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Modelling students' visualisation of chemical reaction

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ABSTRACT
This paper proposes a model-based notion of 'submicro representations of chemical reactions'. Based on three structural models of matter (the simple particle model, the atomic model and the free electron model of metals), we suggest there are two major models of reaction in school chemistry curricula: (a) reactions that are simple rearrangements of particles, where particles are the most basic units of rearrangement and do not change their identity in the reactions, and (b) reactions involving the interactions of chemical species with – depending on the type of reaction – electrons and protons. In the latter case, chemical species change their identities/structures in reactions; for example, atoms become ions. Based on these two models, we analysed how 18 Grade 10–11 students mentally visualised the reaction between magnesium and hydrochloric acid. Each student was interviewed twice – once after they were taught the reactions of acids and once after they learned about redox. Their visualisations could be fitted into these two models. There was a developmental trend among the students, who progressed from the simple model to the more sophisticated model. None of the students regressed. Curriculum planning and teaching should consider how students should be helped to learn about different reaction models.

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Introduction

Roles of models in science learning

The learning of scientific models and being able to reason with them play an important role in science learning (Erduran & Duschl, 2004; Gilbert & Justi, 2016; Windschitl, Thompson, & Braaten, 2008). Reasoning with models is one of the key skills that has made science a distinctive enterprise (Kind & Osborne, 2017) and is essential for the achievement of functional scientific literacy (Ryder, 2001). Model-based reasoning involves the ability to provide explanations to physical phenomena, usually based on theoretical and unobservable entities or processes. Developing such a capability is believed to be more meaningful than learning a collection of scientific facts (Gilbert, 2004). As noted by Nersessian, the 'cognitive cultural systems of the classroom … have their own unique constraints and affordances' (2008, p. 203). This mandates the use of distinctive strategies to develop students' model-based reasoning. Even in the second decade of the

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twenty-first century, the vast majority of the classrooms are still dominated by the teaching of scientific facts (e.g. reactants and products of a variety of chemical reactions) prescribed in a top-down manner. It is important that research in science education is able to help teachers to adopt model-based teaching in their classrooms even if they teach in systems where there are centralised curricula.

There are studies that have already investigated the implementation of model-based teaching in science classes (Bamberger & Davis, 2013; Gilbert & Justi, 2016; Oliva, del Mar Aragón, & Cuesta, 2015; Windschitl et al., 2008). We contribute to the literature by proposing that there are two models of chemical reactions included in school curricula. Based on these two models, we were able to analyse how 18 students mentally visualised the chemical reaction between magnesium and hydrochloric acid (a typical reaction studied at the high school level) at the submicro level. The findings of this study will, we hope, inform the development of progressive model-based curricula.

Structural models of metals and models of chemical reactions

Chemistry involves the use of different models for the same entities (Carr, 1984; Justi & Gilbert, 2000, Shiland, 1995). Students have to learn to use different models of metals and of chemical reactions at the senior secondary level (Curriculum Development Council, & Hong Kong Examinations and Assessment Authority, 2014). The issue has not been extensively researched in Hong Kong or elsewhere. The structural models involved are the following:

(1) *Simple particle model* (Figure 1(a)). Each metal is thought to be made of one type of metal particle. This model does not consider subatomic particles and may not differentiate atoms, molecules and ions. The spatial distribution of particles in three states of matter is commonly represented by this model. The simplicity of this model also allows representations of different structures of metals (e.g. hexagonal close-packed and body-centred cubic).

(2) *Atomic model* (Figure 1(b)). Each metal is made of its atoms. An atom is made of electrons, protons and neutrons. Magnesium metal, for example, is thought to be made of magnesium atoms and each has an electronic arrangement of 2,8,2. The idea that everything is made of 'atoms' is a dominant way of thinking about chemistry (Taber, 2003). Explanations of chemical reactions and metal reactivity utilise this model. For example, when magnesium reacts with an acid, its outermost shell electrons are thought to have 'given' to hydrogen ions.

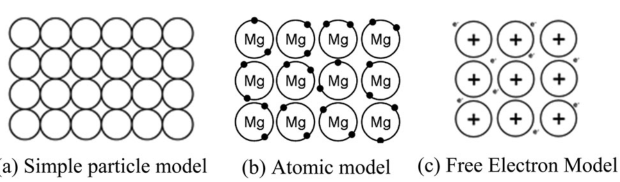


Figure 1. Three structural models of metals.

(3) *Free electron model* (Figure 1(c)). A piece of metal is made of its metal cations and delocalised electrons. The model describes metallic bonding as the electrostatic force between metal cations and the delocalised electrons. This model explains physical properties of metals such as malleability, heat and electrical conductivity.

The above structural models invoke different models of chemical reactions. However, models of chemical reactions at the submicro level are under-discussed in the literature. We would like to propose two models for this.

(1) *Particle model of reactions.* Chemical reactions involve a simple rearrangement of particles, which can be likened to a rearrangement of Lego® blocks. It assumes that the particles/atoms merely rearrange and form a new product, which does not involve interactions of electrons and protons. The labels 'atoms' and 'particles' are sometimes used interchangeably. They are treated as intact and indivisible entities, which are the fundamental entities in the simple particle model. Many popular chemistry books adopt this model or its variations as an explanation for chemical reactions, for example, 'the atoms … tumble into the … new arrangement' (Atkins, 2013, p. 46). This model can explain to the public recent advancements in data storage technology at the atomic scale (*The Economist*, 2016). On the one hand, this model of reaction is coherent with the simple particle model of matter (which can be referred as the 'basic' particle model (Johnson, 1998)), in the sense that interaction of subatomic particles is not considered. These changes can be represented by space-filling models. The model allows the visual representations of many molecular reactions, such as the formation of ammonia from its constituent elements; the combustion of a covalently bonded solid such as graphite (assuming that graphite is made of carbon atoms/particles) and organic reactions (Dori & Kaberman, 2012). It may even allow the visual representation of reactions involving ions, such as the reaction between calcium carbonate and acid (Ross, Lakin, McKechnie, & Baker, 2015, p. 126). The visualisation system 'Chemation' also made use of this model for students to express their understanding of chemical reactions (Chang, Quintana, & Krajcik, 2014). On the other hand, this model of reactions demands more understanding than the simple particle model of matter. This is so because the simple particle model of matter does not necessarily embrace the concept of molecules; for example, a water particle may be assumed to be a single-unit particle as it is often represented as a sphere or a circle. This is in contrast to the visual representation of a H_2O molecule as being made of three particles/atoms. In short, this model regards a reaction as a simple rearrangement of particles (or atoms); subatomic particles are not considered.

(2) *Atomic model of reactions.* The reaction of magnesium and hydrochloric acid is modelled in this system as the 'transfer' of electrons from magnesium atoms (with the electronic arrangement of 2,8,2) to hydrogen ions, which leads to the formation of magnesium ions (2,8) and hydrogen molecules. The simple particle model does not offer such a nuance. It takes the subatomic particles in the atomic model (Figure 1(b)) to facilitate the reasoning of such interactions, which helps to represent the above reaction, and other redox reactions, and reaction mechanisms in organic chemistry.

The role of the free electron model in this model of reactions is less straightforward. It is generally accepted that, for example, the reaction of magnesium and acid involves magnesium atoms. Nevertheless, there are no strong reasons to disregard the free electron model in providing a submicro-level explanation, namely the interaction of delocalised electrons and hydrogen ions. If this model is used, we would be able to provide an identical model for the explanation of chemical reactions and for physical properties (such as electrical conductivity and malleability). One issue is that in the half equation $Mg \rightarrow Mg^{2+} + 2e^{-}$, at a submicro level, the symbol 'Mg' commonly means 'atoms' (atomic model, Figure 1(b)), rather than a collection of two delocalised electrons and a metal cation (free electron model, Figure 1(c)). No matter which structural model is used, it should not affect the nature of the atomic model of reactions in which chemical species and electrons are invoked in the reaction.

The two models of reaction differ at least in terms of the structural entities participating in reactions and the process involved in the reaction at the submicro level. They are juxtaposed in Table 1.

In the *atomic model* of reactions (labelled as italicised *atomic model* hereafter), each type of entities is more precisely defined. For example, atoms, ions and molecules have relatively well-defined structures; that is, an atom has an equal number of protons and electrons, an ion has an unequal number of protons and electrons and bears a net electric charge, and a molecule is conceived as being made of a cluster of atoms. In the *particle model* of reaction (labelled as italicised *particle model* hereafter), however, the idea of particles carries broader and more unspecific meanings. A water particle may be represented by a single sphere/circle, or a cluster of two hydrogen particles and one oxygen particle. Because this model does not consider electrons and protons, particles are conceived to be electrically neutral. The *particle model* considers the conservation of matter in terms of conservation of particles only; the *atomic model* also considers the conservation of chemical species and electrons, hence the electric charges.

The processes involved in the *particle model* are mainly about structural changes, that is, concerning changes in the spatial arrangement of particles. The *atomic model* goes beyond structural changes to the consideration of electrostatic interactions between reacting entities also. For example, the positive hydrogen ions are thought to combine with electrons in the formation of hydrogen molecules when an acid reacts with magnesium. Although this study did not investigate students' ideas of energy changes associated with reactions, energetics can be related to bond breaking and formation as a result of electrostatic interactions (e.g. Barker & Millar, 2000).

Students' understanding of chemical reactions

There have been many studies that examined students' understanding of chemical reactions. Based on some everyday scenarios such as rusting (of iron nails) and burning (of wood,

Table 1. A comparison of two models of chemical reactions.

	Particle model of reactions	*Atomic model* of reactions
Structural entities participating	Particles or atoms – unitary in nature and are not made of subatomic particles	Atoms, ions, molecules, electrons and protons as subatomic particles
Process involved	Spatial rearrangement of structural entities (particles or atoms)	Spatial rearrangement of chemical species, some reactions involve electron transfer between chemical species

alcohol and steel wool), Andersson (1986) identified a number of intuitive ways that students might have understood chemical changes. Some students made use of macro-level explanations, some used submicro explanations. Stavridou and Solomonidou (1998) modelled students' understanding of chemical reactions as consisting of three stages: from stage one 'understanding of reactions as macro changes', through stage two with an 'awareness of reactants and products (as new substances)', to stage three understanding that involves 'submicro-level changes'. The literature in general agreed that an understanding at the highest level should involve a sound grasp of submicro representations, such as recognising that reactions involve both the 'reorganisation of atoms' (Ahtee & Varjola, 1998, p. 309) and the 'conservation of mass' which implies that matter is neither created nor destroyed, that is, the 'atoms remain the same' (Øyehaug & Holt, 2013, p. 465). There have been studies that particularly probed into students' understanding of chemical reactions specifically at the submicro level (Kern, Wood, Roehrig, & Nyachwaya, 2010). By the use of diagrams and students' drawing, many of these studies demonstrated consistently that students' conceptual understanding of stoichiometric coefficients, subscripts in chemical formulae, and limiting reagents and mass conservation in chemical changes emerged as issues for concerns. These studies contributed to the development of teaching strategies that tackled the students' difficulties so identified.

The present study drew upon the idea of chemical models, and acknowledged that students have to learn different structural models and to use different models to explain chemical reactions. We chose the reaction between magnesium and hydrochloric acid because the reaction is among the simplest reactions that involve a metal. This enabled us to investigate students' choice of model without this being complicated by having them to reason with several reactants and complicated formulae. For example, although rusting is a common daily phenomenon, it involves three reactants (i.e. iron, oxygen and water), and forms rather complicated products (i.e. $Fe_2O_3 \cdot nH_2O$). In order to identify if the two models are progressive in their explanatory nature and if they are acquired by students successively, we interviewed students after they were taught the unit 'Acids and bases' and after they were taught 'Redox' in the curriculum. This paper addresses the following research questions:

- Which models of reaction did students use to explain the chemical reaction between magnesium and hydrochloric acid?
- What changes in students' explanations took place after they were taught the idea of 'redox reactions'?

Although the teaching and learning of the particulate nature of matter have caught the attention in science education for some years (e.g. Bucat & Mocerinob, 2009; Davidowitz & Chittleborough, 2009; Tsaparlis & Sevian, 2013), there has been little attention paid to students' progressive learning of the two major models of reactions. Compared with previous studies of students' understanding of chemical reactions, this study further focused on the expected learning outcomes of understanding at the submicro level.

Methodology

This paper reports interview data of 18 students from three secondary schools. Schools in Hong Kong are classified into three bands according to students' previous academic results. The three schools are each from one of the three bands. From each school, two students from the top 10th percentile, from the 45th to the 55th percentile and from the lowest 10th percentile based on their chemistry examination results were interviewed. As this qualitative study aimed to obtain insights into students' understanding, we hoped that such a sampling would garner a maximal range of students' ideas about the chemical reaction. We only included students who were taking chemistry in Years 10–11. Before data collection, the first author had sought ethical approval from the university where he worked. All the students, their parents, their teachers and school principals agreed to participate voluntarily in the study.

Context of data collection

To elicit students' changes in their mental visual representations of the reaction (in relation to the second research question), each student was interviewed twice. The interviews were conducted within a week after the students were taught 'Acids and bases' and 'Redox', respectively. All interviews were conducted by the first author. He communicated closely with the teachers about their teaching schedules and content coverage. This ensured the timely interviewing of students.

Teachers of the students who participated in this study were informed that this project was to investigate students' understanding of some chemical ideas. They were not told the analytical framework of this study (i.e. that it was about two models of reaction). They taught as they usually did. Typically, reactions of acids were taught with the use of demonstrations and focused on helping students to write balanced chemical equations. Submicro representations were not highlighted. The teachers did not particularly use animations in their teaching of the reactions. Before the teaching of 'Acids and bases', students had been taught all the three structural models, and different types of bonding, in which ionic bonding involved electron transfer between atoms and involved electrostatic forces between ions so formed. In short, ideas about the *atomic model* of reactions had been introduced in an earlier teaching unit. But similar ideas were not reiterated in the teaching of the reaction between Mg and H^+.

In the interviews, the students were shown an interview card (Figure 2), and were told that the pictures and the equation show the reaction between magnesium and hydrochloric acid. As this study focused on model use rather than stoichiometry, we simplified

$$Mg\ (s) + HCl\ (aq) \rightarrow MgCl_2\ (aq) + H_2\ (g)$$

Figure 2. Interview card (printed on a piece of A4 paper).

the equation by not including stoichiometric coefficients (after Laugier & Dumon, 2004; Taber, 2009). Also, we did not want to load students with information that was not entirely relevant to the purpose of this study. They were asked to draw in order to represent their views about what happened at the submicro level (Cheng & Gilbert, 2009). They were thus required to respond both orally and by drawing. Such strategies have been used in investigating students' mental visualisation of scientific ideas (e.g. Cheng & Gilbert, 2014; Ben-Zvi, Eylon, & Silberstein, 1987)

The second interviews were conducted within a week after they had been taught the unit 'Redox', which covered the movement of electrons in electrochemical cells, redox as electrons gain/loss, oxidation number and electrolysis. In this way, ideas about the *atomic model* of reactions were used. Nevertheless, the teaching was not model-based. It was conducted as if it was the way that reactions happened. Also, students had to learn to write half equations (including H^+/H_2; Mg^{2+}/Mg) and to combine two half equations into a full equation.[1] Although all the 18 students followed the same chemistry curriculum, the pace of teaching and students' learning varied. There was a four- to six-month time lag between the teaching of the two units.

The students were provided with the same interview card and were given the same information in the second interview. The task they were asked to do was the same as in the previous interview.

Data analysis

All interview data were transcribed. Their drawings were added to the transcripts for analysis. We approached the analysis by identifying the model of reactions that students might be using. We acknowledged that students' drawings and oral responses could be very diverse and would not be modelled easily (Taber, 2014) as a strictly *particle model* or a strictly *atomic model*. Thus, some defining features of both models (Table 1) were adopted. Representations that demonstrated only the spatial rearrangement of submicro entities and no changes in the identities of those entities were regarded as being more akin to the *particle model*. Those that demonstrated awareness of different types of submicro species and referred to changes in identities of submicro entities (e.g. from magnesium atoms to ions, or magnesium losing electrons), or referred to electrons (as subatomic particles) were regarded as more akin to the *atomic model*. The first author did the classification of each student's interview data into either the *particle model* or the *atomic model*. Then a colleague of the first author specialised in chemical education was informed of the classification criteria and was invited to classify the data independently. There was a 91% agreement between them. In this study, we did not aim to identify 'students' misconceptions'; our data interpretations were not concerned with whether their representations were scientific or unscientific. Such an analysis was intended to inform us of the model that they might use, and hence to shed light on how teaching should be conducted to facilitate students' progression in modelling reactions.

To address the second research question, students' distribution of model use and changes over the two interviews are reported. Examples of students' progression from the *particle model* to the *atomic model* in the two interviews are reported.

Results and discussion

Eighteen students were interviewed. Fifteen students were interviewed in Cantonese, which is the most popular spoken language in Hong Kong. Three students, who were from the Philippines or India, were interviewed in English. All students were able to articulate during the interviews. We assumed that language use would not significantly affect students' visualisation. To report the data, students are coded according to the banding of their school (B1, B2 and B3, where B1 is the top banding school and so on), their chemistry achievement within their school (T1, T2, M1, M2, L1 and L1, where T represents the top 10 percentile student; M, the medium; and L, the lowest 10 percentile student) and occasion of the interview ('a' stands for right after they were taught 'Acids and bases'; 'r' stands for after redox was taught). For example, the code 'B3-T2-r' means that the data were drawn from a top 10 percentile student of the Band 3 school at the interview after the student was taught 'Redox'.

Students starting with the simple particle model of metals

Almost all students (17 out of 18) understood the instruction of the interview that they were required to represent the chemical change at the submicro level. None of the students started with the drawing of the atomic model (Figure 1(b)) in which each magnesium atom has two outermost shell electrons. They in general started with drawing closely packed circles and named them as 'magnesium atoms' or 'particles' (see Figure 3 for an example). The drawings were akin to the simple particle model of metals. Based on these initial drawings, it was impossible to discern their mental representations of these circles as merely unitary particles or atoms (with electrons orbiting) until these drawings were made use of in explaining the reaction.

A student represented the submicro particles as positively charged particles (see Figure 4). But there were no electrons around the particles. We took this representation as more akin to the simple particle model of metals. As will be shown in the next section, these 'atoms' stayed the same after the reaction with acid.

Three students started by drawing diagrams based on the free electron model, which showed electrically neutral magnesium particles/atoms surrounded by a 'sea' of electrons (Figure 5).

In short, in order to start explaining the reaction, students represented magnesium metal as a collection of particles/atoms. Their representations developed further as they explained the reaction. Our analysis of representations as the *particle model* and the *atomic model* is reported below.

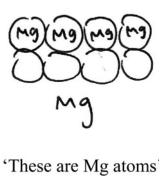
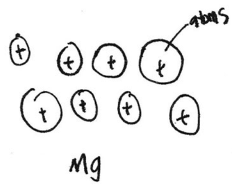


Figure 3. (B1-M2-a).



'This is magnesium… These are atoms.'

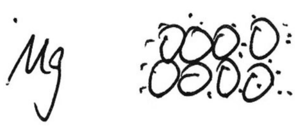
Figure 4. (B3-T1-a).

Particle model of reactions: the reaction as a simple rearrangement of particles/atoms

Half of the students in the interview sample (i.e. 9 out of 18), after they were taught 'Acids and bases', used the *particle model* in representing the reaction. Four of them used the *particle model* in representing the reaction after they were taught 'Redox'. Magnesium metal was represented as magnesium particles. Hydrochloric acid was represented as H and Cl particles. These particles were unitary particles and were the basic units of participants of the reaction. The representations did not involve subatomic particles. Figure 6 shows the drawings of two students from two schools. The reaction was represented as the rearrangement of reactant particles/atoms; products were the result of particle recombination. Both the submicro structure of magnesium metal and the reaction were consistently based on the simple particle model of matter.

In a similar way, the student who represented magnesium atoms as positively charged particles (Figure 4) represented the reaction as a simple rearrangement of particles (Figure 7). Although it looks as though there were hydrogen ions present, the student called them 'hydrogen atoms'. The reaction was represented as a simple rearrangement of particles – two positive hydrogen atoms combined to form H_2; Cl^- became closer to magnesium. There was no change in the identity of the reacting particles (e.g. H^+ was still H^+) or evidence for the consideration of subatomic particles. This representation is regarded as more akin to the *particle model* of reactions than the *atomic model*.

We suggest that these responses should not be treated as merely 'misconceptions' or incompetent representations. There was considerable attainment present in these representations:



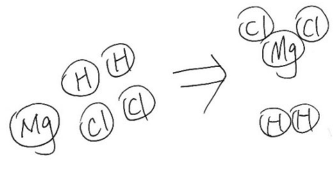
'Atoms. These are electrons (referring to the dots in the drawing)'

(a) B3-T2-r

'…a lot of Mg, there are a lot of electrons next to it'

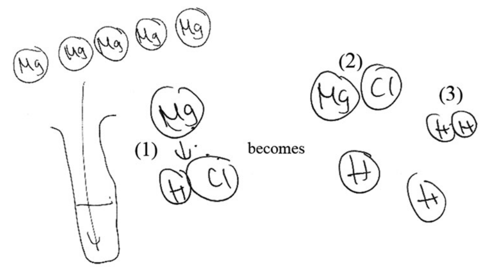
(b) B1-T1-r

Figure 5. Representations akin to the free electron model.



(a) B1-T2-a

After finished drawing the diagram, the student said, '[the Mg circle] represents one of the magnesium atoms. .. The others are hydrochloric acid. .. Placing inside [the test tube], this one (pointing at the left Mg circle) will stick to this one and this one (pointing at each of the Cl circles left to the arrow) and become this (pointing at the Cl-Mg-Cl unit). This will stick together by themselves (pointed at the H circles left to the arrow).'



(b) B2-T2-a

'…it will like to react with this (while drawing the arrow from Mg to HCl, see (1) in the diagram). So this will… stick to Mg (while drawing the Mg-Cl pair, see (2)) and left H alone. After reaction, there are a lot of H, and then the two of them will stick together and become H_2 (while adding the H-H pair in the drawing, see (3)).'

Figure 6. Simple particle model of magnesium and its reaction.

- There was evidence of students' visualisation of the particulate nature of the chemical reaction and matter conservation. Although the photograph in the interview card (Figure 2) showed that magnesium metal is consumed after the reaction, students' drawings showed magnesium particles as still existing. Also, students did not represent the solution product in the photograph as continuous matter (such as by wavy lines).
- Students' representations of the chemical reaction were consistent with the most basic understanding of reactions at the submicro level, that is, reactions as the rearrangement of particles/atoms. Such a rearrangement was consistent with the chemical formulae in the chemical equation. That is, magnesium atoms then combined with Cl^{-}; two hydrogen particles combined as a product.

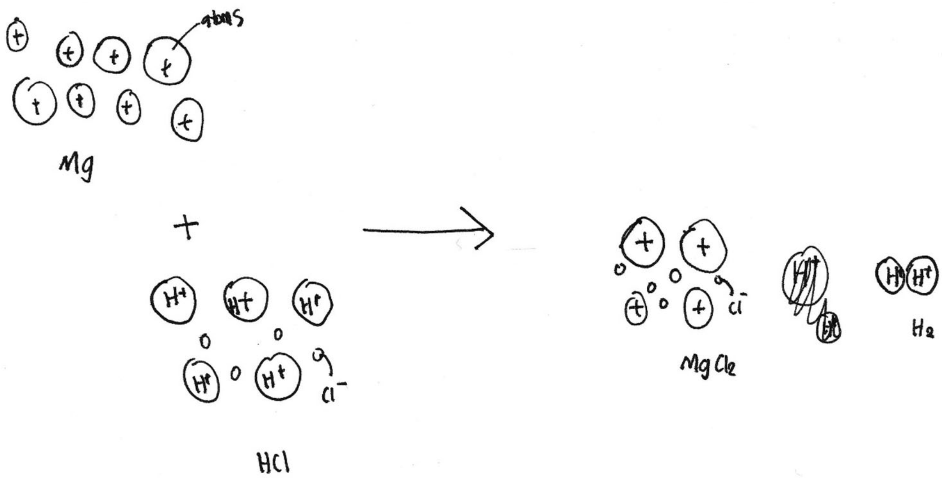


Figure 7. The identity of submicro particles remains the same after the reaction (B3-T1-a).

In fact, such drawings would have been adequate for representing the interaction of atoms in reactions that do not involve charged particles (e.g. the formation of water from its elements). We also note that after the reaction, Mg and Cl particles stuck together. Students' representation of aqueous ionic compounds in solutions as ion pairs has been extensively reported (Kelly & Jones, 2008; Smith & Metz, 1996; Taskin & Bernholt, 2014). We do not repeat here the discussion of this representation. We also found Mg-Cl connected drawings from students who deployed the *atomic model* of reactions. They are discussed in the next subsection.

Atomic model of reactions – the reaction invoked changes in identities of reactants

About half of the students (8 out of 18), in the interview after they were taught 'Acids and bases', represented the reaction as involving the formation of magnesium ions from their atoms. These students maintained such views after they were taught 'Redox'. Five students who represented the *particle model* in the first interview then adopted the *atomic model* after they learnt 'Redox'. In short, 13 students (out of 18 students in this study) adopted the *atomic model* after they had been taught 'Redox'. An example of the *atomic model* drawing is shown in Figure 8.

Compared with the data reported in the previous subsection, in which the identity of submicro particles did not change (i.e. magnesium atoms remained as magnesium atoms after the reaction), responses in this category indicate changes in magnesium from being particles/atoms to ions (through the loss of electrons). In this sense, we regard such representations as being more sophisticated than a simple rearrangement, and more akin to the *atomic model* of reactions. Students' representations of the formation of ions varied – from plain circles (while students described/labelled them as ions) (Figure 9(a)) to detailed electron diagrams of magnesium (Figure 9(b)).

After the formation of magnesium ions, students in general demonstrated the following:

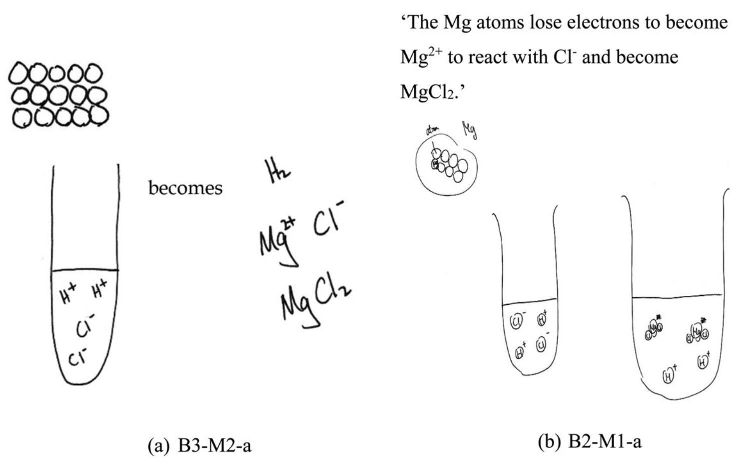
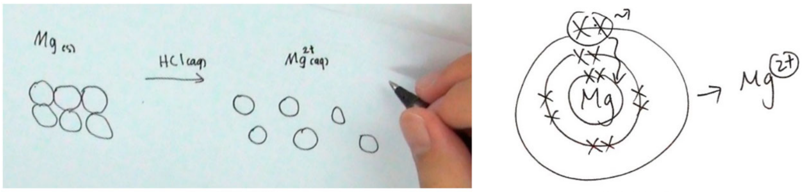


Figure 8. Changes from magnesium atoms to magnesium ions, and the interaction between magnesium ions and chloride ions.



(a) B3-T1-r (b) B1-M2-r

Figure 9. Students' representations of the formation of magnesium ions.

(1) The magnesium ions combined with chloride ions – an indication of electrostatic attraction between positive and negative ions. These 'molecular unit' representations of aqueous compounds have been extensively reported in the literature (Naah & Sanger, 2013; Nyachwaya et al., 2011; Smith & Metz, 1996).
(2) Students did not further represent or mention the electrons originating from the magnesium atoms. Just as in Figure 9(b), the students did not mention where the electrons went to – they just 'left the magnesium atoms'. Scientifically, and as students were taught in the redox unit, the electrons go to hydrogen ions, which then form hydrogen molecules. In this study, among the 18 students' interviews conducted after they were taught the 'Acids and bases' unit, none them represented the interaction of electrons and hydrogen ions. Only three students, in the interview after they were taught 'Redox', represented electrons from magnesium as leading to hydrogen ions.
(3) In relation to the above observation, students in general either represented the formation of H_2 by simply combining two hydrogen ions (e.g. as the student who drew Figure 8(a); she referred to a H^+ in the test tube and indicated 'it doesn't have anything to attach to. So, its stability isn't too high, so there are two sticking together') or did not address the formation of hydrogen molecule(s) (as in Figure 8 (b)).

The above observation also applies to a student (B3-T2) who represented the free electron model. His verbal description can be summarised as the following sequence as the diagram in Figure 10 shows: (1) HCl ionises to become H^+ and Cl^- in water; (2) a chloride ion reacts with a magnesium atom; (3) the atom loses electrons and bears a charge ('the electrons leave the atom go somewhere, it carries a charge') and (4) the charged Mg sticks with $Cl^-$and becomes $MgCl_2$. His visualisation is coherent with the features identified above; namely magnesium sticks with two chloride ions, and no mention is made of exactly where the electrons from magnesium go to and how hydrogen gas is formed.

It is apparent that students' representations did not cohere with the scientific view of redox reactions, in which the electrons released from magnesium atoms ($Mg \rightarrow Mg^{2+} + 2e^-$) are gained by hydrogen ions ($2H^+ + 2e^- \rightarrow H_2$). Nevertheless, we suggest that students' representations are different from the *particle model* of the reaction as reported in the previous section. This is because, in the *particle model*, reactant particles were treated as intact and unitary. There was no evidence of charges being represented in the identity of submicro entities or the involvement of electrons. Even for those diagrams which look as though they represented magnesium ions (Figure 7) – although the student called them as

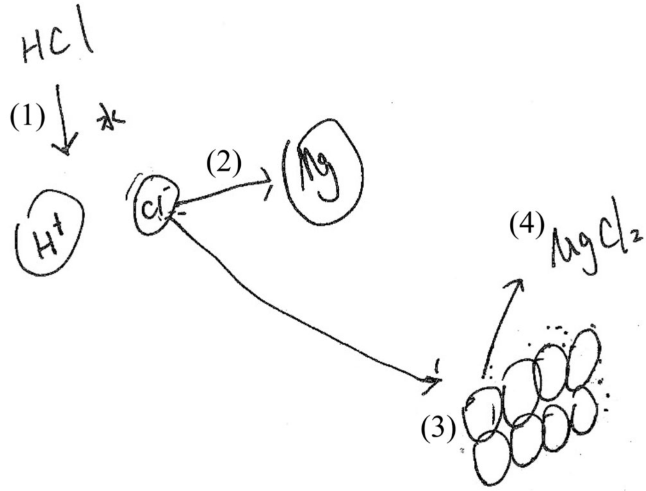


Figure 10. An example where a student used the free electron model to explain the reaction. The numbers (1)–(4) are added to facilitate readers to understand his drawing process. These numbers should be read along with the main text. (B3-T2-a).

'magnesium atoms' – these particles were still represented as intact and unitary before and after the reaction. The reaction was still *only* a simple rearrangement in nature – from a collection of combined 'magnesium atoms' to a collection of 'magnesium atoms' being combined with Cl particles. However, students' representation as exemplified in Figures 8 and 9 showed that there was a change in a reactant from magnesium atoms to magnesium ions, and some represented electrons as a subatomic particle of magnesium atoms. In Figure 10, the student represented the electrons of magnesium lattice, and the formation of charged magnesium particle after magnesium atoms lose electrons. This went beyond a simple rearrangement of particles. These representations were impossible without a consideration or some knowledge of atomic structure. In other words, students in this category were unlikely to have treated magnesium as being made of unitary particles (*particle model* of reactions).

Development of models of reaction

This section reports data that address the second research question. We discuss changes in models that students represented after they were taught the units 'Acids and bases' and 'Redox', respectively. After reporting the general pattern, we will exemplify some changes in model usage demonstrated by students.

Table 2 shows the distribution of number of students who used different models in representing the chemical reaction. Out of the 18 students, one (B2-L2) did not use submicro representations to explain the reaction. Hence, each row adds up to 17 students. There was a change in models represented by the students after being taught 'Redox': the number of students who represented the reaction as the *particle model* fell from nine to four, while the number of students who represented the *atomic model* increased from eight to thirteen. The change in model usage was unidirectional.

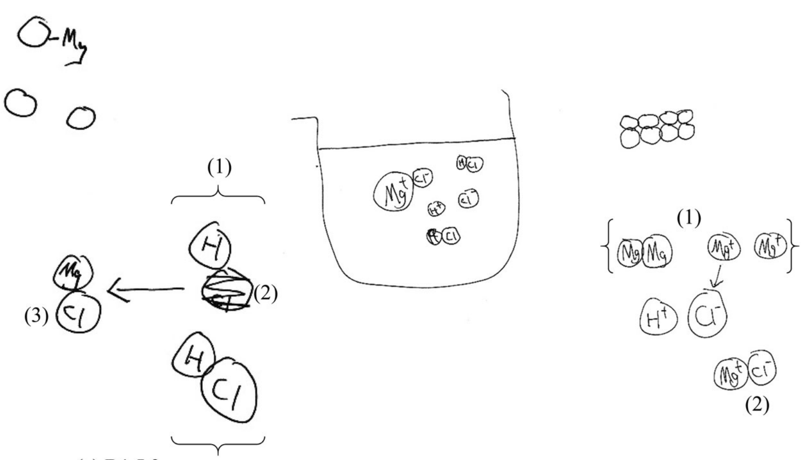
Table 2. The distribution of number of students who used different models in representing the chemical reaction.

	Number of students	
	Particle model of reaction	*Atomic model* of reaction
After being taught Acids and bases	9	8
After being taught Redox	4	13

None of the students regressed their representations from the *atomic model* to the *particle model* in the interview after they were taught 'Redox'. It is likely there was a developmental trajectory in representing the reaction from the *particle model* to the *atomic model*.

The changes can be exemplified by data from two students which illustrate how we can make sense of students' development through the use of two different models of reactions.

(1) After the student B1-L2 had studied the unit 'Acids and bases', he represented the reaction as the displacement of Cl from H to Mg (Figure 11(a)). Before the reaction (refer to the numbers in Figure 11(a) that represent the sequence of his drawing), (1) there were two pairs of H-Cl. As he explained the reaction, (2) he crossed out a Cl and (3) drew a new Cl that 'stuck' to Mg. In the interview after he was taught 'Redox', the student indicated 'when placed inside HCl, Mg atoms will separate and become ions' (refer to label (1) of Figure 11(b)). Instead of just representing 'particles' in the previous interview (Figure 11(a)), there was a change in identities of the submicro entities. Also, the unspecific combination in Figure 11(a) also changed to electrostatic attraction (in label (2) of Figure 11(b)).
(2) The student B2-T2 who represented the *particle model* (reported in Figure 6(b)) expressed the *atomic model* in the subsequent interview. In Figure 12, the reactants and products were represented by electron diagrams (labelled as (1)–(3)). The top



(a) B1-L2-a (b) B1-L2-r

Figure 11. Changes in a student's representations of the reaction – from (a) simple rearrangement to (b) the formation of ions and electrostatic attraction.

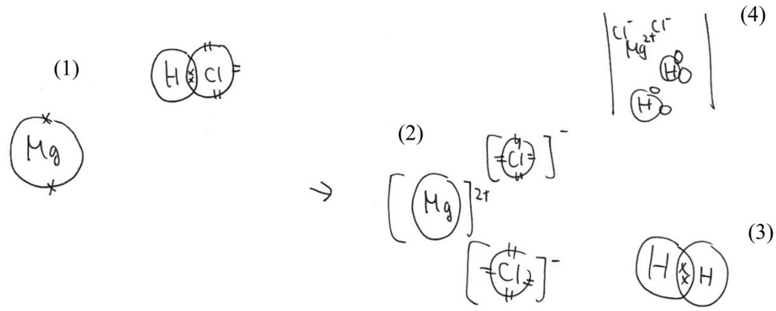


Figure 12. The formation of $MgCl_2$ and H_2 based on the atomic model. The numbers represent the drawing sequence (B2-T2-r).

right-hand corner of the diagram (label (4) of Figure 12) represents how $MgCl_2$ and water were distributed in the test tube as shown in the interview card (Figure 2). In the interview, the student also expressed that both Mg^{2+} and Cl^{-} formed octet structures and connected together.

Conclusion

We propose that there are two models of reactions in the school chemistry curriculum, namely, the *particle model* and the *atomic model*. We investigated how 18 students used these models in visualising the reaction between magnesium and hydrochloric acid at the submicro level. Students were found to be able to reason at the submicro level when they were prompted to. Although the majority of the students did not visualise the reaction in a way that was completely coherent with the scientific view, their representations could be made sense of by the use of these two models. Also, we demonstrated students' progression from the *particle model* to the *atomic model*. This study offers new insights into the general way that students should be expected to develop their understanding of chemical reactions, that is, from the *particle model* to the *atomic model*. Acknowledging these two models can further refine levels of attainment about chemical reactions as proposed by other researchers (e.g. Ahtee & Varjola, 1998; Øyehaug & Holt, 2013).

In the context of this study, after the students had been taught 'Acids and bases', in which submicro representations and models of reactions were not even implicitly touched upon, about half of the students represented the reaction by each of the models. After they had learnt the topic 'Redox', which addressed submicro phenomena such as the working of simple chemical cells and electrolysis, more students visualised the formation of magnesium ions from magnesium atoms (*atomic model*). The results of the first interview may relate to the fact that the curriculum lacked an explicit focus or a clear expected learning outcome on the submicro model of reactions. Hence it left students to construct their own models. Thus, we suggest that when curriculum planners or teachers refer to 'submicro representations of chemical reactions', they would have to be very clear and explicit about the exact model of reactions they expect students to acquire.

Students in this study demonstrated fewer challenges in visualising the chemical reaction as the spatial rearrangement of particles (akin to the *particle model*) than in visualising the reaction as processes that involved electrons, changes in identities of reactants (from magnesium atoms to magnesium ions) and the roles of electrons in forming new products (hydrogen molecules, versus just combing two hydrogen ions). This finding may shed light on the teaching sequence for chemical reactions. For example, it may be fruitful to commence the teaching of reactions at the submicro level with simple molecular reactions such as the formation of ammonia. Also, although this study made use of a single reaction as the case in point, the two models that we proposed can be general to the learning of all chemical changes. For example, rusting may be represented as the combination of iron and oxygen particles (*particle model*). It may also be represented as the formation of a lattice of iron ions and oxide ions with water molecules surrounding the iron ions (*atomic model*). These models of reactions should guide teachers in planning their teaching that targets at different levels of sophistication.

Limitations of this study

This paper analysed students' visualisations of a chemical reaction through the *particle model* and the *atomic model*. Our observations were limited by this theoretical perspective. A limitation is that we did not systematically report students' 'misconceptions' (e.g. HCl (aq) was represented by an unified HCl molecule (Figure 12), magnesium ions bore one positive charge (Figure 11(b)) and the product $MgCl_2$ was represented by many students as 'molecular' triplet units). We did not interpret students' visualisation in terms of their 'correct' or 'incorrect' features. We instead focused on the level of sophistication of the model that students might use. We thus suggest that readers can refer to previous studies if they are also interested in common 'mistakes' students made when they learnt chemical reactions (e.g. Kern et al., 2010; Naah & Sanger, 2012). We believe our findings and interpretations were complementary to these studies. While this study acknowledged students' use of *atomic model* in visualising the reaction, these studies offer valuable advice on tackling students' 'misconceptions'.

In relation to the above limitation, we did not capture the nuanced development in students' visualisation. For example, in Figure 11(a), the student represented magnesium metal as a collection of sparsely spaced particles. However, in the interview after he was taught 'Redox', before he explained the reaction, he drew a cluster of eight magnesium atoms (instead of just three atoms) (see the upper right part of Figure 11(b)). The spatial arrangement of atoms was consistent with the accepted scientific representation of solids. This could be regarded as a development. Yet we did not further analyse such a progression. Also he drew the reactant–product mixture as if the reaction happened in a beaker (Figure 11(b)). Although this demonstrated his capability to represent connections between macro phenomena and submicro interaction that he did not do before, this capability was not taken into account in our data analysis. Nevertheless, examining this piece of data does not affect the validity of our analysis based on the models of reactions used by the students.

We also acknowledge that this study examined only 18 students from a particular context in which students were studying a particular school chemistry curriculum. Further studies in other contexts should be welcome to examine students' learning of the two models of reactions.

Implications for research and curriculum planning: model-based teaching of chemical reactions

This study points out that students have to learn to use three structural models of metals and two models of reactions in a single curriculum. This conceptualisation and the findings of this study open up new questions for researchers, curriculum planners and assessment bodies about how to organise progressive teaching, learning and assessment of chemical reactions.

There is quite a consensus that the triplet of understanding is important in chemistry (Dori & Kaberman, 2012; Gilbert & Treagust, 2009; Taber, 2013; Talanquer, 2011). In the literature, there is little discussion about what models of chemical reactions should be taught at which levels and at which occasions. Ascertaining expected learning outcomes is essential for good curriculum planning and teaching (Loughran, Berry, & Mulhall, 2012). This study found that some students tended to represent reactions in terms of simple rearrangement of particles after they were taught the unit 'Acids and bases'. Although such an understanding is not adequate for redox reactions that involve a transfer of electrons, the particulate view of reactions demonstrated by students was indeed an achievement (compared with those understandings reported in Andersson, 1986). Also, the *particle model* of reactions has its support in chemistry teaching and assessment (e.g. Chang et al., 2014). It is important that we are clear about what we would expect our students to learn at the senior secondary level. This issue should be further discussed among researchers. For example, when we introduce the reaction of magnesium and acids to Grade 10 students as an example of chemical properties of acids, which model should we use, and on what basis? This question should apply not only to this particular reaction, but also to all other types of reactions (as in Atkins, 2011).

Implications on model-based teaching of chemical reactions

In the context of this study, the Hong Kong curriculum expected students to write chemical equations to represent chemical reactions. Also, students were taught atomic structures and chemical bonding before they were introduced to the reaction Mg/H^+. Thus, the curriculum may imply that students are also expected to use elements of the *atomic model* to reason chemical changes. (As noted in the previous subsection, such an expectation should be further discussed.) If this is to be achieved, we would suggest that teachers should utilise students' possible understanding of the *particle model* as a basis for their teaching of the reaction. While the simple rearrangement view is acknowledged, its limitation should be critiqued (Henderson, MacPherson, Osborne, & Wild, 2015). For example, this view does not explain how two positively charged hydrogen ions can combine to form a hydrogen molecule. This issue should then lead to the participation of electrons, and hence the *atomic model* of chemical reactions.

Research and practice have suggested that it is more effective and meaningful when students are asked to learn *with* rather than merely learn *from* scientific representations (Prain & Tytler, 2012; Tippett, 2016). It is likely that guided peer discussion as students construct their own representations collaboratively is a promising teaching strategy

(Pande & Chandrasekharan, 2017; Smetana & Bell, 2012). These representations may be simple drawings supported by viewing animations (Zhang & Linn, 2011) or self-constructed animations (Hoban & Nielsen, 2013; Isaac, 2016). These studies suggest two likely effective teaching strategies for students' learning of the *atomic model* of the reaction: (1) collaborative viewing and discussion of animations that represent the reaction at the submicro level, and then the students draw to represent key stages of the reaction; (2) collaborative construction and guided critique of their own computer-generated representations of the reaction.

Students' idea of 'reactions as rearrangement of particles' can be tenacious. Some students could apply it even to dissolution of ionic solids (e.g. $LiCl(s) + H_2O(l) \rightarrow LiH_{2}$-(aq) + ClO(aq)) (Naah & Sanger, 2012). Therefore, appropriate teaching strategies should be adopted so that such a view can be developed into the *atomic model* of reactions. In this connection, whichever model of reactions is used in the teaching of the reaction Mg/H^+ in the unit 'Acids and bases', there is a need to revisit the reaction when students learn redox reactions. This specific reaction must be reiterated explicitly as an example of redox reaction. It is important to construct a chemical cell based on this reaction through which electric current is generated. It would thus provide an opportunity for students to study the reaction from another perspective, such thatthe test tube reaction they learnt earlier could be useful as a chemical cell when the set-up is altered. The reaction should be revisited in such a way that it can enhance students' understanding of the reaction through their study of redox (i.e. generation of electric current). In this way, the affordances of the *atomic model* of reactions as compared with particles' simple rearrangement can be highlighted. Such a revisit is essential given the findings that only 3 out of 18 students in this study referred to the transfer of electrons from magnesium atoms to hydrogen ions even after they were taught 'Redox'. Also, the idea of matter conservation (Table 1) has to be drawn upon so students are more likely to consider the role of electrons in the formation of hydrogen gas. We believe that such teaching strategies that cultivate model-based reasoning should be applicable to other contexts where there is also a top-down and rather traditional chemistry curriculum.

Note

1. There were two teaching units between 'Acids and bases' and 'Redox', namely 'Fossil fuels and carbon compounds' and 'Microscopic world II'. They covered hydrocarbons as components of fossil fuels, chemical reactions of alkanes and alkenes, intermolecular forces, and structures and properties of molecular crystals.

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