Chapter 6
Teaching Stoichiometry with Particulate Diagrams – Linking Macro Phenomena and Chemical Equations

Maurice Man Wai Cheng and John K. Gilbert

Abstract This chapter explores a way stoichiometry is introduced to secondary school students that aims at fostering a conceptual understanding and a relational understanding of the chemistry triplet (i.e. macro, submicro and symbolic). We start by discussing students' difficulties in understanding macro phenomena, submicro and symbolic representations that are relevant to the learning of stoichiometry. Then we argue that a teaching sequence starting with macro phenomena, then a submicro representation of the corresponding macro phenomena, and finally deriving a chemical equation based on the submicro representation, should be likely to facilitate students' understanding of stoichiometry. Strategies that guide the selection of a particular macro phenomenon and diagrammatic representation of submicro interactions are proposed. We then analyze a lesson that was conducted based on the design. Particularly, we focus on good practice of teaching with diagrammatic representation of submicro phenomena that served to link macro phenomena and chemical equations as symbolic representations.

Keywords Stoichiometry • Equations • Chemistry • Macro and micro phenomena • School science culture • Symbolic representations • Teaching sequence • Graphic organizer • Mental representation • Diagram

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6.1 Introduction

This chapter is based on the premises that chemistry learning can be a very challenging task to many students. A part of the reason is that a chemical idea is often represented in different ways. We will discuss some difficulties students may face when they learn stoichiometry in the light of their possible experiences in doing practical activities (the combustion of magnesium, for example), and in understanding submicro and symbolic representation of the concept.

6.1.1 Learning of Macro Phenomena

In chemistry, a vast variety of substances are reduced to ‘simple’ and pure forms so that models of properties of substances, such as solubility, hardness, chemical reactivity, the amount of which that would react with another substance, can be developed. Pedagogically, instead of investigating metal objects in the form of window frames, water pipes or the body of mobile phones, very often strips of pure metals are studied. We teachers may use ‘oxygen’ to replace ‘air’ or use them interchangeably (irrespective of the possible students’ prior learning that oxygen constitutes only around 21 % of air!) when we talk about a practical activity that involves oxygen, for example, the combustion of metals. While teachers can easily move from the daily phenomena to the macro phenomena – metal objects of different specific functions represented as decontextualized metal strips; air represented as oxygen – they may not be aware that such a ‘simplification’ can be a hurdle to many students. Having to reason with macro phenomena can be regarded as a ‘border crossing’ activity in which students would have to cross from their daily culture to the school science culture (Aikenhead 1996).

Students also have to handle the procedural and conceptual aspects of practical activities, understand the conceptual underpinnings of procedures, and to arrive at certain conceptual understanding from the results, after completing the procedures. Yet much of the lesson time seems to have spent on the procedural aspect of practical activity (Abrahams 2011) and that there are so much procedural ‘noise’ in practical activities (Hodson 1993). Moreover, students have to deal with ‘inconsistent results, inconclusive results, and even no results’. There should be little surprise that students find learning macro phenomena in chemistry a formidable task. Watson et al. (1995) investigated the effect of practical work on students’ understanding of combustion. In one of their assessment items, students were asked to choose among five possible reasons why burning of 6 g magnesium could yield a product of 10 g. It was found that among 149 English students aged 14–15 who had extensive practical experience of burning of metals, only 26 % picked the scientific explanation (21 % chose the option ‘the result was impossible’; 27 % did not respond). Take another item that assessed the idea of mass conservation – as a basis for the learning of stoichiometry – as an example, only 30 % of Hong Kong Year 8 students (aged 13–14) believed that the total mass of 10 g salt and 100 g water conserved after the salt is dissolved in water (Cheng 2013). Although the question demanded macro understanding only, it could still be a challenge.

6.1.2 *Learning of Submicro Representations*

Chemistry can be characterized as making sense of macro phenomena through the interactions of submicro entities. In this connection, there are three issues that may impede students learning:

(1) Research studies over the years have reported that some students may ascribe macro properties of substances to the properties of individual submicro entities. For example, some students explained the thermal and electrical conductivity, malleability and the strength of metals in terms of individual atoms having these properties (Ben-Zvi et al. 1986). Combustion of a substance was regarded as the burning of atoms, and hence these atoms vanish (Andersson 1990). Rusting was regarded as the rusting of iron atoms. Students' commitment to perceptual-based explanations of physical phenomenon can impede their learning of chemistry in terms of submicro entities (Jaber and BouJaoude 2012).

(2) Some representations used in classroom teaching (in textbooks and in science curricula) may impede meaningful learning (Taber 2002). For example, ionic compounds such as sodium chloride are often represented and emphasized as an ion pair formed by the electron transfer from a sodium atom to a chlorine atom. Such a representation is believed to be closely related to students' representations of an ion pair of sodium and chlorine atom (e.g., in Ben-Zvi et al. 1987) and hence their difficulties in explaining macro properties of substances (Taber 2001). Also, it has been shown that teachers' talk may rapidly jump between macro phenomena and submicro entities, and use words and symbols unspecifically (e.g., the use of "water" and "H_2O" to refer to liquid water and water molecules at different occasions). Such a practice have made the successful learning of science unlikely to happen (Stieff et al. 2013).

(3) The learning of submicro entities is complicated by the variety of representation modes. Inherently each of these modes has its limitations. For example, a weak acid is usually represented in diagrams by a few circle pairs (usually labeled as 'HA') and two (or four) solitary circles (labeled as H^+ and A^-). While it represents the idea of partial dissociation of a week acid, it significantly amplifies the percentage of week acid molecules that dissociates in water. It is through the degree of dissociation (a mathematical mode) that the percentage of dissociated molecules is represented (Cheng and Gilbert 2009). Students would have to select and integrate ideas represented in the diagrammatic and mathematic modes. It is likely that some students may not be able to select and construct meanings in the scientific sense. In a similar way, diagrammatic

mode may not represent the relative size of an atom, electron shells and atomic nucleus accurately. Other modes of representation, such as an analogy, have to be used to represent the massive size of an atom as compared with that of its nucleus (Harrison and Treagust 1996). The demands for selecting and integrating information from different modes of submicro representations could create a hurdle to students' learning.

6.1.3 Learning of Symbolic Representations

Learning to manipulate symbols that represent macro phenomena, submicro entities and their interactions is an extremely demanding task (Taber 2009). There might have been an unexamined assumption that learning of science would be deemed successful if students were able to just handle this most abstract representation. However, it has been shown that those who were able to balance the chemical equation $3H_2 + N_2 \rightarrow 2NH_3$ would represent the product as a row of six connected hydrogen atoms (Yarroch 1985); and students are more likely to solve a simple task in stoichiometry that demanded algorithmic mathematical manipulation than a similar task that assessed conceptual understanding (Nurrenbern and Pickering 1987). Also, although there was a significant difference between higher and lower ability students in solving algorithmic problems on stoichiometry, these groups demonstrated no difference in their performance in solving conceptual tasks (Cracolice et al. 2008). In short, being able to balance chemical equations or to solve quantitative problems in stoichiometry does not guarantee a conceptual understanding or an understanding of the meanings behind these symbolic manipulations.

The learning of stoichiometry in school chemistry demands a prior understanding of concepts related to that of the mole. Other than having to understand chemical formulae, the meaning of 'stoichiometric coefficient' and the notation of chemical equations (e.g., Sanger 2005), the learning of stoichiometry is complicated by need to manipulate the wide range of numerical figures that are often represented by scientific notations. Such a difficulty was reported in Gabel and Sherwood (1984). Students ($n = 332$, high school level) were asked to calculate the number of oranges/granules of sugar, their weight or their volume based on some given data. The tasks were analogical to those demanded in calculation based on the mole concept, for example, to find out the mass, volume or number of particles based on given information. It was found that there were statistically significant differences between students' performance when they handled granules of sugar that demanded manipulations of (i) the number of concrete item 'bag' and the word 'billion', and (ii) huge numerical figure represented as 'billion' and using scientific notation. Also, it was found that students performed significantly better when the numbers they manipulated involved a whole unit rather than a fractional unit (e.g., if a dozen oranges weighted 4 lbs, how many oranges would you have if you had 20 lbs of oranges *vs.* if you had 3 lbs of oranges?). In short, students face two aspects of challenges in their learning of symbolic representations of stoichiometry: (i) to make sense of various notations and their conceptual meaning used in chemical equations; (ii) to handle the mathematics that represents the amount of reactants and products.

Given the myriad number of possible challenges students might face in their learning of stoichiometry, careful decisions must be taken on how various representations are orchestrated in classroom teaching in order to facilitate meaningful learning. In the next section, we will propose a teaching sequence on the use of different representations in the teaching of introductory stoichiometry. A chemistry lesson will then be analyzed in the light of such a teaching sequence.

6.2 Towards a Teaching Sequence for Introductory Stoichiometry

There have been various suggestions on the teaching of concepts related to amount of substance and stoichiometry. These suggestions included: using the idea of 'amount of substance', 'chemical amount' and 'the mole' according to consensus in the scientific community (Nelson 2013); using a graphic organizer to tabulate the simplest stoichiometric ratio and hence the mass of each of the reactants and products (so as to highlight the concrete mass relationship) before embarking on solving a problem (Koch 1995); having students to visualize – through imagination – the gigantic magnitude of Avogadro's number (e.g., the volume of 6.02×10^{23} grains of sand (van Lubeck 1989), the volume of Pacific Ocean as 7×10^{23} ml (Alexander et al. 1984)). These strategies have their values in enhancing students' understanding. As the roles of the triplet (Gilbert and Treagust 2009; Talanquer 2011; Taber 2013), and their visual representations (Gilbert et al. 2008), have now been established, they should inform the development of teaching strategies that enhance students' conceptual understanding of stoichiometry.

The reaction between magnesium and oxygen, which may be regarded as an exemplar chemical reaction for the teaching of stoichiometry, can be represented as one or many of the following ways:

(1) The chemical equation with or without the physical states of the substances: $2\ Mg + O_2 \rightarrow 2MgO$ (symbolic).
(2) The concrete amount of magnesium metal and oxygen gas reacted and the amount of magnesium oxide produced, e.g. 24.3 g Mg, 16.0 g O_2, 40.3 g MgO/48.6 g Mg, 31.0 g O_2, 80.6 g MgO. (macro)
(3) Students may compare the mass of a piece of magnesium and the mass of its oxide after a complete combustion (macro). The recorded data would form the basis through which students would learn, explore, or verify stoichiometry.
(4) Students may conduct and observe the combustion of a piece of magnesium (macro). Also, they may be asked to predict and measure the relative mass of the magnesium and its oxide qualitatively.
(5) A 2D diagram showing the simplest ratio of the number of magnesium atoms, oxygen molecules and formula units of magnesium oxide involved in the

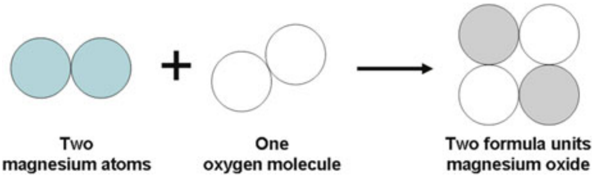

Fig. 6.1 A submicro representation of the combustion of magnesium

chemical reaction/equation (submicro) (see Fig. 6.1). In many textbooks, such a kind of diagram is placed under its corresponding chemical equation. It is likely that textbook authors intend to support students' understanding of the chemical equation.

(6) A 2D diagram showing a certain number of the chemical species involved in the chemical reaction/equation (submicro), e.g., a stack of 6×6 regularly and closely packed circles representing a part of magnesium solid and some circle pairs representing oxygen gas at one side, and a stack of 6×12 regular and closely packed circles at an other side representing a part of magnesium oxide as the product. Compared with Fig. 6.1, this diagram, to a certain extent, represents the physical state of the chemicals. Such a diagram intends to facilitate students' association of the combustion of magnesium (macro) with the interaction of chemical species at the submicro level. Nevertheless, the number of chemical species is not identical to the stoichiometric coefficient. It would be a challenge for students to associate the diagram with its chemical equation.

Given the variety of activities and representations that are available, how to select them and how they should be orchestrated in classroom teaching becomes an issue. Research studies have shown that students tended to adopt algorithmic manipulations and lacked conceptual understanding of stoichiometry represented in particulate diagrams (a form of diagram in which submicro entities are represented as circles or clusters of circles). There have been suggestions that teachers should use more proper definitions of scientific concepts and should help students to relate Avogadro's number/stoichiometry with macro phenomena. While we find these advices useful, we believe that unless students are taught to mentally visualize submicro phenomena/interactions, their conceptual understanding of stoichiometry cannot be guaranteed. In this connection, we would like to suggest that the teaching of introductory stoichiometry will possibly be most meaningful to students when the macro phenomena, submicro and symbolic representation are utilized. And it is important that teachers should avoid confusing students by jumping across different representations (Stieff et al. 2013) before students develop competence in each of the representations. In the following sections, we will propose,

(i) a general sequence of representations that teachers may adopt in order to facilitate students' construction of ideas of stoichiometry, and
(ii) specific representations, based on (1) to (6) discussed above, that teachers may use to facilitate learning of stoichiometry.

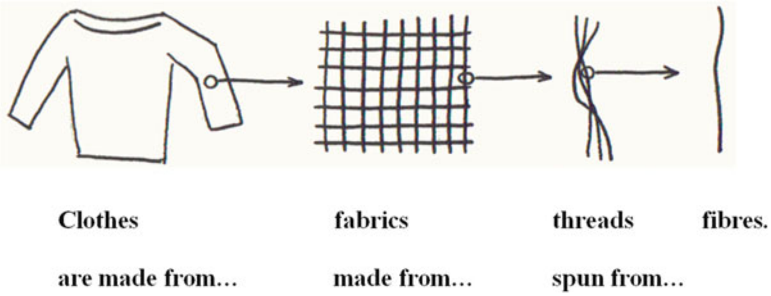

Fig. 6.2 An approach of exploring properties and structure (Redrawn based on Hill et al. 1989, p. 41)

6.2.1 A General Approach to a Teaching Sequence

We concur with Johnstone (1982, 2010) that macro, submicro and symbolic representations are equally important and that simply working with macro phenomena alone may constitute meaningful learning experience for students. We are also aware that teachers around the world are working with curricula that are decided by local or national authorities (Risch 2010). It is still a norm that competence in school chemistry is defined in terms of students' relational understanding of macro phenomena, submicro and symbolic representations.

It has been suggested that it is good practice to start teaching a new chemical idea with an investigation of the corresponding macro phenomena. Take the teaching of structure and properties of materials as an example, Millar (1990) recommended that students could start by exploring (1) the properties of a woolen jumper, and then (2) how pieces of fabric make up the jumper, (3) how threads make up the fabric, (4) how threads are spun from fibres (Fig. 6.2). This exploration exemplifies a sequence through which students would better handle the materials macroscopically (the woolen jumper) at the outset.

The sequence is coherent with the psychological principle of learning that students should explore phenomena that they are familiar with at the outset (Nelson 2002; Johnstone 2010). The properties of the phenomena under investigation are made sense of at another level that students can readily visualize. Such a sequence is useful for teachers when they plan their teaching of structure–property relationships in chemistry. We propose that the sequence can readily be extended in the teaching of stoichiometry.

Pedagogy that starts with exploring macro phenomena has also been investigated in the teaching and learning of chemical reactions, such as the combustion of reactive metals, metal ion displacement, the neutralization of acids and alkalis/metal oxides, ionic precipitation reactions (Treagust and Chandrasegarana 2009). This study suggested a teaching sequence that fosters Grade 9–10 students' understanding of the triplet relationship. In the control group, students were taught 'traditionally', meaning that teaching activities involved practical activities (macro) and writing balanced and ionic equations (symbolic). In the experimental group, students were taught submicro representations of the corresponding chemical reactions as well. Post-test comparison of the two groups showed that the learning of the experimental group was better than the control group.

The teaching sequence adopted in the experimental group was that students were taught submicro representations of the macro phenomena before they learnt to represent through chemical equations. Also, submicro representations were used as an explanation of the observed chemical changes. Ionic equations were hence deduced, rather than merely arrived at by crossing out the spectator ions from chemical equations (*ibid.* Figure 7.3, p. 159). Given the positive outcome of this teaching strategy, it is suggested the teaching sequence can be extended to the introduction of stoichiometry. A general teaching sequence of stoichiometry is hence proposed:

(1) A macro phenomenon/phenomena are introduced to students, possibly as a practical activity. As suggested by Hodson (1993) and Abrahams (2011), measures should be taken to ensure students are not distracted by the procedural understanding and handling apparatus. Also, observable results should be apparent to students.

(2) A submicro representation(s) of the macro phenomenon is then discussed with students. As suggested by Johnstone (2010) and Stieff and his colleagues (2013), it is important that teachers should avoid too rapidly jumping across different representations in their teaching. As submicro representations are often in the form of diagrams, measures should be taken to ensure students are able to decode and relate different components of the diagrams so that they can interpret the diagrams as intended by the teachers.

(3) A symbolic representation(s) is deduced from the submicro representation. As far as writing a chemical equation is concerned, students should be guided towards its relationship with the submicro representation and macro phenomena. The meaning of stoichiometric coefficient and subscript, where applicable, should be differentiated. It is through the chemical equations that stoichiometric calculation is conducted.

The key to the success of this sequence will be the care with which the macro phenomena for study are selected and the submicro representations to be used arrived at.

6.3 Selection of Macro Phenomena and Representations

6.3.1 Macro Phenomena

In a previous section, two similar practical activities involving the combustion of magnesium were proposed. One was the observation of the appearance of magnesium and its product after combustion, and to compare qualitatively the changes in mass of the solid before/after the burning; the other involved measuring the exact mass of magnesium and magnesium oxide so that stoichiometry between the reactant and the product can be inferred or verified.

In conducting a practical activity that aims at the learning *of* science, it is essential that students could easily identify good results so that their learning of the target concept can be supported (Hodson 1993). We note it is unlikely that the combustion of magnesium in the school laboratory could yield good results that support the learning or verification of stoichiometry. Some of the magnesium may remain unreacted, while some materials may escape from the crucible where the combustion takes place. Indeed, the results of this activity have been known to be so inconsistent that it has been used as a critical incident for teachers' decision making (in Nott and Wellington 1998). Therefore, quantitative study of the exact mass relationship between magnesium and magnesium oxide does not seem to be a recommendable activity in the learning of stoichiometry.

Some students hold the preconception that residues from burning are lighter than their reactant. The combustion of magnesium can be framed as a cognitive conflict activity. Students are asked before the activity their expected change in the mass (unchanged, increased, or decreased) of the piece of magnesium after combustion. It is likely some students would predict that the mass would decrease after burning. The increase in mass would be contradictory to some students' preconception and constitute a cognitive conflict that demands explanations alternative to their prior understanding (Limón 2001). Given the spectacular observable changes, it is likely that simply having students experience the phenomena of combustion and measuring the mass of the piece of magnesium and the mass of the product would be useful in motivating students and to prepare them for a submicro explanation of the reaction.

6.3.2 Submicro Representation

A major difference between the two particulate diagrams (proposed in Fig. 6.1 at point (5) and the description in point (6) on p. 4) is the number of particles represented. These two diagrams may fit into the idea of single-particle diagrams and many-particle diagrams respectively (Bucat and Mocerinob 2009). In general, a single-particle diagram, i.e., a diagram showing a single molecule, would be sufficient to represent ideas such as the stereostructure of molecules and bond angle of certain atoms/groups. Some ideas, such as melting, boiling, dissolution, states of matter, equilibrium, strength of ionic substances and metals, cannot be meaningfully represented by single-particle diagrams. Rather, they have to be represented through a collection of the particles that are involved in the process. Based on their investigation of how students visualized chemical reactions, Ben-Ziv and colleagues (1987) suggested that some of students' misunderstanding of chemical reactions related to textbooks' misuse of single-particle diagrams in representing ideas that should have been done with many-particle diagrams.

We postulate that the single-particle diagram (in Fig. 6.1) may not support learners' translation of the submicro representation into a chemical equation. Particularly, its convention does not differentiate when to represent the number of particles as a stoichiometric coefficient (as 2Mg rather than Mg_2) and as a subscript (O_2 rather than 2O). As some students have confusions about the two numbers (e.g., Sanger 2005), the single-particle diagram that may create the confusions should be avoided. Moreover, the single-particle diagram does not give students any hints about the physical states of the substances involved in the reaction. We are aware that such hints (i.e., the random spread of particles far apart to represent a gas, regularly and closely arranged particles to represent a solid) are themselves conventions and they may not be apparent to students. Yet such conventions are the representations that we expect students to learn. Therefore, the many-particle diagram should better support students' understanding of the macro phenomena of burning magnesium.

6.3.3 Symbolic Representation

We have proposed that a many-particle diagram would better be used as a submicro representation of the combustion. We would suggest that the same diagram should also serve as a bridge to the formulation of a chemical equation. Given that some students were known to have difficulties in writing a chemical equation based on particulate diagrams (Nurrenbern and Pickering 1987; Sanger 2005), teachers should support students' translation of the diagram to the equation. Such a support includes counting the number of magnesium atoms, oxygen molecules and the number of formula unit of magnesium oxide in the diagram with the students, which would then lead to the simplest ratio of these entities and hence the equation $Mg + O_2 \rightarrow 2MgO$. This stage of the teaching should focus on the translation from the number of submicro entities from the many-particle diagram into a balanced chemical equation. We propose that the physical states of the chemicals may not be necessary at this moment. An inclusion of the state symbols simultaneously may confuse students about whether the focus should be on the macro phenomena or the many-particle diagram. It is envisaged that the physical state should be included only when the teacher would link the equation to the macro phenomena.

6.4 A Sequence for Introducing Stoichiometry

It is suggested that the following activities or representations in sequence should be likely to facilitate students' learning of introductory stoichiometry:

(1) Observation of the burning of magnesium, and the prediction of the changes in mass of magnesium and its combustion product;
(2) A many-particle diagram representing the submicro entities involved in the chemical reaction. The cognitive conflict (that the mass of the product is less

than that of the magnesium) may be resolved by focusing on the number of magnesium ions and oxide ions produced from the given number of magnesium atoms.

(3) The balanced chemical equation of the reaction is derived from the many-particle diagram. State symbols are added subsequently when teachers intend to draw students' attention to the linkages of the equation and the macro phenomena.

It is envisaged that such a teaching sequence would offer students meaningful experience for a mathematical manipulation of the exact mass relationship between the reactants and product. This sequence was trialed, as is shown in the following two sections.

6.4.1 Background of the Lesson and Students' Prior Learning

This section describes and then analyzes a chemistry class in which the teacher introduced the idea of stoichiometry. The teacher has around 10 years of teaching experience. We collaborated with the teacher in a project that aimed at developing teachers' competence in teaching chemistry with respect to the macro-submicro-symbolic relations. Before the lesson, the first author of this chapter discussed with teacher our proposed teaching strategies, which is presented in the earlier part of the chapter. The teacher indicated she would use it in her teaching of stoichiometry.

The class was Year 10 (15–16 years old) students in Hong Kong. It had around 30 students; with roughly an equal number of male and female students. Based on the teacher's estimation of students' performance in territory-wide public examinations, the students were at around the 50th percentile among Hong Kong student population.

Before the students were introduced stoichiometry, they had been taught the idea of the mole, and its relationship with the mass and the molar mass of substances. In those lessons, students worked on various problems typical of mole calculation, e.g., given a certain amount of copper (in grams), how many copper atoms are there? Given a certain amount of water (in moles), what is its mass? Given a certain mass of glucose, how much glucose (in moles) are there? Other than these typical problems,

(1) the teacher would like the students to have a perceptual feel of the abstract mathematical manipulation. So the students were shown the corresponding amount of substances before they embarked on the calculation. For example, they were shown the exact amount of copper before they calculated the number of copper atoms in the sample. In some tasks, students would have to weigh a certain amount of water. Such activities aimed to help students to link up their symbolic manipulation with the corresponding macro phenomena.

(2) In order to facilitate conceptual understanding rather than merely algorithmic manipulation, students were challenged with some questions that demanded

> reasoning of the relationship between number of particles and mass (Stavy and Rager 1990). For example, they were asked whether there were a same number of atoms in 1 g of gold and 1 g of silver. And if they do not have the same number, which sample, 1 g of gold or 1 g of silver, would have more atoms?

During the class time, students were keen to work on the tasks. Video clips (with English subtitles) of the lessons are available at the Internet.[1]

6.5 A Description of the Lesson

In the chemistry lesson that we describe here, the focus is on the way the teacher introduced students the concept of stoichiometry, i.e., a conceptual understanding of the quantitative relationship between the mass of reactants and products in chemical reactions. In the teaching, a submicro representation of a chemical reaction was utilized. We are aware that some students faced considerable difficulties in mathematical manipulation, e.g., handling scientific notations. The aim of the lesson was not to tackle this problem. Rather, the focus was on fundamental concepts of stoichiometry.

Before the lesson to be described here, students had burned magnesium and observed magnesium and magnesium oxide. At the beginning of the lesson, the teacher reminded the class they had the experience of burning magnesium and that there was some white ash (without the name of the ash mentioned) left behind.[2] She asked whether they thought the ash was heavier or lighter than the piece of magnesium. A class vote (through students raising their hands) was conducted to elicit students' views. Half of the students opted for 'heavier', while the other half opted for 'lighter'. The teacher did not tell them immediately that it was heavier. Rather she told the students that the lesson was going to answer that question. She added that,

> "Different people have different views. Some think that it becomes lighter. Some think that it becomes heavier. Ask yourselves for the reasons. What are the reasons for being 'lighter' or 'heavier'?"

She also mentioned the burning of paper as an example to illustrate that there were reasons to believe that the product of burning magnesium was lighter than the metal. After that, she showed students a YouTube video of the combustion of magnesium. Her focus was the macro phenomenon of the formation of a white residue,

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[1] Please click the button "Mole" in the left hand side of the page: http://web.edu.hku.hk/knowledge/projects/science/qef_2010/d6/main.html

Episodes of the lessons can be found from "Macro: Is 1 g Ag or 1 g Au heavier?" to "Empirical nature of science"

[2] Episodes of the lesson is available at: http://web.edu.hku.hk/knowledge/projects/science/qef_2010/d6/6c13_probe_S_idea.html

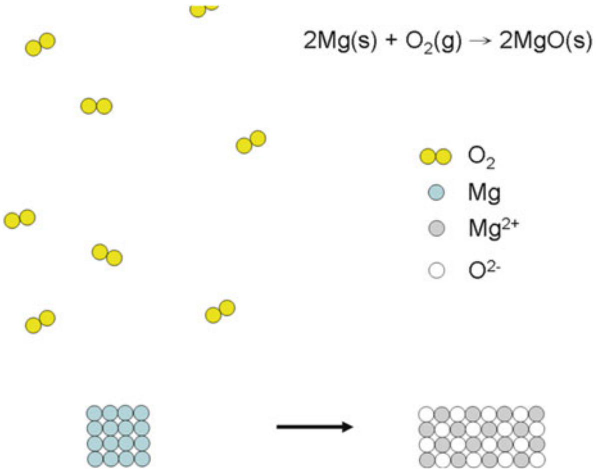


Fig. 6.3 A submicro representation of the reaction between magnesium and oxygen with the formation of magnesium oxide

called magnesium oxide. Then she explicitly stated her intention that she wanted students to think about what happened at the submicro level,

> "… this is what you can see in reality; but if we think about what has happened inside the sample, what actually has happened to the particles?"

After posing the question, the teacher showed the class the following diagram through an LCD projector (Fig. 6.3).

Immediately she drew students' attention to the particulate diagram. Whilst pointing to the corresponding parts of the diagram, she told the class the meaning of those particles:

(1) The yellow circle pairs represented oxygen gas. As she pointed to the space with yellow circle pairs, she linked to the YouTube video:

> "Those yellow balls are oxygen gas. Obviously just now when it burned, there's a lot of oxygen nearby. There's a lot of air, isn't there?"

(2) The array of light blue circles represented magnesium metal.
(3) The array of alternating white and grey circles to the right of the arrows represented magnesium oxide:

> What did they [while pointing to the block of light blue circles with the mouse pointer] finally become? A student just told me a moment ago that it was… 'magnesium oxide' [answered many students] …this pile of product. They are ionic bonding arranged in a regular pattern. They are in regularly layered, crystal arrangement.

After explaining the meaning of the diagram, the teacher referred to the equation in the top right hand corner and said,

> If you're asked to write… a chemical equation, the one at the top right hand corner. You'll express that it's a reaction between magnesium (while moving the mouse pointer over the term 'Mg' in the equation and then the block of light blue circles) and oxygen (while moving the mouse pointer over the term 'O_2' in the equation and then the space where the

> yellow circle pairs scattered). Then it becomes magnesium oxide (while moving the mouse pointer over the term 'MgO' and the block of grey and white circles), this pile of magnesium oxide.

In this part of the talk, the teacher did not mention the stoichiometry of the reaction. Rather, she just focused on the relationship between the submicro representation and the equation. Then she further highlighted the variety of ways that a chemical reaction could be represented,

> … in this process, we can, if you like, use the chemical equation to represent what is happening. Your observation of this experiment was like that. But you can also think about what actually has happened inside by taking a microscopic perspective.

It was only after the teacher had emphasized the multiple ways of representing the reaction that she started to deal with the quantitative aspect. She counted with the students the number of 'atoms' participated in the reaction in the light of the submicro representation. The way she dealt with oxygen is reported here.

Teacher: How many "O" are there?
Students [in echo]: Sixteen.
Teacher: There are 16 "O". Yes. There are 16 "O". How many O_2 are there?
Student: Eight.
Teacher: Eight O_2 molecules, that means there are 16 "O" atoms.

Similar question and answer interactions were conducted for the number of magnesium atoms involved and the number of magnesium and oxide ions formed. After ascertaining students' interpretation of the submicro representation, the teacher asked again whether the product should be lighter than the magnesium metal. There was an echo from students that the product became "heavier".

6.6 Some Notes on the Lesson

6.6.1 Cognitive Conflict

It was noted that cognitive conflict as a teaching strategies should not be taken as a single variable that determines students' success in learning. Among many other factors, it is essential that the problems or the anomalous data presented must be intelligible and relevant to students. Students must also have the reasoning abilities to solve the conflict (Limón 2001). As some students might think matters 'vanished' after combustion, the question of whether the product would be heavier or lighter than the magnesium challenges students' existing belief that the 'ash' would be lighter. It is observed the class was very active in giving responses to the questions. The students were willing to participate in the class vote; some students spoke very loudly their views, which may mean that they were engaged and were confident in their answers.

We have noted that the success of this strategy depends on how teachers interact with the conflict event and students such that students would find a resolution that they are satisfied with and is intended by the teachers (Baddock and Bucat 2008). After the class vote, the teacher did not immediately discuss the scientific view or ask students to defend their preconceptions. Rather, she used the burning of paper to justify how students might believe that the 'ash' was lighter. While the voice of students was not elicited, extensive research in science education has suggested that students tend to apply their daily observation of burning to make sense of similar phenomena, e.g., the combustion of metals. In that sense, the teacher created a safe environment for learning in which students did not have to openly defend their views that the teacher knew would have to be modified in the later part of the teaching. In this way, she was not trying to 'replace' students' views with the scientific view. She acknowledged students' ideas and tried to limit the scope of application of their ideas (Smith et al. 1993/1994). It is likely that the learning environment the teacher created has facilitated students' learning. The students were still very keen to express their options in class vote after the teacher explained the reaction with the use of the submicro diagram. The engagement was evidenced irrespective of the fact that their earlier views were refuted. Watson et al. (1995) reported that some students could disregard their observation that the product became heavier than the magnesium – a merely observation of data did not guarantee conceptual learning. We would propose that the particulate diagram (and the way the teacher discussed with the class about it) might have served as a means through which students have found the resolution of the conflict intelligible.

6.6.2 Representing Macro Phenomena in a Particulate Diagram – Air and Oxygen Gas

The teaching started with a recall of students' experience of the macro phenomena, namely, the burning of magnesium. A video of the burning was also shown. Then, the particulate diagram was presented to the whole class. She made explicitly that the diagram represented 'what actually has happened to the particles'. To help students to understand the notations used in the diagram, she told the class directly that the cluster of yellow circles *are* oxygen gas and referred students to think about the surroundings where the burning happened. In this part of the teaching, it seems that many students were able to grasp at the conventions of the diagram. It was reflected from their responses about the area that represented magnesium oxide. Nevertheless, we notice that the abstraction of 'air' to 'oxygen gas' as macro entities was not addressed in the lesson. In the diagram, only oxygen molecules were represented. We are thus unsure whether such an implicit modelling of air as oxygen gas would hamper students' understanding of the phenomena.

6.6.3 Highlighting Different Representations

Instead of discussing with students the number of submicro entities involved in the reaction in the diagram, the teacher directly showed students the balanced equation. Her focus was to emphasize to students that there could be different ways of representing the combustion of magnesium. At this point, while she intended to foster relational understanding of the triplet, we cannot be sure if the students could meaningfully relate the balanced equation with the number of submicro entities involved in the reaction. Also, it might leave a question about whether students can appreciate why the reaction had to be represented in the form of a chemical equation.

6.7 A Detailed Reading of the Particulate Diagram

A detailed examination of the particulate diagram came in after the teacher showed students the chemical equation. She counted with students the number of particles of magnesium, oxygen and magnesium oxide. After ascertaining the results of the student's counting of particles, she again asked students' view about the relative mass of magnesium and its combustion product. Most of the students expressed the view that the product was indeed heavier. Although the students were not asked for the rationales behind their changes of views, it seems that the particulate diagram has facilitated students understanding of the submicro interaction and a prediction of the increase in mass after the reaction.

The activity overall might seem to have been straightforward and unchallenging to students. In a general sense, it served the function of assessment *for* learning – students' views were probed into and subsequent teaching was conducted based on those views. In the light of the learning occurring with the diagram, the activity did seem to facilitate students' formation of mental representations of the referent that as intended by the teacher. That is, the reaction between 16 magnesium atoms and 16 oxygen atoms that formed 16 formula units of magnesium oxide (as a submicro phenomenon); and the reaction between magnesium metal and oxygen gas with the formation of magnesium oxide solid (as a macro phenomenon). Ensuring a shared or coherent mental representation between students and the teacher is not a trivial or dogmatic demand. Such mental representations would be essential for the development of target knowledge, i.e., stoichiometry of the chemical reaction. It is apposite here to discuss what is entailed in understanding a diagram. Running the risk of over-simplification while maintaining the essence that should guide and inform classroom practice, a model for diagram comprehension (based on Hegarty 2011) is presented in Fig. 6.4.

When students looked at the diagram, their visual senses would attend to its different features and components (called the *Visual features* in the model). It may be different ways the circles were arranged in the diagram, for example, some existed randomly while some existed orderly. It may be the two blocks of circles near the arrow. It may also be those yellow circle-pairs. These *visual features* were encoded as students' *Mental representation of the diagram*, which we hope would become a

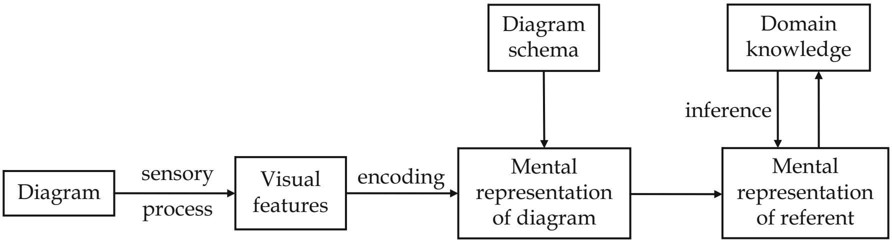


Fig. 6.4 A model for comprehension of diagram (Modified from Hegarty 2011, p. 453)

Mental representation of the referent. It is unlikely that such a diagram is exactly replicated, or copied, in students' minds. In other words, it is unlikely that the mental representations formed by different learners are exactly the same. Different learners encode different objects and different features of the diagram as their *mental representation of the diagram*. The encoding depended on students' understanding of conventions through which submicro entities are represented. For teachers, a pair of connected circles represents a molecule, randomly and spaced out circle-pairs represented the gaseous state, a block of circles connected regularly resting on a line represented the solid state, circles left and right to the arrow represented reactants and products respectively. Such an understanding is called *Diagram schema*. If students lacked the *diagram schema* that was required, comprehension of the diagram would not be possible.

As chemistry teachers, our *mental representations of the diagram* very swiftly – if not instantaneously – become *mental representations of the referent*, which is the reaction between magnesium and oxygen at the submicro level and its stoichiometry. Instead of merely encoding two connected circles as such, they are represented as oxygen molecules in our mental system. Our existing knowledge of the kinetic molecular model allows us to represent the random circle pairs (in the diagram) as some oxygen gas in our *mental representation of the referent*. Similarly, the block of circles on the left to the arrow (in the diagram) are not a block of circles as such, but is solid state magnesium in our *mental representation of referent*.

There is a considerable chance that our expertise in chemistry would blind us from appreciating students' challenges in comprehending meanings carried by the *Visual features* of the diagram. There has been evidence from elsewhere that students did not move beyond the *mental representation of diagrams* and fail to form a *mental representation of referent*. They would interpret a diagram without recognizing what was actually being represented (Bucat and Mocerinob 2009). For example, based on the structural formula of bromobenzene, some students regarded the molecule did not have a plane of symmetry – because "B≠r" (Kleinman et al. 1987). As far as comprehending the submicro diagram is concerned, without prior knowledge, such as that oxygen molecules are made of two atoms (diatomic), that closely and orderly packed circles are a representation of a solid state, and that alternate circles arranged in a block are made of two different types of ions, it is unlikely students would properly comprehend the diagram. Therefore, making explicit the meanings of each of the circles and the meaning of the collection of circles was essential in classroom teaching.

The intended purpose of the submicro diagram went beyond the interaction of the magnesium and oxygen. It also involved the stoichiometric relationship between the reactants and the product, which was the target *Domain knowledge* to be developed by students. Support is needed to engender the knowledge development. It is represented by the arrow pointing to *Domain knowledge* emerging from *mental representation of referent* (in Fig. 6.4). For those who have already possessed this knowledge, they can infer (*Inference* in the model) the stoichiometry relationship from the diagram. Nevertheless, some students may appreciate the intended meaning of the number of circles in the diagram. Therefore, it is important that the teacher counted with students the number of each of these submicro entities, such that students could infer how the mass of the product was different from that of the reactant. It is likely that students' learning of stoichiometry could be better supported if they are more explicitly showed the exact relationship between the diagram and the balanced equation.

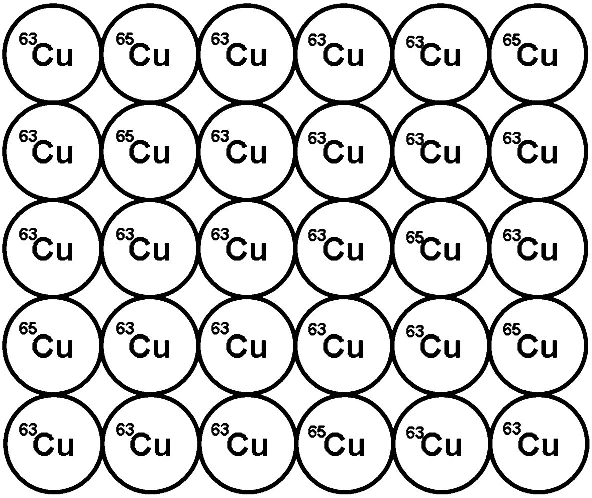
The formation of the *mental representation of referent* involved more than a direct matching of the *mental representation of the diagram* and our *domain knowledge*. It also includes a selection, of which part of the existing knowledge is included and which part to be ignored. For example, although students may be aware of the electron-sea model of metals, as it is not directly relevant in stoichiometry here, they have to screen out this model and regarded metals as a collection of metal atoms. Therefore, having a repertoire of *domain knowledge* is not enough, in understanding a diagram, students have to select the piece of existing knowledge that is relevant to the context such that a *mental representation of the referent* conducive to future problem solving (stoichiometry) can be formed. Such an awareness is not trivial. It points to some possible challenges faced by students and the need for teachers to devise suitable strategies that facilitate students' comprehension of diagrams. In the trial lesson reported above, the explicit reference between the circles and their referents made by the teacher and the explicit counting of the submicro entities might have facilitated students reading of the diagram such that they could tell how the mass of the product has changed after the reaction.

6.8 Conclusion

In this chapter, we have proposed a teaching strategy that introduces stoichiometry to secondary school students. The proposal was developed based on our understanding of some difficulties students faced in learning of macro phenomena (the combustion of magnesium) as an abstraction of daily phenomena, in understanding the idea of mass conservation and in reasoning with submicro and symbolic representations. We suggest that the practical activity in this context should be procedurally straightforward and intellectually challenging enough to be in conflict with students' existing knowledge, yet simple enough so that they can find the resolution intelligible. In this proposed teaching strategy, a submicro representation in the form of a many-particle diagram plays a key role in facilitating students' conceptual understanding of the chemical reaction and its stoichiometry. As far as the macro phenomenon is concerned, the diagram serves as an explanation to the reaction between a piece of magnesium ribbon and oxygen gas, and represents the increase in mass of the product as compared with that of the magnesium. As far as the symbolic representation is concerned, with a careful design of the number of particles in the diagram, it serves to support students working out of the balanced equation of the reaction. That is, the diagram serves as a bridge for the macro phenomenon and a symbolic representation.

The suggested teaching strategy was implemented in a Year 10 classroom. While we are unable to generalize the experience of teaching and learning in a single classroom, we observed that students were engaged in the cognitive conflict activity. The submicro diagram did facilitate resolving the cognitive conflict, which may imply that students were able to associate the submicro representation to the macro phenomenon that they explored. We would like to ascribe students' engagement and learning not by the diagram as such, but by the teacher's effort in making sure that students understood the ways that different components of the diagram represented submicro entities and how they related to their corresponding macro phenomena. It is likely the explicit teaching facilitated students' transformation of different *visual features* of the diagram (i.e., different arrangement of circles) into *mental representations of their referents* (i.e., different submicro entities of the reactants and the product) and possibly students' development of the idea of stoichiometry as the target *domain knowledge*.

The use of particulate diagrams with the sequence of macro-submicro-symbolic representations has been extended to the teaching of different types of chemical reactions. In a similar way, the introduction of the idea of isotopes and the calculation of relative atomic mass can be supported by the following diagram (or a diagram with less copper atoms):



Like the teacher we discussed in this chapter, we suggest that teachers may first ascertain students' understanding of the diagram as a representation of a part of a piece of copper metal, and students' understanding of the symbols ^{65}Cu and ^{63}Cu. Instead of starting with abstract formula or drilling of algorithms, teachers may work with students the number of ^{65}Cu and ^{63}Cu atoms and then figure out the relative atomic mass of copper based on the diagram. In short, this chapter proposes the use of particulate diagrams in supporting students' linking of submicro representations to macro phenomena and symbolic representations.

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