

TEXT BOOK ANALYSIS OF THE MOLE AND ITS UNDERLYING CONCEPTS. A TEACHING-LEARNING PERSPECTIVE

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ABSTRACT

In this paper the concepts underlying the mole are identified and discussed from the perspective of the teaching-learning process. Fourteen chemistry textbooks recently or currently in use in Australian secondary schools have been analysed in terms of their descriptions of the mole and its underlying concepts. Such an analysis reveals important trends in the teaching and learning of secondary school chemistry. Calculations using the mole concept are not dealt with in this paper but will be discussed in another paper.

UNDERLYING CONCEPTS

The concepts identified here are atom, molecule, giant structure, formula, relative atomic mass, relative molecular mass, mole (including Avogadro's number) and molar mass (following Gower, 1977).

In recent years there has been some debate as to whether a change in name from atomic weight to relative atomic mass is warranted. Holden (1982) is worth reading in regard to this matter. He concludes that

"no strong or compelling reasons (have) yet been presented for making a change. The alternative most often suggested to atomic weight, relative atomic mass, would cause more confusion than presently exists".

In Holden's opinion,

"'atomic weight' has been used for almost two hundred years and there appears to be no confusion on the part of users".

Some teachers would argue that there has been no confusion on the part of *chemists* but possible confusion for *students* learning the subject. This is probably reflected in the fact that the majority of textbooks examined have adopted the term relative atomic mass (see Table 1).

Table 1
Mass of atom terms and concept sequence for textbooks

TEXT BOOK ¹		CONCEPT SEQUENCE ^{2,4}	MASS OF ATOM ³
CHEM STUDY	1969	/BADHIEF/C/	AW
STRANKS	1975	/AEBFGHI/D/C/	AW, RAW
COTTON	1976	/BAHID/JEF/C/D/	AW, AM
PARRY	1976	/BFHI/ADE/C/	AM
MACARTNEY	1978	/AB/DEF/HI/J/C/	AW, RAM
VERMA	1981	/AB/E/C/DFGIHJ/	AW, RAM
CARSWELL	1982	/ABEF/D/C/EFHIJ/	RAM
McTIGUE	1982	/AB/EFGIHJ/D/C/	RAM
ACADEMY	1983	/ABCD/EFHJGI/	AW, RAM
HUNTER	1983	/B/AD/EFIHJ/C/	AM
JONES	1983	/AE/IHBD CFG/	RAM
BEARD	1984	/ABD/EFG/C/HI/	AW, RAM
BROOKES	1984	/A/EBFHIJDG/C/	RAM
LEWIS	1984	/A/EBFIHJD/C/	RAM
GOWER	1977	ABCDEFGHIJ	RAM

Footnote 1 — Full references are given at the end of the article.

Footnote 2 — A = atom, B = molecule, C = giant structure, D = formula, E = relative atomic mass, F = relative molecular mass, G = relative formula mass, H = mole, I = Avogadro's number, J = molar mass.

— the strokes, /, indicate chapter divisions

— the bars, —, indicate the concepts could be alternated.

Footnote 3 — AW = atomic weight, RAW = relative atomic weight, AM = atomic mass, RAM = relative atomic mass.

Footnote 4 — The sequence is that as presented by the text which is not necessarily that used by a teacher when using the text.

Gower et al (1977) have not included relative formula mass because they took the view that the term molecular mass could be extended to substances which are not strictly molecular making terms such as formula weight obsolete. The authors of recent textbooks, however, have considered it desirable to distinguish between molecular units and formula units, the former being applicable to groups of atoms having independent existence and the latter being applicable to substances like ionic solids. In any case, relative formula mass could be considered an underlying concept along with relative molecular mass. The term relative formula mass is introduced in seven of the fourteen textbooks examined. (See Table 1).

The mole and its underlying concepts are now discussed in terms of an individual analysis and a global analysis.

INDIVIDUAL ANALYSIS

The fact that the mole and each of the underlying concepts are, according to Gagné's model (1970), definitional rather than concrete probably explains why teachers and students, by and large, have experienced difficulty in the teaching and learning of the mole concept. Concrete concepts are those related to directly observable objects while defined concepts are not related to directly observable objects but proceed from verbal cues. Victor (1969) has made a similar distinction in that he classifies concepts as empirical (matters of discovery) or conventional (matters of definition). Since the mole and its underlying concepts are primarily matters of definition I think it important to examine the profile of definitions used in current texts and also their significance for teaching and learning.

Profile of Definitions

Gower et al (1977) arrived at definitions for the concepts by a consensus approach amongst chemists. The definitions appear in Table 2 along with the corresponding definitions from the Handbook of Chemistry and Physics (Weast, 1980). The use made of these definitions across the textbooks examined is shown in Table 3.

Table 2
Definitions of underlying concepts and the mole

CONCEPT	DEFINITION FROM GOWER et al (1977)	DEFINITION FROM HANDBOOK (Weast, 1980)
ATOM (D1)	An atom is the smallest electrically neutral particle of an element which can take part in a chemical change.	An atom is the smallest particle of an element which can enter into a chemical combination.
MOLECULE (D2)	A molecule is the smallest portion of a pure substance which is capable of existing independently and retaining the properties of the original substance.	A molecule is the smallest unit quantity of matter which can exist by itself and retain all the properties of the original substance.
GIANT STRUCTURE (D3)	When large numbers of atoms are bonded together in a regular, repeating pattern, the product is called a giant structure.	—
FORMULA (D4)	The empirical formula of a compound is a representation of a molecule or smallest unit using symbols for the atoms of the constituent elements and numbers to indicate the ratio in which the atoms are present. The molecular formula of an element or compound is the representation of a molecule using numbers and symbols to indicate the numbers of atoms of each element present.	The empirical formula is formed by juxtaposition of the atomic symbols to give the simplest possible formula expressing the stoichiometric composition of the compound in question. The molecular formula is a formula corresponding with the correct molecular weight of the compound.
RELATIVE ATOMIC MASS (D5)	The RAM of an element is the number of times one atom of the element is heavier than 1/12 of an atom of carbon 12.	Atomic mass (weight) is the mass of a neutral atom of a nuclide. It is usually expressed in terms of the physical scale of atomic masses ie. in a.m.u. which is a measure of atomic mass defined as equal to 1/12 of the mass of a carbon atom of mass 12.
RELATIVE MOLECULAR MASS (D6)	The RMM of a pure substance is the number of times one molecule or smallest part of a substance is heavier than 1/12 of an atom of carbon 12.	Molecular weight is the sum of the atomic weights of all the atoms in a molecule.
MOLE (D7)	A mole is the amount of substance which contains an Avogadro number of specified particles.	A mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12
AVOGADRO'S NUMBER (D8)	Avogadro's number is the number of atoms in exactly 0.012 kg of carbon 12.	Avogadro's number is the number of molecules in one mole or gram-molecular weight of a substance.
MOLAR MASS (D9)	The mass in grams of one mole of a pure substance is called its molar mass.	—

Table 3
Definition usage in textbooks

TEXTBOOK		D1	D2	D3	D4	D5	D6	D7	D8	D9
CHEM STUDY	1969	X	X	—	✓	X	X	X	X	—
STRANKS	1975	X	X	—	✓	✓	✓	✓	✓	—
COTTON	1976	—	X	—	✓	X	X	X	X	✓
PARRY	1976	X	X	—	✓	X	X	X	✓	—
MACARTNEY	1978	—	✓	—	—	X	X	X	—	—
VERMA	1981	✓	✓	—	✓	✓	✓	✓	—	—
CARSWELL	1982	—	✓	—	—	✓	X	✓	—	✓
McTIGUE	1982	—	—	—	✓	✓	✓	✓	—	✓
ACADEMY	1983	—	—	—	✓	✓	✓	✓	✓	✓
HUNTER	1983	X	X	—	✓	✓	✓	✓	✓	✓
JONES	1983	—	X	—	✓	✓	✓	✓	✓	—
BEARD	1984	✓	X	—	X	✓	✓	✓	✓	—
BROOKES	1984	—	✓	—	✓	✓	✓	✓	✓	—
LEWIS	1984	X	X	—	✓	✓	✓	X	✓	✓

KEY:- (✓) effectively *identical* to either definition in Table 2.

(X) effectively *different* to either definition in Table 2.

(—) no definition given.

One noticeable fact is the low usage of the formal definitions for atom and molecule. There are some difficulties associated with the use of these definitions in an educational context. The Handbook (Weast, 1980) definition for atom does not really preclude the possibility that an electron could be defined as an atom since it is a particle of an element which can enter into a chemical combination. This is probably why Gower et al (1977) defined the atom as the smallest *electrically neutral* particle of an element which can take part in a chemical change. Also textbook writers may be reluctant to introduce the formal definition of atom before the notion of chemical change has been introduced. This, of course, is critical to the understanding of the definition.

In the initial stages of a chemistry course a teacher usually considers it important to distinguish between an atom and a molecule. However, the formal definition for molecule implies that the monatomic noble gases are molecular since the atoms of these gases are the smallest parts having independent existence. Thus particles of neon could be classified as atoms or molecules. This probably explains why teachers and textbook authors are reluctant to use the formal definition for molecule, especially since one usually thinks of molecules in terms of combinations of atoms, at least in the initial stages.

The notion that molecules must have independent existence can be traced, according to the dictionary of the history of science (Bynum, 1983), to Seventeenth Century European corpuscular philosophers. The property of *separate existence* is used by modern chemists to distinguish the molecule from network ionic and covalent solids. Thus if one defined a molecule simply as a combination of atoms one could regard network solids as molecules. The idea of *separate existence* appears therefore to have been retained in the definition to distinguish between the different substances in terms of the nature of the chemical bond. Thus the formal definition for molecule does not preclude the fact that in the majority of cases it is a combination of atoms but it specifies only the attributes of *smallest part, separate existence, and same properties as the substance*.

Most textbooks written in the 1980's use the formal definition for the mole while texts written in the late sixties and the seventies use alternatives. The alternatives have often met with criticism such as that by Hudson (1981) who questions the definition of the mole as the chemists' dozen. The illustration of 'dozen' for a mole is used by five of the fourteen textbooks examined (see Table 4). Hudson (1981) says that the chemists' dozen is really Avogadro's number and not the mole. He is obviously identifying the concept of 'dozen' with that of 'number' and not 'amount'. Macdonald (1975), on the other hand, believes that 'dozen' is a unit of amount and not number. He says that

Table 4: Explanations and Illustrations for RAM and Mole.

TEXTBOOK	RAM		MOLE	
	E	I	E	I
CHEM STUDY	1969 1 (Definition)	0	2 (Definitions)	2 (dozens, dollars/cents)
STRANKS	1975 2 (Mass Spectrometry, Definition)	0	2 (Definitions)	4 (basketful, dozen, pound, emus)
COTTON	1976 1 (Definition)	0	1 (Definition)	2 (dozen, dollars)
PARRY	1976 1 (Definition)	0	1 (Definition)	1 (dozen)
MACARTNEY	1978 2 (Double pan balance, Definition)	0	3 (Atomic masses, Definition, Chemical Equations)	1 (dozen)
VERMA	1981 1 (Definition)	0	3 (Atomic masses, 2 definitions)	0
CARSWELL	1982 2 (Mass Spectrometry, Avogadro's Law)	0	2 (Definitions)	0
McTIGUE	1982 1 (Mass Spectrometry)	0	2 (Definition, molar amounts)	0
ACADEMY	1983 2 (Electrolysis Definition)	0	1 (Definition)	3 (2 kg potatoes, 3 L milk, 5 eggs)
HUNTER	1983 3 (Definition, Determination of, Historical)	0	2 (Definitions)	2 (sand grains, golf balls)
JONES	1983 2 (Definition, Mass Spectrometry)	0	2 (Definitions)	1 (cake making)
BEARD	1984 1 (Definition)	0	1 (Definition)	0
BROOKES	1984 2 (Definition, Mass Spectrometry)	0	2 (Definitions)	1 (apples)
LEWIS	1984 2 (Definition, Mass Spectrometry)	0	1 (Definition)	0

KEY:- — RAM = Relative atomic mass
 — E = explanation in terms of chemical phenomena
 — I = illustration from the observable world.

"even first-form pupils appreciate the conceptual difference between number and amount without realizing it. You must try counting up to 20 saying 'dozen' instead of '12'..... They will very quickly point out the error of your ways"

I believe Hudson's argument, however, is correct since children rejecting 'dozen' in the one to twenty series are correcting the paradigm, not the concept. 'Dozen' is a number related to ancient base 12 number systems. A statement such as *'a mole is 6.023×10^{23}* , is obviously incorrect since the mole is being identified as a number. However, to say that 6.023×10^{23} molecules of oxygen, or 32 gram of oxygen, or 22.4L of oxygen at STP, represents a mole of oxygen in the form of molecules must be correct since it identifies *mole* with *amount*.

Definitions and Learning

Herron et al (1977) identified three important steps in the learning of science concepts. These steps are

1. find the critical attributes
2. find the variable attributes
3. look for examples and non-examples

Since the concepts being discussed here are definitional and not concrete, the examples and non-examples must take the form of models. Herron (1977) applies his three-step process to the mole concept and I have reproduced his analysis in Appendix 1. Irwin and Davis (1980) have also advocated the use of examples and non-examples in stating concepts in terms comprehensible to students. Ben Selinger (1984) has proposed the use of 'cultural observables' in making science concepts more relevant. In a recent paper, Gabel et al (1984) report their analysis of the use of analog tasks in the teaching of the mole concept. The analogs used were oranges and granules of sugar. The use made by current textbooks of analog tasks or cultural observables for the concepts of relative atomic mass and mole is shown in Table 4. Illustrations from the observable world are non-existent for relative atomic mass and the illustrations for the mole are more by way of comment than instruction. An analysis similar to the type given by Herron (1977) would be most valuable particularly with associated exercises involving examples and non-examples. Too little time is spent in providing for the understanding of these fundamental concepts. Usually a definition of the concept is given and then exercises involving calculations are set. While it is true as Hudson (1981) states that the use of a concept can precede its understanding, it does not necessarily follow that exercises involving the various calculations with a complex concept such as the mole can provide an understanding of it. Exercises involving calculations undoubtedly provide an understanding of the calculations but not necessarily the fundamental concepts. Identification of examples and non-examples, however, can give clearer insights into the fundamental concepts.

An exercise I have found useful in introducing the idea of relative mass is shown in Appendix 2. Circular pieces of cardboard are joined together with tape and weighted (if necessary) with pieces of tape so that the mass corresponds to some predetermined value. In the exercise four circular cardboard objects, representing atoms, were weighted to give masses of 0.10, 0.20, 0.50, 0.70 gram respectively. These masses were chosen so that relative masses of 1, 2, 5, 7 could be easily deduced and ten of each cardboard object would be used to give masses of 1 g, 2 g, 5 g and 7 g respectively. This was then related to Avogadro's number and the mole as shown in Appendix 2. Once a student has examined a concept in a culturally observable context, the learning of a formal definition can then become, as Sutton and Haysom (1974) say, a useful revisory summary.

GLOBAL ANALYSIS

Given the concepts underlying the mole, the question arises as to whether these concepts should be ordered or networked in a certain pattern for learning. Robert Gagné (1970) has proposed that before certain concepts can be learnt certain prerequisite concepts should be understood. This has led to the idea of learning hierarchies. Gower et al (1977) proposed a hierarchy for the concepts dealt with in this paper as shown in Figure 1.

Textbook sequential development of the eight concepts is compared to that of Gower et al in Table 1. This shows quite a variety of approaches across the textbooks, but I do not think that as scientists and educators we are yet in a position to state that one sequence or hierarchy is more valid than another. A study of hierarchy validation literature will reveal some of the difficulties inherently involved in validating hierarchies (see Gower et al, 1977 and Griffiths et al, 1983). It appears that, for the time being, hierarchies and sequences of development will be arrived at through logical analysis of content.

The introduction of giant structures before formulae as proposed in Gower's model is

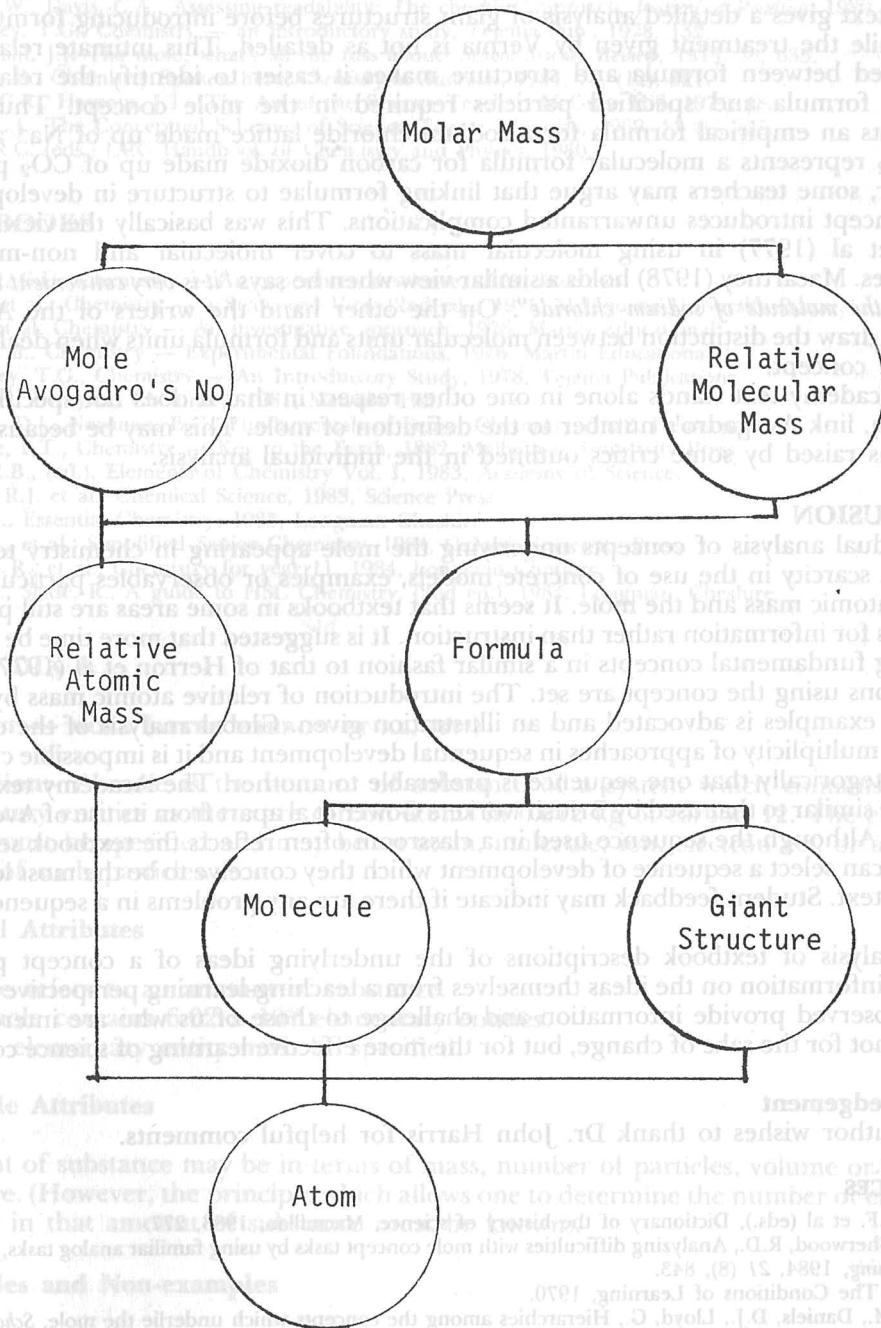


Figure 1: Hierarchy of theoretical concepts underlying the mole (Gower et al, 1977)

that used by only two texts in this study (Academy of Science and Verma). The Academy of Science text gives a detailed analysis of giant structures before introducing formulae and mole while the treatment given by Verma is not as detailed. This intimate relationship established between formula and structure makes it easier to identify the relationship between formula and specified particles required in the mole concept. Thus NaCl represents an empirical formula for a sodium chloride lattice made up of Na^+ and Cl^- and CO_2 represents a molecular formula for carbon dioxide made up of CO_2 particles. However, some teachers may argue that linking formulae to structure in developing the mole concept introduces unwarranted complications. This was basically the view held by Gower et al (1977) in using molecular mass to cover molecular and non-molecular substances. Macartney (1978) holds a similar view when he says "*it is very convenient to refer to NaCl as the molecule of sodium chloride*". On the other hand the writers of the Academy textbook draw the distinction between molecular units and formula units when dealing with the mole concept.

The Academy text stands alone in one other respect in that it does not specifically, in definition, link Avogadro's number to the definition of mole. This may be because of the objections raised by some critics outlined in the individual analysis.

CONCLUSION

Individual analysis of concepts underlying the mole appearing in chemistry textbooks reveals a scarcity in the use of concrete models, examples or observables particularly for relative atomic mass and the mole. It seems that textbooks in some areas are still primarily mediums for information rather than instruction. It is suggested that more time be given to analysing fundamental concepts in a similar fashion to that of Herron et al (1977) before calculations using the concept are set. The introduction of relative atomic mass by way of concrete examples is advocated and an illustration given. Global analysis of the concepts reveals a multiplicity of approaches in sequential development and it is impossible currently to say categorically that one sequence is preferable to another. The Academy text uses a sequence similar to that used by British workers Gower et al apart from its use of Avogadro's number. Although the sequence used in a classroom often reflects the textbook sequence, teachers can select a sequence of development which they conceive to be the most logical in their context. Student feedback may indicate if there are any problems in a sequence being used.

An analysis of textbook descriptions of the underlying ideas of a concept provides valuable information on the ideas themselves from a teaching-learning perspective and the trends observed provide information and challenge to those of us who are interested in change, not for the sake of change, but for the more effective learning of science concepts.

Acknowledgement

The author wishes to thank Dr. John Harris for helpful comments.

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APPENDIX 1

CONCEPT — MOLE (AFTER HERRON ET AL, 1977)

Definition:- A mole is the amount of substance of a system which contains as many elementary entities as there are carbon atoms in 0.012 kg of carbon 12. The elementary entity must be specified and may be an atom, molecule, ion, electron etc. or a specified group of such particles.

Critical Attributes

1. Mole refers to an amount of substance.
2. A mole contains 6.02×10^{23} elementary entities.
3. The elementary entity must be specified.

Variable Attributes

Amount of substance may be in terms of mass, number of particles, volume or any other measure. (However, the principle which allows one to determine the number of elementary entities in that amount of substance must be known).

Examples and Non-examples

Group 1

(In these examples, the student must apply certain rules of arithmetic but nothing more. They serve to focus on critical attributes 2 and 3).

Examples

6.02×10^{23} cars (car)

Non-examples

6.02×10^{22} cars (car)

3.01×10^{23} bikes (wheel)

6.02×10^{23} bikes (wheel)

1.20×10^{21} reams of paper (sheet)

1.20 gross pencils (pencil)

Group II

(In these examples the student must apply a rule which relates the atomic mass of the element and the number of particles in that mass expressed in grams).

Examples

16g oxygen (O atom)

14g nitrogen (N atom)

35.5g chlorine (Cl atom)

Non-examples

15g oxygen (O atom)

28g nitrogen (N atom)

35.5g chlorine (Cl_2 molecule)

Group III

(In these examples the student must apply rules which relate molecular weight to numbers of molecules).

Examples

32g oxygen (O_2 molecule)

18g water (H_2O molecule)

9g water (H atom)

Non-examples

16g oxygen (O_2 molecule)

18g water (atom)

9g water (H_2O molecule)

GROUP IV (other rules)

Examples

2g oxygen (electron)

22.4 L of gas at STP (gas particle)

1.0×10^{23} C^{12} (proton)

Non-examples

2g oxygen (O atom)

22.4 L of H_2 at STP (H atom)

1.0×10^{23} C^{12} (nucleon)

APPENDIX 2

EXERCISE ON RELATIVE MASS

Apparatus:

- electronic balance
- pieces of weighted circular cardboard representing atoms A, B, C, D.

Procedure:

1. Find the mass of one atom of A,B,C and D and record your masses in the format:

A _____g

B _____g

C _____g

D _____g

2. If we let the mass of atom A be represented as 1 unit, write down what the masses of the other atoms would be. Record vertically beside the masses determined above.
3. If we let the mass of atom C be represented as 1 unit, write down what the masses of the other atoms would be. The masses recorded in 2 and 3 are relative masses whereas the mass in 1 is an actual mass.
4. The relative atomic mass of the elements is determined by letting the mass of carbon 12 be exactly 12 units.
5. Add atoms A to the pan until 1 g is measured. Write down the number of atoms on the pan. In the same way, add atoms B, C, D to the pan until masses of 2g, 5g and 7g respectively are measured. Write down the number of B, C and D atoms on the pan for their respective masses of 2g, 5g and 7g.
6. What do you notice about the number of atoms in each case?
7. Thus when relative masses 1, 2, 5, 7 are expressed in gram to give 1g, 2g, 5g, 7g, these masses require the same number (10 in this case) of atoms in each case. When relative masses of 1, 12, 16 for hydrogen, carbon and oxygen are expressed in gram to give 1g, 12g, 16g of these elements, these masses contain the same number of atoms in each case. The number for real atoms is 6.02×10^{23} just like we obtained 10 for our example. (This exercise can be extended depending on the needs of the class).