books it would be better still to modify slightly the original phrase to "A picture provokes a thousand thoughts" since it is usually required by the reader of the text to consult some part of the text, check some pictorial presentations, make some observations, derive some trends or anomalies, define some specific points of interest and reach to the conclusions provided by the text author. All the above mental activities are propagated through a sequence of thoughts which have emerged at the sight of the pictorial presentation, which acts as the initial provocation. A completely analogous phrase can be and has been used for mathematical (and extended to chemical) equations one of which is set equal to a thousand pictures.

Misconceptions, however, are still lurking in the background ready to intervene and negate the expected positive effect of the above stated equivalence of a single picture to a thousand words. The thoughts that emerge may therefore be of diverging nature and provide a step (or several steps) backwards in the formation of the scientific background of the young students (Barke et al 2012).

2. DEPICTIONS OBSERVED BY TOPIC

Teaching Chemistry provides some additional challenges to the teacher relative to the rest of the Sciences. The main difficulty arises from the fact that the chemical reaction is described in terms of atoms and bonds which cannot be observed directly although several laboratory experiments provide data for the senses to understand that some reaction has occurred and some new product has been formed. Furthermore, the student is provided with a specifically strict language to use for the description of the phenomena, in the form of symbols used for the representation of atoms and combinations of symbols and numbers used to describe the stoicheiometry of molecules. The student is required to understand the three distinct ways of referring to a chemical phenomenon (Johnstone 1991) and to perform a series of mental acrobatics jumping from one to the other as does the teacher during the latter's teaching process. Studying with the aid of either printed textbooks or web pages naturally involves the reading of text and the observation, inspection and understanding of photographs, line draws and function plots. Specific to Chemistry is also the presence of various types of presentations of atoms, molecules, as well as the bonds present in the latter. Furthermore, reaction mechanisms and energetics are also reported accompanied usually by reaction schemes which involve various kinds of molecular structure presentations, each with its own merits and drawbacks (Papadopoulos and Akrivos 2022). Besides the apparent utility of the above pictorial representations there exist some points where their careless or simplified draw may lead to erroneous understanding of principles and relations between observables. In the following, several such cases are reported and in each case a specific example of a picture which may lead to erroneous assumptions is given. Our report is not meant to be polemic in nature but reference should be made of the origin of the graphics presented and as such some representative web sources are reported picked at random out of many analogous ones.

2.1 Atomic orbitals

Chemistry teachers struggle to convince their students, especially ones at senior high-school about the validity of quantum mechanics. The situation gets even tenser with university undergraduates when they are asked to understand that the electron is described by a function which is in part imaginary. This specific point is circumvented by introducing the Ψ^2 of the electron wavefunction, and indicating that from then on reference to an orbital will be made using a suitable graph of the above Ψ^2 function which represents the probability distribution of the electron described by the specific wavefunction (Born 1926). However, there is a subtle point in discussing the Ψ^2 of the 1s atomic orbital which is used as an example in order to introduce the idea of the equivalence of the calculated radius of maximum electron density to the better understood radius of a Bohr-type circular trajectory.

The assumption that there is an extremely small but definite probability of finding an s-type electron at the nucleus is beneficiary to many areas of interest besides eliminating unnecessary elaboration as to whether there is or is not a knot at the 1s electron distribution function at the point zero, where the nucleus is situated. Besides the fact that a nucleus is not an idealized geometrical feature like the "point" which is dimensionless, the idea of defining the quantity $4\pi r^2\Psi^2$ is that one actually considers an infinitely small shell in the region $r + \delta r$ in order to perform the integration. In this respect there is also an infinitely small δr increment around the $r = 0$ point where the value of Ψ^2 is actually large.

2.2 Hybrid orbitals

A lot of discussion in a chemistry classroom relates to the formation of chemical bonds. The main didactic approach applied involves the extension of atomic orbitals, used as a starting point to discuss the formation of molecular wavefunctions which describe the distribution of the electrons over the whole of the molecule considered. Closely related and especially connected to the structure adopted by small or medium size molecules is a further extension of the atomic orbital principle towards the formation of hybrid orbitals. This topic is readily understood by students, however the typical representation of hybrid orbitals contribute to the misunderstanding of their actual nature. It is well defined that, a sp^n hybrid is a new orbital, centered on a specific atom but not described by the traditional quantum numbers and that it reveals both s and p type behavior. The representation that is generally given follows in Figure 1 and it obviously concentrates on the more interesting parts of the new wavefunction, namely its spatial distribution and orientation towards similar wavefunctions of neighboring atoms in an effort to overlap and give rise to a bond.

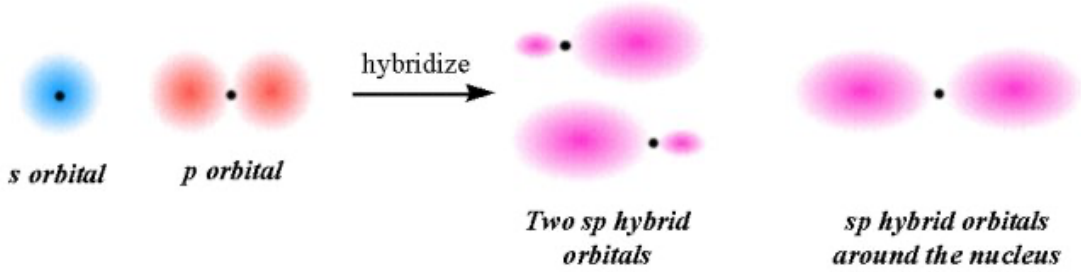

Fig. 1. Traditional representation of the formation of a hybrid orbital with indication of the nucleus position within it. Obtained from https://users.stlcc.edu/gkrishnan/Molecularorbital.html

However, as one keen observer will detect (as it has occurred in many instances) there is apparently no s-type character in the above representation since the two lobes where the wavefunction possesses opposite phases lie on either side of the dot representing the nucleus. There exist several elegant computer programs which produce actual graphs of the probability distribution in hybrid orbitals like the one reported in Figure 2 bellow, however they almost never indicate the position of the nucleus (represented by the dot placed by us assuming the graph has been centered on the nucleus under consideration). If this is done it becomes apparent that the wavefunction under consideration is

retaining some characteristics of s orbitals and some characteristics of p orbitals, verifying its characterization as sp^n

There is no need to actually intervene to a great extent when the simplification is applied, for clarity and brevity, of representing only the larger lobes which will be responsible for any bonding interaction. However, when it is just the shape of the hybrid orbitals under consideration the actual nucleus position should be clearly defined.

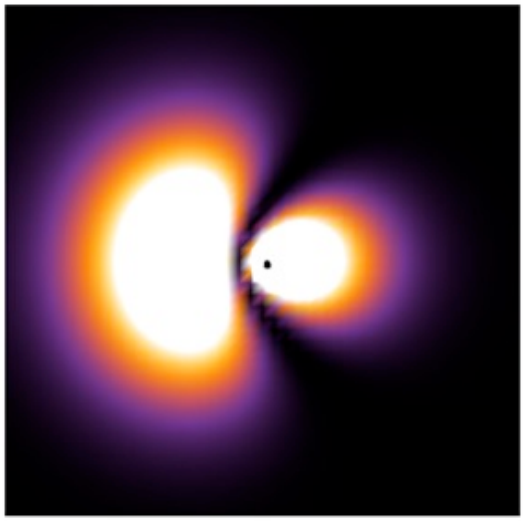

Fig. 2. Computer generated probability distribution of a hybrid orbital. The dot added indicates the approximate position of the nucleus. Adapted from https://mathematica.stackexchange.com/questions/32378/is-there-something-like-densityplot3d-to-visualize-atomic-orbitals

2.3 Non-bonding orbitals

Again, clarity and brevity play their subtle role by directing authors to present the hybrid orbitals as in Figure 3, which provides some confusion to the students when it comes to discuss the VSEPR principle and categorize the magnitude of the inter-electron repulsions where the non-bonding to non-bonding electron interactions rank by the far the strongest ones. The actual graph clearly shows that the hybrid orbital is centered close to the nucleus while the more elegant and clear draw of the traditional lobes makes it necessary to have an elaborate and in some cases inconclusive discussion about the spatial distribution of bonding an non-bonding orbitals around the nucleus.

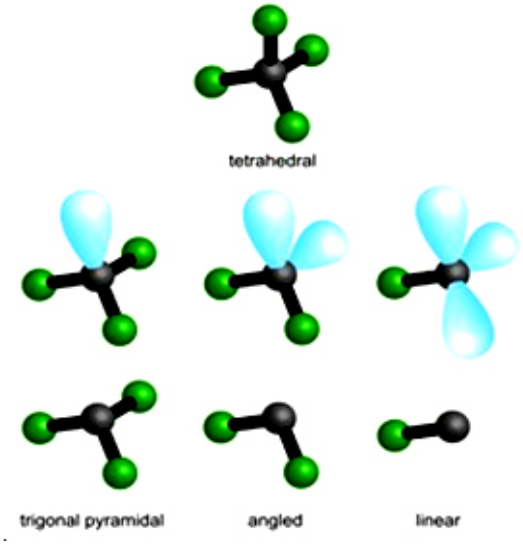

Fig. 3. Structures involving non-bonding orbitals.

2.4 Reaction energetics

Catalysis is a topic discussed in many chemistry textbooks because it is directly related to the structure-to-reactivity correlation and is further related to a wide range of applications both in industry and in the human body. The main argument in favor of using a catalyst in a reaction is that is helps to complete the reaction in a shorter period of time relative to the non-catalyzed reaction. Of course, in the initial stages of the discussion it is not specifically indicated that under certain conditions completely different products may be realized. However, the most traditional pictorial representation of a catalyzed versus non-catalyzed reaction is the one reported in Figure 4 where, apparently the main above argument has been dropped. While care has been taken to indicate that the catalyzed reaction proceeds stepwise, with each step being defined by a smaller activation energy, the reaction coordinate, which is traditionally being considered as “time” is intercepted by the two graphs at exactly the same point.

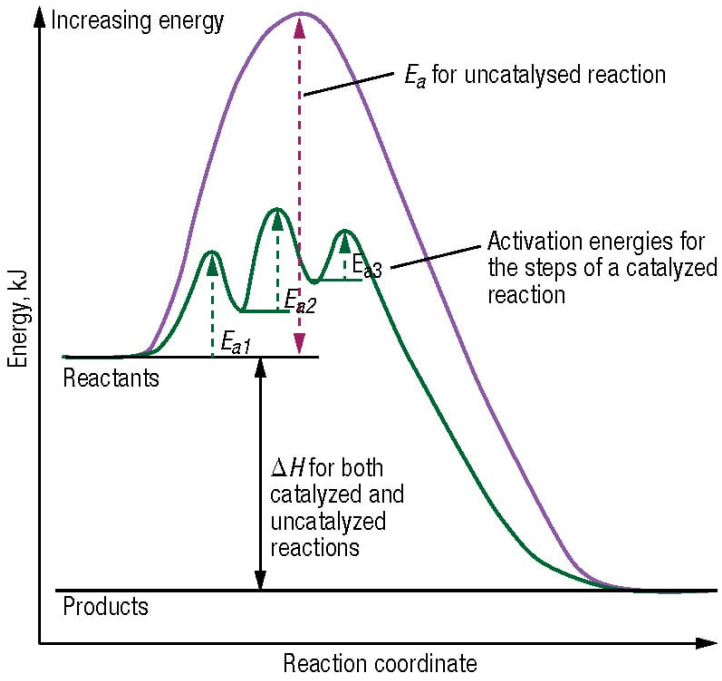

Fig. 4. Typical comparison diagram for the discussion of catalyzed vs non-catalyzed reaction. Adapted from https://www.chemengonline.com/catalysis-fundamentals/

The argument therefore, of an unpremeditated reader would be that catalysis is related to less heat required for the completion of a reaction rather than less time required to do so.

2.5 Reactions at equilibrium

All those who have gone through a general chemistry book are acquainted with the graph describing the energetics of a chemical reaction (see Figure 4) and are easily introduced into the concept of endothermal/exothermal processes that can be introduced with reference to the above graph, where the total energy levels of the reactants and the products are noted along with the corresponding level for the activated intermediate. The concept of ΔH change during the reaction is in general well understood and thermodynamics appear to work very efficiently for the purpose, since the reaction is expected to proceed towards the lowest energy stationary state. Following some arguments about the unexpected spontaneous character of some endothermic reactions, the concept of entropy is introduced and immediately follows the absolute criterion for the determination of the spontaneous character of a reaction in the form of Gibbs free energy. It is apparent, from the definition of the latter that both ΔH and ΔG are measured in units of energy. However, at a not so later stage, discussion has to be carried out about the concept of equilibrium whereupon one of the following kinds of representation is given and the value of the equilibrium constant is related to the free energy change (Figure 5).

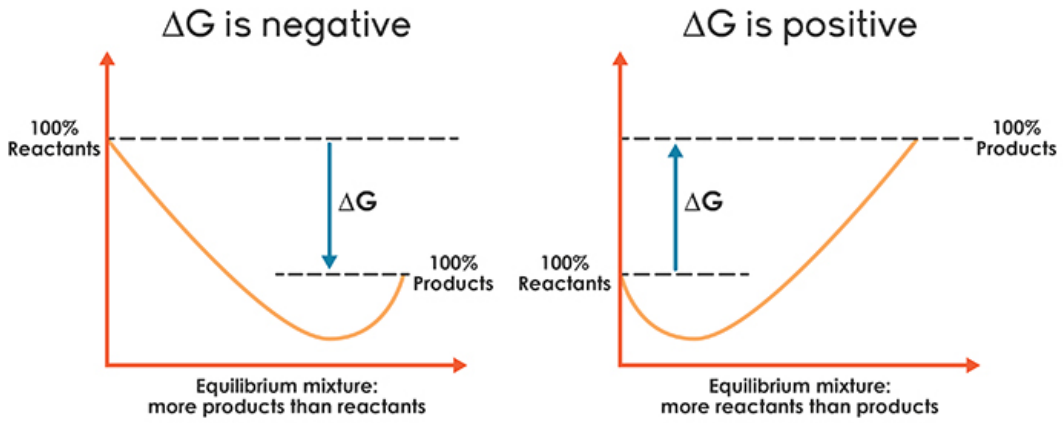

Fig. 5. Presentation of the variation of free energy at the equilibrium of a reversible reaction. https://www.learner.org/series/chemistry-challenges-and-solutions/equilibrium-and-advanced-thermodynamics-balance-in-chemical-reactions/

The misconception arising from such a didactic approach is that the two graphs concern two different situations and that reversible reactions are described in a distinct way, in which it is not possible to directly and simply derive a value for the ΔH of the reaction. It has to be emphasized that the values of ΔH or ΔG are reported per mole of reactant consumed or product produced. Furthermore, it has to be clarified that ultimately the ΔG graph has to be used since Gibbs free energy is the absolute criterion for the spontaneous character of every reaction and that

2.6 Further complications at equilibrium

In order to circumvent misconceptions about the chemical events occurring during a reversible reaction, the introduction of half arrows has been advanced. Using these half arrows is probably a means to indicate to the students that a reversible reaction it is not actually the summation of two reactions occurring one on either direction but a single reaction involving all the chemical compounds indicated on either side of the coupled half arrows.

$A + B \rightharpoonup C + D$ half reaction heading right

$A + B \leftharpoondown C + D$ half reaction heading left

$A + B \rightleftharpoons C + D$ total reaction

Closely related to the above topic are redox reactions the spontaneous direction of which is discussed in terms of the standard electrode potentials of the half-reactions involved. Usually, the role of the recorded or tabulated electrode potentials is related to the one of the equilibrium constant Kc, while the reduction quotient is directly related to the electrode potential through the Nernst equation (Nernst 1889). However, in the presentation of redox reactions, the half-reactions involved are reported in the form

$$A \longrightarrow C \quad E_1^o$$

$$D \longrightarrow B \quad E_2^o$$

$$A + B \longrightarrow C + D \quad E_1^o - E_2^o$$

Students are easily confused since the term half-reaction is expected to implement the use of half arrows as well and, furthermore, the final equation is represented as an irreversible one-way reaction while their expectation is that it must be a reversible one.

2.7 Spectroscopy

The coupling between vectors related to protons and electrons respectively, can be much easier to understand in view of the assumption presented in the first of the above points. It is rather easily understood and accepted that vectors can be coupled in the case where they possess the same origin and in this respect the small but actual probability of an s-type electron being at the nucleus helps to provide this common point. In several of the spectroscopic methods discussed, especially those referring to measurements in a magnetic field the discrete regions of the spectrum where certain valence states or geometries can resonate becomes more apparent as they are all related to the distribution of valence electrons in several types of hybrids with varying contributions from the related s orbital. A typical report of spin-orbit coupling is presented in Figure 6. The figure implies that the early Bohr type model for the atom is used; however, this does not seem to impose a severe obstacle in the assimilation of the basics of the vector coupling process.

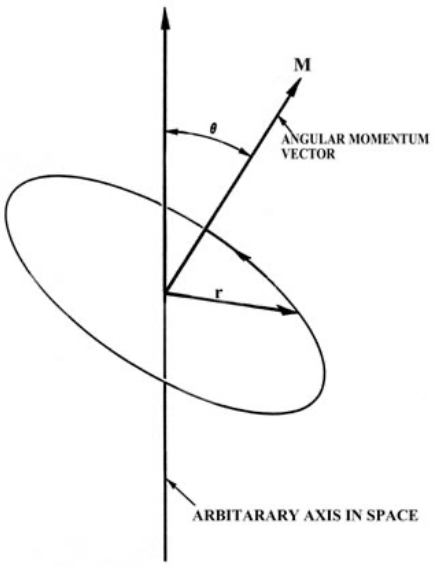

Fig. 6. Spin-orbit coupling graph. Adapted from https://www.chemistry.mcmaster.ca/esam/Chapter_3/section_2.html

2.8 Ionic bonding

Ionic bonding seems rather simple in its description although it requires clarification of the fact that it is not actually a bond analogous to the covalent bond where one expects at least one pair of bonding electrons between the two atoms of a bond.

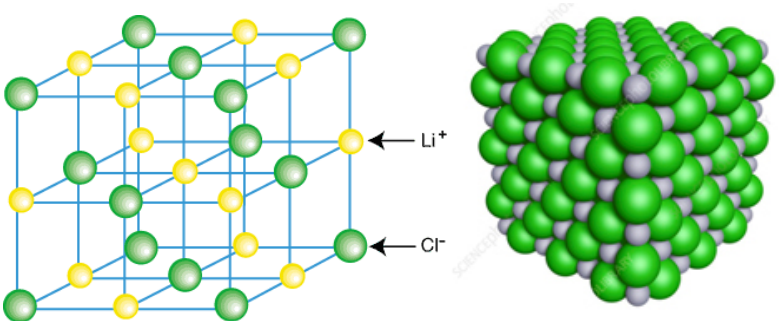

Fig. 7. Crystal lattice presentation. Adapted from https://www.askiitians.com/iit-jee-Solid-State/crystal-lattices-and-unit-cells.html and https://www.sciencephoto.com/media/1240747/view/crystal-structure-of-sodium-chloride-illustration

In theory this is something that can easily be overcome and in fact most of the young students understand the formation of discrete but interrelated pairs of ions with opposite charges as a consequence of the complete transfer of one or more electrons to the more electronegative atom. However, immediately follows reference to the three-dimensional alternative sequence of positive and negative ions forming the crystal lattice, which is accompanied by presentations like the ones in Figure 7. In the typical crystal lattice presentation on the left lies a source of confusion for the students since the neighboring spheres representing the ions are connected by solid lines, resembling the notation of the covalent bond and therefore in many cases when required to write the molecular formula of a salt, something like Li-Cl is reported and the idea is further advanced to the point of assuming the formation of the crystal lattice as alternating Li-Cl units rather than the corresponding ions. The figure to the right supports the idea that atoms have to actually touch one another for the formation of a solid. The misconception arising leads to the idea that it is actually the nuclei or the cores of the atoms presented which are touching each other.

2.9 Stereochemistry

Stereochemical representations are a challenge to the chemist as the task of projecting a 3D arrangement of entities on a 2D medium has always been full of problems and has to be treated with a specific number of assumptions and symbolisms. For example, straight lines represent bonds lying on the printing surface, while full and dotted wedges are placed in the positions of bonds extending out of this plane towards or away from the reader respectively. However, the common rule of perspective is not actually followed as the example bellow reveals. While for the outcoming bond the wide end of the wedge aims at the reader, the outgoing bond presents some problem as of the understanding of the relative orientation of the atoms involved. This is because the wide end of the dotted wedge points again away from the central atom towards the one supposed to be more distant from the viewer.

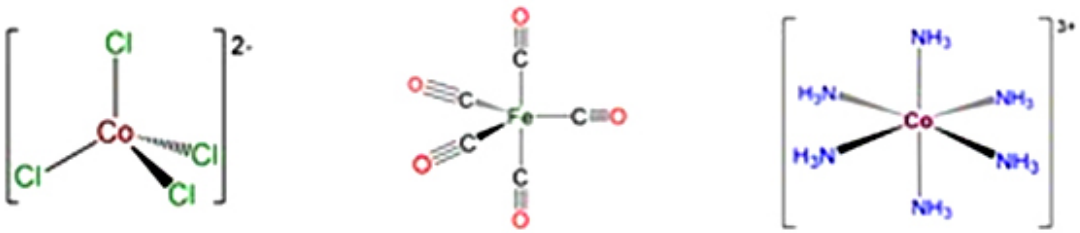

Fig. 8. Geometric arrangement of some coordination compounds. Adapted from https://chem.libretexts.org/Courses/CSU_Fullerton/Chem_325%3A_Inorganic_Chemistry_%28Cooley%29/05%3A_d-Block_Metal_Chemistry-_General_Considerations/5.06%3A_Coordination_Numbers_and_Structures

3. CONCLUSIONS AND PROPOSALS

The above are some points that happened to be noticed by us or pointed at as queries from our students. It is almost certain that several other analogous cases exist both in chemical textbooks and in web pages that have escaped our notice.

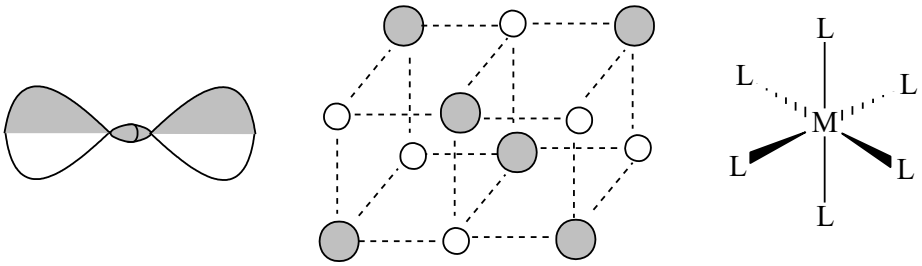

Fig. 9. Proposed scheme for the depiction of hybrid and non-bonding orbitals (left) an ionic solid (centre) and a coordination compound geometry (right).

Each one of the cases discussed may be or may not be in line with the strict scientific truth, in the latter case having been used as a simplification or accidentally due to underestimation of its importance and of its consequences in the buildup of the scientific background of young students. In each case, the adjustment required can be performed with minimum effort and even if not strictly scientifically accurate will certainly provoke thoughts towards a better understanding of chemical principles by the students who visualize the specific pictorial representations.

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