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Secondary School Students' Difficulties in Learning the 'Mole Concept' — A Preliminary Study in Singapore

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ABSTRACT

This study uses the relevant test results from the Second International Science Study and the Local G.C.E. 'O' level Chemistry papers to show some difficulties faced by Singapore students in understanding the mole concept. It also advocates that in teaching and learning the mole concept, teachers should make use of every opportunity to train students to "think in mole or number of particles" rather than to follow rigidly certain patterns to solve problems. "Think in mole" is the key to many problems, and hence the fundamental skill in solving all the problems in the mole concept.

Introduction

The 'Mole Concept' in Chemistry deals with (1) the concept of number of moles, (2) the relationship between 'mole' and other physical quantities, and (3) the quantitative relationship among particles taking place in a chemical reaction.

While the periodic table is concerned more with the qualitative aspects of matter, the mole concept focuses on the quantitative aspects of matter. Several findings have provided sufficient evidence about the students' difficulties in learning this concept (Schmidt, 1984; Punzalan, 1984; Graham, 1983; Duncan and Johnstone, 1973; and Cervellati et al., 1982). The mole concept is even identified as one of the more difficult concepts in 'O' and 'A' level Chemistry (Johnstone et al., 1971). At this juncture, it might be interesting to raise the following questions:

- Do Singapore students encounter any difficulties in learning the mole concept?
- If so, what are the difficulties faced by them and what are the possible causes for these difficulties?

Gathering Data

To look for the difficulties our students face in understanding the mole concept, we used the relevant multiple-choice questions from the following sources:

(a) Second Internationnal Science Study (SISS), Population 3, Chemistry Items (Jacobson and Doran, 1985). The test was given in April 1984 to a group of students (N = 945, between 18 and 19 years), randomly selected, taking pure chemistry in the final year of the 'A' level course in the junior colleges.

(b) Local GCE 'O' Level Examinations (abbrev. Local 'O' Level) Chemistry Paper One for November 1982 (Chan et al., 1984) and November 1983 (Sim and Koh, 1984). The Chemistry Paper One was a one hour paper consisting of 40 multiple-choice questions. The total candidates in 1982 and 1983 were 474 and 342 respectively (between 16 and 17 years). Although these groups of candidates did not represent all the Singapore candidates taking the Chemistry papers, because most of the cohorts sat for the Cambridge GCE 'O' level Examinations, the outcome of the test results, to a great extent, was representable because of the following reasons:

(i) Candidates sitting for the Local papers and those sitting for the Cambridge papers followed exactly the same Chemistry course for the same duration.

(ii) The standard of the Local papers was comparable to that of the Cambridge papers.

Analysis and Discussion of the Results

The test items are presented, in general from simple to complex, according to the following themes:

Theme 1: Mole Quantities
Theme 2: Empirical/Molecular Formulae
Theme 3: Calculations from Equations
Theme 4: Concentration expressed in mol per dm^3
Theme 5: Reactions involving Concentration

The item analysis and distractor analysis for each item were carried out. Besides the facility index (FI) and the discrimination index (DI), the percentage(%) of candidates who selected each option of a test item will be presented directly together with the item. The asterisk(*) shows the key answer for the item. Perhaps, it is not justifiable to compare FI and DI of the items across different tests. But with a relatively high KR20 for all the three tests (the KR20 for the Second International Science Study, Local 'O' Level 1982 Examination and 1983 Examination were 0.81, 0.87 and 0.84, respectively), the comparison of FI and DI of items from different tests can reflect, to a certain extent, some of the nature of the problems encountered. In the following, the source of each item is indicated in the parenthesis after each item number.

Theme 1: Mole Quantities

Item 1 (1982 Local 'O' Level, Paper 1, Q21)

What mass of carbon dioxide contains the same number of molecules as 20g of hydrogen at s.t.p.?
(Relative atomic masses: H, 1; C, 12; O, 16)

A 44 g B 96 g C 440 g D 880 g
E 960 g

	A	B	C*	D	E	Omit	FI	DI
%	5.5	7.0	49.0	34.0	4.0	0.5	0.49	0.60

Item 2 (1983 Local 'O' Level, Paper 1, Q19)

Which of the following gases has the most number of molecules?

A 2 g of hydrogen B 2 g of helium
C 14 g of nitrogen D 20 g of oxygen
E 50 g of chlorine

	A*	B	C	D	E	Omit	FI	DI
%	48.9	10.9	5.4	6.0	28.3	0.5	0.49	0.48

Items 1 and 2 were similar in nature. They both tested the students' understanding of the Mole Concept. Students were also required to know the exact formulae of the compounds mentioned in order to get the key answer correctly. As such in Item 1, option D was attractive, probably because candidates forgot to take into account the existence of hydrogen as a diatomic molecule. Perhaps, this indicated that candidates could not really differentiate between moles of molecules and moles of atoms.

But in the case of Item 2, option E was the most attractive one (28%) besides the correct key. This provided evidence that to associate 'number of mole' with the 'mass' of that particular substance in a direct proportional manner is probably one of our students' misconceptions. For the above two items, about 50% of the candidates could not comprehend the concept of mole correctly.

Theme 2: Empirical Formulae/Molecular Formulae

Item 3 (1983 Local 'O' Level, Paper 1, Q15)

A compound containing nitrogen and oxygen only has 36.4% by mass of oxygen. Its empirical formula is

A NO B NO_2 C N_2O_5 D N_2O_3
E N_2O

	A	B	C	D	E*	Omit	FI	DI
%	3.3	20.1	6.0	7.6	62.5	5.0	0.63	0.53

The above item was quite easy for most of the students. Instead of obtaining the correct ratio of 2:1 for N:O, about 20% of candidates had opted the ratio 1:2 (option B). It is possible that this group of students did not really understand the meaning of mole and the process for deducing empirical formula from the percentage of composition by mass of the constituents of a compound.

Item 4 (1983 Local 'O' Level, Paper 1, Q17)

The percentage of calcium sulphate in gypsum, $CaSO\cdot x\ H_2O$ is 79. Calculate the value of x.

A 1 B 2 C 3 D 4
E 5

	A	B*	C	D	E	Omit	FI	DI
%	4.9	51.1	18.5	8.2	16.1	1.1	0.51	0.54

Although Items 3 and 4 were in nature similar, Item 3 was very straight forward, whereas to solve Item 4, students needed the skill to group the atoms instead of taking individual atoms into consideration. Therefore, a drop of FI from 0.63 for Item 3 to 0.51 for Item 4 was observed.

Once a student knows how to classify $CaSO_4$ and H_2O as two groups, the problem can be solved in the usual manner. This item did reflect certain misconception in mole — e.g. how to classify particles.

In general, to find the empirical formulae/molecular formulae is not a problem for most of the students. Students have drilled and practiced them, and have patterns to follow in solving this type of problems. Therefore, for 'A' level students, this type of questions could be considered as easy. But given a question in which the content and the phrasing were similar to those requested for finding the empirical formula of a compound, except that the final stage requiring them to write the empirical formula was omitted, the outcome of the performance was surprising.

Item 5 (SISS, Pop 3, Q3C14)

One kind of stainless steel contains approximately 13 per cent chromium and 1 per cent nickel by mass; the rest is iron. Which of the following gives the closest approximation to the ratio of the number of chromium atoms to iron atoms in this stainless steel?
The relative atomic mass of chromium = 52. The relative atomic mass of iron = 56.

A $\frac{13}{52} : \frac{14}{56}$ B $\frac{13}{52} : \frac{86}{56}$
C $\frac{13}{108} : \frac{86}{108}$ D $\frac{13}{(100-52)} : \frac{87}{(100-56)}$
E $\frac{13}{100} \times 52 : \frac{86}{100} \times 56$

	A	B*	C	D	E	Omit	FI	DI
%	1.2	57.9	4.7	0.9	35.3	0.0	0.58	0.40

Even for 'A' level students who had gone through three or four years of a chemistry course, the FI for this type of basic question was only 0.58.

A remarkable point to note is that option E attracted about 35% of the candidates, indicating that they probably thought that "the ratio of the mass of chromium to that of iron" was directly proportional to "the ratio of the number of chromium atoms to that of iron atoms".

This type of question is no different from the standard ones that students have been practising all the time. Why then is there still a handful of 'A' level students making such mistakes? Do they really think in terms of mole in solving this type of question or do they just follow patterns to solve problems?

Theme 3: Calculations From Equations (excluding those solving concentration)

With the given balanced equation, students seem to have more difficulty in relating mole with 'volume' rather than with 'mass'. This can be judged from the following items.

Item 6 (1983 Local 'O' Level, Paper 1, Q28)

The equation for the complete combustion of propane in oxygen is

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

The volume of carbon dioxide which can be obtained on burning 100cm^3 of propane in 250cm^3 of oxygen is

A 100 cm^3 B 150 cm^3 C 250 cm^3
D 300 cm^3 E 500 cm^3

(All the volumes are measured under the same temperature and pressure).

	A	B*	C	D	E	Omit	FI	DI
%	8.2	46.2	19.0	22.3	3.8	5.0	0.46	0.34

If students knew clearly the meaning of the coefficient given in a balanced equation and its relationship to the volume occupied by the gas, this problem is a simple one.

About 54% of the candidates did not select the correct key answer. Generally, students interpreted wrongly either because they related the number of mole to the volume occupied by the substance directly, regardless of the other conditions given (Options A, D and E), or they still clung to the 1:1 relationship of O_2 to CO_2 inspite of the fact that five oxygen molecules would produce three molecules of carbon dioxide (Option C). It seemed that students related mole better to mass rather than to volume.

Item 7 (SISS, Pop 3, Q3C13)

What volume of carbon dioxide is produced by burning 3 g of carbon in excess oxygen?

Assume that the gas volume is measured at STP (0°C, 1 atmosphere pressure). The relative atomic mass of carbon is 12. The relative atomic mass of oxygen is 16. One mole of any gas occupies 22.4 dm^3 at STP.

A 0.25 dm^3 B 5.6 dm^3 C 11.0 dm^3
D 44.8 dm^3 E 67.2 dm^3

	A	B*	C	D	E	Omit	FI	DI
%	3.0	85.2	6.3	2.8	2.8	0.0	0.85	0.37

The high FI obviously indicated that straight forward 1:1 relationship (mole of C: mole of CO_2 = 1:1) presented little difficulty. Although a balanced equation was not given, it did not really pose any difficulty for the students, since they were at 'A' level and the reaction was simple and common. But a non-1:1 relationship showed the other picture:

Item 8 (SISS, Pop 3, Q3C15)

What is the minimum mass of sodium chloride (NaCl) that is needed to prepare 7.1 g of chlorine?
The relative atomic mass of sodium = 23. The relative atomic mass of chlorine = 35.5.

A 5.9 g B 7.1 g C 11.7 g
D 12.7g E 14.2 g

	A	B	C*	D	E	Omit	FI	DI
%	16.5	4.1	65.3	4.1	10.0	0.0	0.65	0.35

There is a difference of 0.20 between the FI of this question and that of the previous question. Some of the candidates might have known that 7.1 g of chlorine corresponded to 0.1 mol of chlorine. But they ignored the fact that 2 mol of NaCl were required to get 1 mol of Cl_2. A drop of the FI could also be due to the fact that the reaction equation was not given. However, it is expected that 'A' level students should be familiar with this type of simple reactions.

Theme 4: Concentration Expressed in mol per dm^3

When the concepts of 'mole' and 'volume' were merged together, students seemed to have encountered difficulty in applying this new relationship to solve the problem, e.g. Item 9.

Item 9 (1983 Local 'O' Level, Paper 1, Q33)

Which of the following could be added to 20 cm^3 of 2.0 M hydrochloric acid without changing the pH of the solution?

1 10 cm^3 of 2.0 M HCl
2 20 cm^3 of 2.0 M HCl
3 20 cm^3 of 0.2 M HCl

A 1, 2 and 3 are correct
B 1 and 2 only are correct
C 2 and 3 only are correct
D 1 only is correct
E 3 only is correct

	A	B*	C	D	E	Omit	FI	DI
%	13.6	35.3	13.1	13.6	22.9	1.6	0.35	0.36

The values of FI and DI were lower than those found for the simple questions related to mole quantities (e.g. Items 1 and 2). If one applies only the concept of 'mole' and ignores the existence of 'volume', then one would be in error. But if one is able to recognize which is the extensive factor and which is the intensive one, this problem becomes an easy one.

It is possible that students' perceptions of the statement 'without changing the pH of the solution' might have contributed to the low FI and DI. But the main difficulty here was caused by the insignificance of the volume.

Theme 5: Reactions Involving Concentration Expressed in mol per dm^3

We may expect that the stoichiometric calculation on reactions involving concentration expressed in mol/dm^3 will give students more trouble.

Item 10 (1982 Local 'O' Level, Paper 1, Q24)

An aqueous solution contains 0.50 mol/dm^3 of sulphuric acid. Find the volume of this solution required to prepare 6.60 g of ammonium sulphate according to the equation

$$H_2SO_4 + 2NH_4OH \rightarrow (NH_4)_2SO_4 + 2H_2O$$

(Relative atomic masses: H, 1; N, 14; O, 16; S, 32)

A 0.01 dm^3
B 0.05 dm^3
C 0.10 dm^3
D 0.50 dm^3
E 1.00 dm^3

	A	B	C*	D	E	Omit	FI	DI
%	8.0	17.5	48.0	10.0	16.0	5.0	0.48	0.34

The fact that the balanced equation was given and that 1:1 relationship did apply to the substances involved in this item probably helped to maintain its FI at 0.48. But the DI value at 0.34 probably indicates that most candidates did not know how to relate concepts of 'mole' to 'concentration in mol/dm^3' and answered the question mainly by guessing.

Although this question involves more than one stage calculations, if students are able to think in 'number of particles participating in the reaction' and know how to get them, this question will become simple.

But when students are confronted with a reaction in which the equation is not given, and are asked to calculate from a non-1:1 relationship, then they will encounter greater problems, e.g. Item 11.

Item 11 (1983 Local O Level, Paper 1, Q23)

250 cm^3 of a solution containing 0.8 mol/dm^3 of sodium hydroxide is allowed to react with excess copper (II) sulphate solution. The mass of copper (II) hydroxide formed is

A 4.9 g
B 9.8 g
C 19.6 g
D 49.0 g
E 98.0 g

	A	B*	C	D	E	Omit	FI	DI
%	15.1	38.1	23.9	10.4	9.7	2.7	0.38	0.30

Of course, the manipulation of the concentration in mol/dm^3 and arithmetical difficulties might contribute to the low value of FI. The low value of DI showed that even some of the good students were finding difficulty in solving this type of questions.

In terms of problem solving skill, it is interesting to note students' performance of the following question concerning neutralization.

Item 12 (1983 Local 'O' Level, Paper 1, Q39)

30 cm^3 of 1.0 M aqueous sodium hydroxide will exactly neutralize

1 15 cm^3 of 2.0 M hydrochloric acid
2 10 cm^3 of 3.0 M nitric acid
3 15 cm^3 of 1.0 M sulphuric acid

A 1, 2 and 3 are correct
B 1 and 2 only are correct

C 2 and 3 only are correct
D 1 only is correct
E 3 only is correct

	A*	B	C	D	E	Omit	FI	DI
%	36.5	27.1	3.8	16.9	12.5	3.2	0.37	0.40

Again, the non-1:1 relationship seemed to contribute more to the difficulty of this question. The reaction between aqueous sodium hydroxide and sulphuric acid has been wrongly eliminated.

Although for such a volumetric problem, six pieces of information are required, i.e. $(M_1V_1)/(M_2V_2) = a/b$, the basic principle to be applied is that at neutralization, the number of moles of H^+ ions = number of moles of OH^- ions. As a result, this problem can be simplified if one could think in terms of particles or moles by taking also the meaning of the chemical formula of a compound into consideration.

From the items which have been discussed above, common problems in learning the mole concept can be identified as being the lack of one or more of the following:

(a) Knowledge of chemical formulae.
(b) Awareness of correct association of 'the number of particles/moles' to the 'mass'.
(c) Understanding of the relationship between 'mole' and 'volume'.
(d) Ability to follow the actual stoichiometric relationship rather than blindly applying the 1:1 relationship.
(e) Understanding of the process for finding empirical formulae/molecular formulae.
(f) Understanding of chemical equations and their balancing.
(g) Awareness of relationship between 'mole' and 'concentration in mol/dm^3'.
(h) Application of concept of concentration in mol/dm^3 to solve problems involving reactions in solution.
(i) Skills in calculation involving more than one stage.
(j) Certain problem-solving skills.

All these difficulties are in fact not new and have already been discovered by many researchers. The occurrence of such difficulties does not lie completely with the learners themselves, but it has certainly something to do with the teaching method (Cervellati et al., 1982). What are their implications for our classroom teaching?

Implications for Teaching and Learning

Certain strategies have already been suggested to tackle students' learning difficulties in this area, e.g.

(a) to use analogy or simulation to teach certain related subconcepts in the Mole Concept (Gabel and Scherwood, 1984).
(b) to stress the correct terms and usage when explaining process (Graham, 1983).
(c) to apply the factor-labelled method to solve the stoichiometric problems.
(d) to carefully design suitable test items for assessing certain structured sequences (Lazonby et al., 1985).
(e) to use proper and appropriate instructional strategies to make the learning of Mole Concept at a more concrete level, e.g. the Piagetian-based learning cycle (Schlenker and Perry, 1983).

We strongly believe that the above-mentioned strategies can help students to acquire a better understanding and application of the Mole Concept. But we are more concerned about the fundamental skill necessary for solving the problem. From all the item analyses presented above, we are aware that on average about 50% of our students did not really comprehend the Mole Concept, or they had not 'thought in terms of mole' as they solved the problem.

It is a common finding that students in secondary school normally think of the number of moles of a substance in terms of mass (Novick and Menis, 1976). The performance of students in Item 5 indicates clearly that even 'A' level students think in the same way. This type of thinking is likely to be the consequence of particular teaching strategy teachers have applied to solve problems related to the Mole Concept.

The meaning of 'mole' might have been grasped by students. Its simple relationship to relative atomic mass (or relative molecular mass) and mass of a particular substance might have been drilled and practised. But not much application of this simple concept in solving problems related to the Mole Concept has been stressed. As a result, students may not have to appreciate 'mole' for solving problems involving the Mole Concept. Consequently, the habit 'to think in mole' will not be established with students.

For example, for solving the following simple and straight forward problem:

"Given that $2Mg(s) + O_2(g) \rightarrow 2MgO(s)$, calculate the mass of magnesium oxide formed when 10 g of magnesium is burnt in air".

Teachers usually would teach if 2 × 24 g of Mg (24 g is the relative atomic mass of Mg) will produce 2 × 40 g of MgO (40 g is the relative molecular mass of MgO), then 10 g of MgO will give x g of MgO.

Following this and using the relationship of proportionality, a simple equation containing one unknown x can be set up and hence x can be solved. The step used is completely logical and correct. Such an approach stresses that each balanced chemical equation is given a quantitative meaning in terms of ordinary weight — units, instead of in terms of atoms and molecules (Holderness and Lambert, 1981).

Although the same problem can also be solved directly in terms of the numbers of atoms and molecules by the concept of 'mole', in general, students seem to be happy to use the former problem-solving skill to handle this type of questions. However, we worry that the lack of frequent use of the concept of 'mole' might affect the learning of the other concepts under the Mole Concept. We are also afraid that the following consequences might arise:

(a) Following such a practice, students might tend to be trained in placing their emphasis on thinking of the relationship of masses of reagents/products, rather than that of number of particles of reagents/products.

(b) The cause-effect relationship might not be clear or might even be confused. In an actual chemical reaction, particles (e.g. atoms or radicals) in reagents will undergo rearrangement to form products. So, the number of particles present is the most characteristic part of any chemical reaction. As a result, for any complete reaction, the number of particles of the reagent(s) used and the number of particles of the product(s) formed will have a definite ratio. And consequently, the mass(es) of the reagent(s) will show certain relationship to the mass(es) of the product(s), since different atoms have different masses.

In short, the relationship of masses of reagents(s) to that of product(s) in fact is the consequence of the number of existing particles of reagents in relation to the number of existing particles of products. Once students confuse such cause-effect relationship, the misconception about reaction stoichiometry can occur easily.

(c) Students tend to have a stronger association of chemical symbols, formulae and equations to the masses of the substances and hence less link or even ignore their relationship to the number of particles. Consequently, students might have only half of the real picture of the terms concerned.

The same would be true when students attempt to solve problems related, for example, to:

- the learning of an empirical formula from percentage composition by mass of a compound (or mass of each of the components forming the compound).
- the volume of a substance participating in a reaction.
- the concentration of an aqueous solution in terms of mol/dm^3.
- the use of $M_1V_1/(M_2V_2) = a/b$, if certain quantitative data are given.

Teachers may try to over-emphasize the method for getting correct answers and may place little emphasis on demonstrating the meaning of the problem-solving processes — what actually happens? Some teachers even ask students to memorize and to follow certain format for solving a problem. As a result, students may use a rigid pattern rather than the thinking process, in terms of the number of particles participating in reactions to solve the problem. This may be especially important when teaching 'slow learners'.

This does not mean that to recognize a pattern and to follow such a pattern is not important. But is this approach essential and generalizable? Research findings clearly show that the factor-labelled method is not in general applicable (Larkin and Rainard, 1984). This supports our belief that following rigidly to a certain pattern is not really a proper way to train students in problem-solving. Students should be given the opportunity to appreciate that there are different ways, rather than only one way, to solve the same problem.

It is quite obvious that the heart of the whole problem lies in the fact that when students solve problems related to the Mole Concept, they do not really think in terms of the 'mole'. Such an important point has indeed not been reflected significantly in any of the previous works in this area.

Among all the research studies discussed above, some directly and some indirectly support our view that to cultivate students to 'think in mole' is the fundamental technique for overcoming students' difficulties in learning the Mole Concept. But 'think in mole' has in fact a wider scope for solving problems. Its total applicability is a useful and practical technique in problem-solving.

Perhaps one might bring up the following points for discussion:

(a) 'Think in mole' could be impractical because Avogadro's number is huge and not easy to be imagined or visualized.
(b) The approach of 'think in mole' might, in certain cases, complicate the mathematical treatment or calculation.
(c) In view of their cognitive thinking level, students might have difficulty in accepting such an approach.

'Think in mole' does not mean that students must always associate with the real Avogadro's number (6.02×10^{23}). In fact, in many of the problems, this huge number does not appear, and also is not necessary. What students have to realize is the particular nature of matter and certain definite number (i.e., number of mole) of particles participating in a reaction.

It is possible that some of the operations seem complicated. But, from the mathematical point of view, it is still a problem of a simple relation of proportionality in many cases. Furthermore, students are allowed to use the calculator. So, by proper training, mathematical operations should not become a real problem for students.

The research finding from Rowell and Dawson (1980) demonstrated clearly that with certain instructional manipulation, Grade 11 students (approximately 15 and 16 years old), including those initially mismatched to the task, are able to "understand" the mole, as revealed by their performances on a test of basic skills considered fundamental to that concept and on more complex questions requiring its use in chemical calculations. A Piagetian-oriented learning cycle on 'the mole concept' provided a good example that the use of appropriate instructional strategies can facilitate students' learning at the concrete level (Schlenker and Perry, 1983).

Conclusion

In this study we have used relevant test results from the Second International Science Study and the Local GCE 'O' level Chemistry papers to illustrate some difficulties faced by our students in understanding the Mole Concept. At the same time, we have also advocated that in teaching and learning the Mole Concept, teachers should make use of every opportunity to train students to 'think in mole or number of particles', rather than to follow rigidly certain patterns to solve problems. 'Think in mole' is the key to many problems, and hence the fundamental skill in solving all the problems in the Mole Concept. Furthermore, 'think in mole' also injects a concrete and lively meaning to the process of solving problems, as well as bringing the two aspects, microscopic and macroscopic, together.

In order to have a thorough understanding on how our students tackle problems related to the Mole Concept, more research work should be carried out. We have planned some experimental approaches as well as a scheme for clinical interview. We hope that in the near future, more fruitful results can be reported.

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