THE VAST AND THE TINY WORLD OF THE MOLE FROM THE UNDERGRADUATE STUDENT POINT OF VIEW.

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Abstract

A survey is reported about the mole-related conceptions shared by first year undergraduate students majoring in Chemistry. The survey was carried out during the 2023-24 academic year. The purpose is to identify which of the commonly shared definitions and applications of the mole are more predominant among undergraduate students. The topic is not free from misconceptions and by checking the particularities of the Greek educational system an effort is made to understand why the specific conceptions were formulated and retained. Furthermore, it is attempted to relate the preferred definitions of the mole to the mathematical and cognitive skills of the students when they are asked to apply the mole in relatively simple chemical problems.

Keywords: *mole, definition, unit of mass, stoichiometry, chemical reaction*

1. INTRODUCTION

Several concepts are considered as being central to the understanding of Chemistry, and each one has indeed a key role within the frame of the science. The understanding of the particulate nature of substances, the electron distribution in atoms and molecules, the formation of the chemical bond and the chemical reaction viewed as the creation and annihilation of chemical bonds as well as the energetics of chemical reactions are certainly all required for anyone who is involved in chemical studies of either elementary or advanced level. Intercalated to most of the above it can easily be traced the concept of the mole. However, mole was elevated to the status of a fundamental quantity as late as the 1960s. Furthermore, the concept of the mole is unique since it may be considered as either a measure of mass or as an amount of a substance and it can also be represented by a number which is by the most modest considerations astronomical. This number is known as Avogardo's number, N_A, and while its name was coined in 1900 (Ostwald 1900) processes of its evaluation had been presented as early as 1865, leading to the closely related Loschmidt constant (Loschmidt, 1865). The current accepted definition as "quantity of substance" is relatively modern and may undergo a variety of interpretations even among the teachers (Strömdahl 1994, Azcona 1997) and may lead to different misconceptions among the students.

The main contribution of the mole in Chemistry is related to the stoichiometry of the chemical reactions, which is more straightforward to interpret now, than in the late 19th century for example. It is much easier to present to young students and to discuss, in view of the mass conservation principle a reaction, for example the syngas synthesis.

$$CH_4 + H_2O \rightarrow CO + 3\ H_2$$

	CH_4	H_2O	CO	H_2
Number of entities	1	1	1	3
	N_A	N_A	N_A	$3xN_A$
moles	1	1	1	3

Once the mass conservation principle is applied and the stoichiometric factors determined, the reaction can be "read" in a simple fashion, as a relation among discrete entities of the substances involved or in a more general one as a relation of their moles (Papadopouls et al 2022). Keeping in mind the "absolute" relation of mole with the discrete entities of every substance and working out the simple mathematics in order to calculate the relative molar mass of each substance (often referred to as molecular weight) one can readily obtain a statement for the above reaction as:

16 g of CH_4 react with 18 g of H_2O to produce 28 g of CO and 6 g of H_2.

With minimal additional effort one may convert the above mass relation to a relation of volumes since all the compounds are gaseous substances. By applying the well-known Avogadro hypothesis, the above statement can be converted to the analogy of

1 volume of CH_4 reacts with 1 volume of H_2O to produce 1 volume of CO and 3 volumes of H_2.

In case that it is either stated or can be assumed that the reaction is carried out under the standard conditions the above ratio of reactants and products may be modified and read as

22.4 L of CH_4 react with 22.4 L of H_2O to produce 22.4 L of CO and 67.2 L of H_2.

It becomes apparent, from the above, that the concept of mole is not just another addition of something to remember in Chemistry but a very efficient and a very much required bridge which can connect the macroscopic and the sub-atomic approaches of chemical studies through the utilization of a symbolic wording, in accordance with the postulate of the existence of these three pathways to interpreting chemical phenomena (Johstone 1991). It is, therefore, of vital importance to teach the mole concept in close relation to analogy, introducing it at every step from the initial contact of young students with the model of chemical reaction (Rowell and Dawson, 1980). The topic is not free from misconceptions, most of which have been proved to be timeless, worldwide and cross-cultural (Kind 2004, Horton 2007).

Students' lack or deficiency in mathematical skills add to their problems in understanding and applying mole to their work. For example, it is difficult to work out the excess (or, limiting) reactant problems because in order to do so there is need to apply analogies and use the mole concept in order to build these analogies, especially when the data given are in the form of masses of the reactants. Typical wrong answers in such problems, i.e. "reaction between *a* g of A and *b* g of B would give how many g of A_2B" include the simple addition of the numerical values of *a* plus *b* (Barker 2001). In this respect, algorithm developing strategies have been proposed and applied in an effort to prepare students to confront problems where the concept of mole has to be utilized. Algorithms have to be carefully worked out by the teacher. It is a growing debate of whether an algorithm should contain few very concise and solid steps or more but simple to understand and easier to carry out. However, educating students to work with predefined algorithms has the drawback that actually deprives them from applying their creativity and elevated level of scientific thinking, furthermore, it has been demonstrated that possession of mathematical skills does not lead to certain development of competence in conceptual problems (Stamovlasis et al 2005).

2. DESCRIPTION OF THE STUDY

A body of nine experts in the field, including staff members of the Chemistry Department and teachers at the secondary education level was consulted in order to form the questionnaire. The initial form of the questionnaire was checked and several indications and corrections were taken into consideration especially ones that would help clarify the requirement of questions. Special care was taken to include questions which would most probably reveal the tendency of each participant to prioritize one of the usual definitions of mole, as quantity of substance, obversion factor from the sub-atomic to the macroscopic level of chemical study as well as the well-known numerical value of Avogadro's number.

The only personal information of the participants collected was their sex and year of studies. Participation in the research was based on the free will of the students. During a class hour in the lecture hall, following a brief introduction, the questionnaire was distributed. After a reasonable amount of time, the response sheets were collected. The data processing of the response sheets was conducted using statistical spreadsheet software, followed by the evaluation of the answers and the necessary descriptive statistics for each question as well as for the entire questionnaire. The initial question of the test was not evaluated because none of the offered answers can be considered wrong or right but they serve as an indicator of the general attitude of the participants towards the concept of mole.

3. RESULTS AND DISCUSSION

The first and most revealing question was put in the form:

Arrange in order of significance to you the following statements about the mole of silicon:

1. It contains as many silicon atoms as one mole of dioxygen molecules
2. It consists of a specific number of silicon atoms, namely 6.022×10^{23}
3. It contains as many silicon atoms as the dioxygen molecules with which they can react completely to produce silicon dioxide
4. Its weight, in g is exactly equal to the relative atomic mass of silicon.

The students were urged to arrange the provided answers in sequence starting with 1 for the most important statement and the results obtained may be summarized as follows:

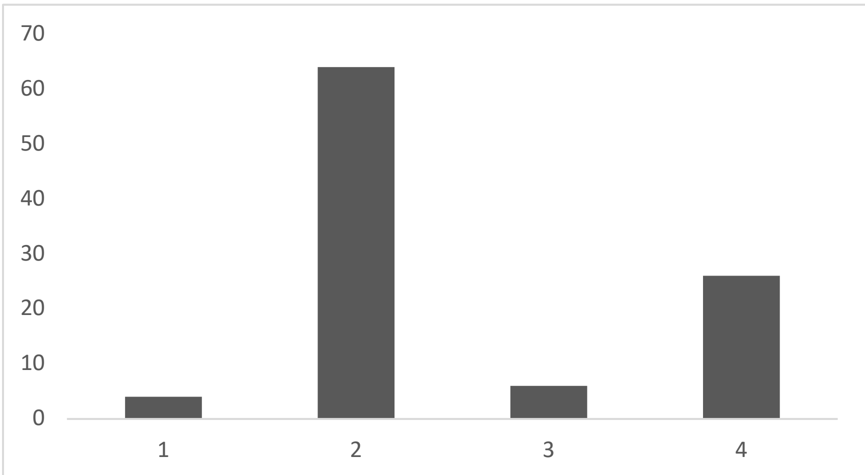

Figure 1. Percent of the primary connection of the mole concept to other aspects. 1= proportionality between substances, 2= numeric value of Avogadro's number, 3= stoichiometry of a reaction and 4= quantity of substance.

The average of the points given to each of the answers by the students is assumed as indicative of the relative importance of the specific statement, the smaller number indicating a more important statement. The actual values for the above four statements are 2.94, 1.56, 3.13 and 2.28 respectively. Of the 157 students who participated in the survey 66.2% gave priority to the most popular answer, 27.4% to the second in accordance with the typical understanding of the mole as represented by the numerical value of Avogadro's number and its use as a conversion factor from atomic mass to mass weighed in a laboratory experiment. It is somewhat surprising that most of the students feel that the numerical value of Avogadro's number is significant, while in chemical calculations they are never required to apply it except in relation to radiochemistry or statistical thermodynamics and then, only if required to produce some numerical results, not for the derivation of some analogy or dependence of observables to other quantities, phenomena or abstract aspects. The second most popular definition is related to the study of stoichiometry since it envisages mole as quantity of substance, however, the two definitions which are directly related to chemical equations do not receive much attention. This is still another verification that the form of the Greek educational system focuses on the addition of data to the background of the students rather that providing intercalation between previous and newly added knowledge.

Of course, the categories produced in this respect do not represent variables that could be subject to statistical analysis other than simply deriving a trend in the answers given, however we thought that it would be of interest to check if the preference for a specific description of the mole would give rise to differences in the overall score of the students in the above questionnaire, in case it was to be considered as a typical test. The mean achievements along with the corresponding standard deviations are given in Figure 2. At first glance it appears that students who considered the mole as a factor of analogy between substances had a better overall achievement, however, given the magnitude of the recorded standard deviations as well a subsequent pairwise analysis of variance, proved that there is no statistically significant difference between students prioritizing any meaning of the mole. There appears to be no statistically significant difference between the total scores achieved by male and female students as analysis of variance suggested, although at first sight male students presented a greater mean achievement (4.51 relative to 3.89).

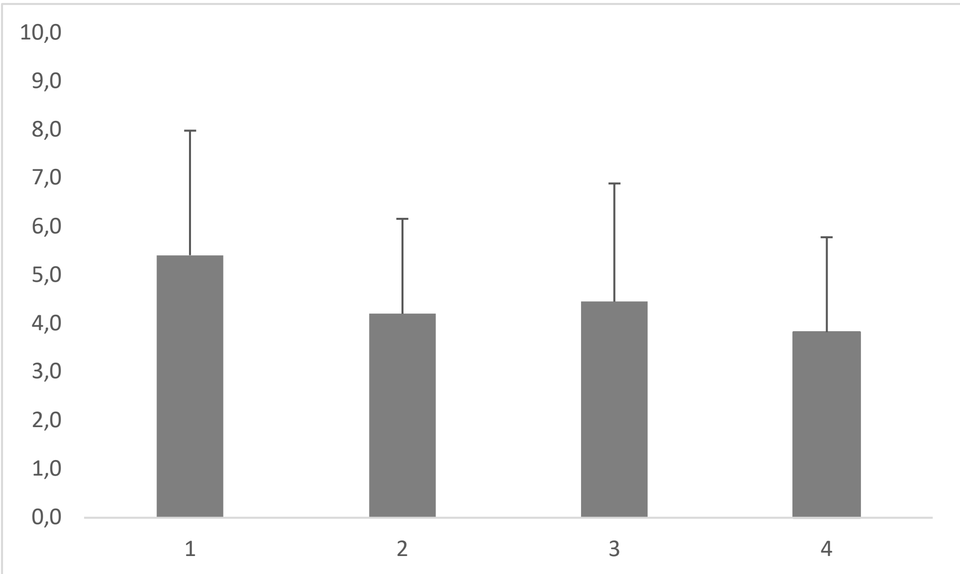

Figure 2. Mean score and standard deviation in the test for the participants according to their preferred representation of the mole. Numbering is in accordance with Figure 1.

In a subsequent question the students were prompted to compute the Faraday constant given its definition and the value of the electron charge. A disappointing 60.5% was able to write the correct simple formula for the calculation and a limited 32.5% to correctly perform the simple task of multiplying the two numeric values and calculating the correct magnitude of the exponent. However, only 20.4% gave the correct units, probably several omitted this step since it was not specifically required to be done, although it is common sense that numerical values of quantities are always accompanied by the appropriate units. As expected, 71,0% of those who prioritized the numerical value of the mole gave the correct formula and 37% of them obtained the correct result, in line with the general expectation that they would appear so efficient since this is one of the very few problems where application of the Avogadro's number value is required. However, the difference from the overall percentages is not indicative of a radically different approach to the concept of mole.

The lack of relatively simple mathematical skills was evident in the results of a question where the total volume of 1 mole of close packed helium atoms, given an atomic radius of 30×10^{-12} m was required. To aid the solution procedure the formulae for the calculation of a sphere, a tetrahedron and a cube were given with the indication that one of them would have to be used. An extremely small 26.1% made the logical advance that the total volume is the volume of a single atom multiplied by the Avogadro number.

To the subsequent step of performing the calculation, a dramatic 75.8% abstained from doing so and the rest gave wrong answers. Once again, those who predominantly link the mole to Avogadro's number are giving only slightly better results (29.1% in the first step of the answer), indicating multiplication of the number of discrete atoms with the volume of one atom. This may serve as an indication that the whole structure of the educational course is based on the memorizing of definitions, rules and even formulae and in this respect, the value of N_A (6.022×10^{23}) represents still another goal in the process and not a standard point of view about the deeper meaning of the mole.

Gases are generally overlooked relative to solutions in the chemistry curriculum in both the secondary and higher education levels. Again, students are scarcely required to experiment with gases and only meet them in problems especially when the volume of a gas has to be worked out or has to be utilized in deriving the stoichiometry of the reaction. A similarity arises with the mole concept in that, students are prompted to memorize that 1 mole of any gas occupied a volume of 22.4 litres and are especially urged to remember that it is so only under STP conditions. It was therefore, intriguing for us to include in the test a question in the form: For a gas A that occupies a volume of 22.4 which of the following statements are correct:

- Its mass is equal to the relative molecular mass of A in g
- It contains N_A molecules of A
- It may have mass equal to the relative molecular mass of A in g
- It may contain N_A in number molecules of A

About 2.5% of the students did not provide any answer at all while 40.1% and 42.7% probably remembered the condition for the molar volume to be 22.4 L and responded with the third and fourth of the above answers. Interestingly, 79.2% of those who connected the mole primarily with Avogadro's number gave the correct answer related to the same number. On the contrary, only 45.2% of those who accepted the typical definition for mole followed up their preference by checking the third of the above answers revealing in the process a less firmly based opinion with respect to the central meaning of the mole. The above question may be considered as a two-tier one since it was followed by one requiring a short answer in the form of indicating the reason for the answer already given. Those who did not attempt to answer the question amount to 16.5% of the total population, indicating that they have not developed a significant scientific literacy level (Bybee 1997, Shwartz et al 2005) and are confined to just remembering statements and figures or relying on their personally constructed mental models for interpreting natural phenomena.

Application of the mole concept is of key importance to the formulation of chemical equations since it is used as a suitable bridge between quantities in grams taking part in a reaction and particles actually reacting. A step to check the ability of students to make use of the above was taken by introducing a simple and straightforward reaction, in the form of

$$NH_3 + 3X \rightarrow NX_3 + 3/2\ H_2$$

where the incorporation of nitrogen to a protein backbone denoted as X consumed 20 moles of ammonia. The question was what volume of hydrogen was produced at STP. For the complete answer to the question, four steps were considered by us, namely the utilization of the mole concept as a conversion factor between reactant and product amounts, the expression of moles of gas in litres using the 22.4 L factor, the application of rather simple mathematical skills in performing the required calculations and finally the correct assignment of units in the final numeric value produced. Owing to the simplicity of the reaction, the above-mentioned steps well completed successfully by the high percentages of 94.3%, 80.3% and 70.1% respectively. The successive drop in the percentage indicates again that the order of the mental steps we assumed for the solution of the problem is probably right since it is expected that more demanding tasks would allow smaller percentage success. The deficiency in mathematical skills is once again evident in the form of an unexpectedly high percent (74.5%) in the correct assignment of the units is the final computed value. This, in line with the previous argument, would not be expected to be higher than 70.1% and the value obtained places the complexity level of the mental process required as lower than the one that is required for the actual computation of the result.

In a similar question a reaction was considered but was only described verbally stating that in a closed vessel there was introduced water vapor until a pressure of 1 at was achieved. Then, the compound was completely dissociated via irradiation. The three-tier question required calculation of the final pressure of the vessel, the principle or law on which the calculation was based and the complete definition of the law. Furthermore, the first step was considered as consisting of several tasks which had to be performed sequentially, the writing of the chemical equation describing the phenomenon, application of the ideal gas law where the number of moles is used as a proportion factor and, of course, the execution of the required simple mathematical calculations. Since no indication of the reaction was given, we considered as valid any balanced reaction providing dissociation products of water and accepted as correct the results, when they were in accordance with the equation provided. A balanced chemical equation was proposed by a 43.9% of the students and the ideal gas law was put to effect by a 51.0%. Mathematical skill deficiency made again its appearance in the statistics as only 38.2% were able to reach the correct (according to the chemical equation they used) final total pressure of the vessel. To further strengthen our argument, this third task was not answered by 36.3% while the ideal gas law did not appear on the answering sheet of 33.8% of the students. This first step of the question was successfully completed by only a 33.8% of the participants. The second step of the question presented a major conceptual problem since only 45.0% were able to provide the correct name of the law used to construct the chemical equation they had just presented, mostly citing that they relied on the Lavoisier principle of mass preservation. A bitter realization came at the third stage of the question where 77.1% of the participants abstained from giving any answer and only 8.9% gave a satisfactory description of the law they used and they were equally partitioned among the two sexes.

However, in a supposedly simpler question, the participants were reminded of the relative atomic mass of chlorine, rounded to 35.5 and supplied with the information that this is a result of the existence of two isotopes and they were asked to specify how many different dichlorine molecules are expected to occur and to calculate the relative molecular mass for each of them. The number of different Cl_2 molecules was reported correctly by 52.9% (58.5% male, 49.5% female) and the expected molecular masses by only 33.8% (41.5% male, 29.5% female) giving the impression that the process of logical analysis is followed easier by male students.

The suitability of the created quiz was checked by applying to the results the difficulty, reliability and discrimination indexes already in use (Eggen et al 2017). Acceptable values for these indexes are between 0.2 and 0.8, larger than 0.2 and generally positive, respectively. For each one of them the only question outside the desired range was the one where the largest failure was recorded and which was the most demanding in the mathematical calculations and required, in addition, 3D geometric considerations.

4. CONCLUSIONS AND PROPOSALS

Owing to the memorizing-oriented teaching in secondary education, undergraduate students have already developed a tendency to relate the concept of mole mainly to the numerical value of Avogadro's number, although it seems that this does not form a solid background on which to develop further conceptions. Those who prioritize this conception of the mole do not appear to do significantly better than the average student in problems requiring application of the number and their mathematical skills are not above the average either. Similar observations hold also for those who incline towards the "unit of mass" definition of mole and their performance in problems where this concept has to be applied. As it has been observed in many analogous studies, algorithmic-based processes appear to produce results to some extent, however, when creative imagination is required, there appears to be need for cultivation of the related mental abilities. In general female and male students do not present any statistically significant differences, however, it appears that females are better in performing mathematical operations while males are better in applying logical analysis as the specific results of a three-tier question revealed.

REFERENCES

Azcona, R. 1997, *Análisis crítico de la enseñanza-aprendizaje de los conceptos de cantidad de sustancia y de mol. Una alternativa didáctica basada en el aprendizaje por investigación*, Doctoral Thesis, San Sebastián: Facultad de Ciencias químicas. Universidad del País Vasco

Barker, V. 2001, "Chemical concepts: introducing chemical reactions", *Education in Chemistry*, vol. 38 no 6, pp. 147

Bybee, R.W. 1997, "Achieving scientific literacy: From purposes to practices Towards an understanding of scientific literacy". In: W. Gräber & C. Bolte. (Eds.). *Scientific literacy. An international symposium. Institut für die Pädagogik der Naturwissenschaven*, pp. 37-68, (IPN): Kiel, Germany.

Eggen, P.-O., Persson, J., Jacobsen, E. E., & Hafskjold, B. 2017, "Development of an inventory for Alternative Conceptions among students in chemistry". *LUMAT: International Journal of Math, Science and Technology Education*, vol.5, no 1, pp. 1–11.

Horton, C. 2007, 'Student alternative conceptions in chemistry', *California Journal of Science Education*, vol. 7, no. 2, pp. 1-78.

Johnstone A.H. 1991, 'Why is science difficult to learn? Things are seldom what they seem', *Journal of Computer Assisted Learning*, vol. 7, pp.75–83.

Kind, V. 2004, *Beyond Appearances: Students' misconceptions about basic chemical ideas*, 2nd Edition, School of Education, Durham University, UK.

Loschmidt, J. 1865, "Zur Grösse der Luftmoleküle", Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften. Mathematisch-Naturwissenschaftliche Classe. Wien. vol. 52, no 2, pp. 395–413.

Ostwald, W. (1900) *Grundlinien der Anorganischen Chemie* (Leipzig: W. Engelmann), as reported by Furió, C. 2000, "Difficulties in teaching the concepts of 'amount of substance' and 'mole'", *International Journal of Science and Education*, vol. 20, no 12, pp. 1285-2304.

Papadopoulos, C., Koumoutsi, A., & Akrivos, P. 2022, 'Stoichiometry within the framework of Greek secondary education Chemistry curriculum', *Educational Alternatives*, vol. 20, pp. 342-351.

Rowell, J.A. and Dawson, C.J. 1980, "Mountain or Mole hill: Can cognitive psychology reduce the dimensions of conceptual problems in classroom practice?" *Science Education*, vol. 64 no 5, pp. 693 – 708.

Shwartz Y., Ben-Zvi R. & Hofstein A., 2005, "The importance of involving high-school chemistry teachers in the process of defining the operational meaning of 'chemical literacy'", *International Journal of Science Teaching*, vol. 27, pp. 323-344.

Stamovlasis D., Tsaparlis G., Kamilatos C., Papaoikonomou D. and Zarotiadou E., 2005, "Conceptual understanding versus algorithmic problem solving: further evidence from a national chemistry examination", *Chemistry Education Research and Practice*, vol. 6, pp. 104-118.

Strömdahl, H., Tulberg, A. and Lybeck, L. 1994, "The qualitatively different conceptions of 1 mole". *International Journal of Science Education*, vol. 16, no 1, pp. 17-26.