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PAPER

Student misconceptions in writing balanced equations for dissolving ionic compounds in water

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The goal of this study was to identify student misconceptions and difficulties in writing symbolic-level balanced equations for dissolving ionic compounds in water. A sample of 105 college students were asked to provide balanced equations for dissolving four ionic compounds in water. Another 37 college students participated in semi-structured interviews where they provided balanced equations for dissolving the same four ionic compounds in water and were asked to explore their thought processes at the particulate level associated with writing these equations. Misconceptions identified from these data included (i) the notion that water reacts with the ionic salts through double displacement to form a metal oxide and an acid; (ii) the notion that ionic salts dissolve as neutral atoms or molecules in water; (iii) confusion regarding the proper use of subscripts and coefficients; and (iv) the notion that polyatomic ions will dissociate into smaller particles in water. This study also describes the possible sources of these misconceptions.

Introduction

Many concepts in chemistry can be very difficult for students to learn (Taber, 2002; Barke *et al.*, 2009), and several chemical education researchers have focused their efforts on identifying common student misconceptions in chemistry (Osborne and Cosgrove, 1983; Andersson, 1986; Stavy, 1990; Garnett and Treagust, 1992a, b; Ebenezer and Gaskell, 1995; Sanger and Greenbowe, 1997; Boo, 1998; Furió *et al.*, 2000; Solomonidou and Stavridou, 2000; Ebenezer, 2001; Coll and Treagust, 2003; Taber, 2003; Cokelez and Dumon, 2005; Drechsler and Schmidt, 2005; Kelly and Jones, 2007; Costu, 2008; Papaphotis and Tsaparlis, 2008; Schmidt *et al.*, 2009; Cartrette and Mayo, 2011; Smith and Nakhleh, 2011). Identifying and describing students' conceptions regarding the process of dissolving compounds in water—both molecular compounds like sucrose and ionic compounds like table salt—is perhaps the most-studied area of misconceptions in the field of chemistry (Ebenezer and Erickson, 1996; Smith and Metz, 1996; Ebenezer, 2001; Ardac and Akaygun, 2004; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Barke *et al.*, 2009; Smith and Nakhleh, 2011). Several of these studies asked students to generate their own particulate drawings to explain the dissolution process (Smith and Metz, 1996; Ebenezer, 2001; Ardac and Akaygun, 2004; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008), while others provided particulate

drawings to be analysed, often in the form of computer animations or hypermedia (Smith and Metz, 1996; Ebenezer, 2001; Kelly and Jones, 2007; Kelly and Jones, 2008).

Ebenezer and Erickson (1996) explored grade 11 chemistry students' conceptions about the solubility of three systems—sugar/water, salt/water, and water/alcohol/paint thinner. Several students confused the process of dissolving sugar or salt in water with melting. Other students believed that when sugar was added to water it reacted to form a new substance, and one student drew pictures showing sugar and tea molecules attached (bonded) together. These students also used density arguments to explain why paint thinner would not mix with alcohol and water. Some of these students also held the view that dissolved solute particles occupy small air spaces or pockets in water and that solute particles will dissolve only if they find enough space in the solvent. In 2001, Ebenezer (2001) analysed another cohort of fifteen 11th graders' conceptions about the process of dissolving sugar in water. Six of these students believed that sugar transformed from the solid state to the liquid state when it dissolves in water, four believed that sugar reacted with water, and three believed that sugar occupied empty spaces between the water molecules. However, when these same students were shown an animation of sugar dissolving in a hypermedia environment, four students revised their initial views of the dissolving process. Three students not only retained their views that sugar reacted with water, but they also insisted that their views were consistent with what they had seen in the animation. Only one of these students was able to draw particulate models close enough to that of the experts.

Kelly and Jones (2007) explored 18 college students' understanding of the process of dissolving sodium chloride in water

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using two different animations. One animation depicted the space-filling ions vibrating in the lattice and focused on the interactive forces during hydration; the other depicted sodium chloride in a lattice structure and showed the charges on the ions and still pictures of water molecules surrounding the hydrated ions. Before viewing the animations, students provided particulate drawings to illustrate their initial understanding of sodium chloride and water before, during, and after mixing. In these initial drawings, 15 students represented sodium chloride as neutral molecules and 8 drew water molecules as linear. Five students showed sodium chloride molecules interacting with water, and two of these students showed sodium chloride molecules forming bonds with water molecules. In a subsequent study, Kelly and Jones (2008) tested to see how viewing particulate animations of sodium chloride dissolving in water affected the same college general chemistry students' abilities to transfer their understanding from the previous week to explain the precipitation reaction of aqueous sodium chloride and silver nitrate. Although all 18 of these students corrected errors in their initial drawings after seeing particulate animations of sodium chloride dissolving in water, none showed the spheres of hydration around the sodium chloride and silver nitrate ions in their particulate drawings one week later. Six students showed sodium chloride as neutral molecules, and three students showed sodium chloride pairs with water molecules. In general, students had trouble transferring their improved conceptions from the particulate animations to the new precipitation reactions one week later.

Smith and Metz (1996) evaluated student-generated drawings for the precipitation reaction of aqueous nickel(II) chloride and aqueous sodium hydroxide, Liu and Lesniak (2006) studied grade 1–10 students' conceptions about the dissolution of baking soda in water, Tien *et al.* (2007) used the Model-Observe-Reflect-Explain (MORE) approach to evaluate college chemistry students' understanding of processes involved in dissolving sugar and salt in water, and Smith and Nakhleh (2011) focused on students' conceptions regarding the bonds that must be made and broken when ionic compounds melt and when they dissolve in water. All four studies found that students believed ionic compounds would dissolve in water as neutral molecules, and three of them showed evidence that students were confused regarding the difference between the processes of melting and dissolving and that they believed that the solute particles would form chemical bonds with the solvent (water) molecules (Liu and Lesniak, 2006; Tien *et al.*, 2007; Smith and Nakhleh, 2011).

Although several chemical education research studies have analysed students' conceptions of dissolving ionic and molecular compounds in water, none have looked at student difficulties when writing balanced equations for the dissolving process. The goal of this study is to identify college-level introductory chemistry students' misconceptions associated with writing balanced equations for the dissolution of ionic salts in water.

Part of the difficulty in discussing the process of dissolving ionic compounds in water is determining whether this represents a physical process or a chemical change. Ebenezer and Gaskell (1995) described the ambiguity very well:

"In the ordinary sense, solutions of sugar and salt in water are said to be the result of a physical change because the components can be separated by simple physical means such as evaporation. In another sense, however, salt dissolving in water can also be characterized as a chemical phenomenon. For example, the behavior of salt solution is different from the behavior of crystalline salt: unlike salt in the solid form, salt solution conducts electricity. Thus the concept of dissolving poses difficulty for students because of its dual behavior—a chemical process in some contexts and a physical one in others." (pp. 13–14).

Another way of framing this ambiguity is that dissolving an ionic compound in water can be classified as a physical process or a chemical change depending on how the ionic solid is viewed. If the ionic solid is viewed as an intact entity, then dissolving this compound into water results in a chemical change and creates new chemical species, the hydrated cations and anions. However, if the ionic solid is viewed as a collection of cations and anions, then dissolving does not create any new chemical species, it simply places the existing species in a new environment and is best described as a physical process.

In this study, students are asked to write balanced equations for dissolving ionic compounds in water. Those readers who view this as a physical process may question the use of the term *balanced equation*, which may imply that a chemical reaction is occurring. We recognize this difficulty and have attempted to minimize any confusion regarding the use of this term by refraining from the use of terms such as *balanced chemical equation*, *chemical reaction*, *reactant*, or *product* unless discussing examples where students actually believe a chemical reaction is occurring.

Theoretical perspective

Constructivist theory of learning posits that knowledge cannot be directly transferred from the instructor to students because students must actively construct their own knowledge that makes sense to them by integrating new ideas into their existing knowledge (Bodner, 1986; Bodner *et al.*, 2001). Unfortunately, many students learning chemistry hold on to their own personal views and inadequate interpretations of particulate phenomena that develop from their individual experiences, culture and classroom instruction (Duit and Treagust, 1995). When these views and interpretations differ from those widely accepted by chemists, they are referred as misconceptions (Bodner, 1986). Often, misconceptions interfere with learning concepts in chemistry, and are known to occur among students capable of successfully solving quantitative problems in chemistry (Nurrenbern and Pickering, 1987; Pickering, 1990; Sawry, 1990).

The use of multiple representations (macroscopic, particulate, and symbolic) in chemistry instruction confuses many students (Johnstone, 1993; Gilbert and Treagust, 2009; Johnstone, 2010; Talanquer, 2011) and research has shown that students have difficulty moving from the macroscopic to the particulate level (Osborne and Cosgrove, 1983; Andersson, 1986; Ben-Zvi *et al.*, 1986; Gabel, 1993; Kelly *et al.*, 2008) and from the symbolic to the particulate level (Yarroch, 1985; Nurrenbern and Pickering, 1987; Pickering, 1990; Sawry, 1990; Gabel, 1993; Sanger, 2005; Kelly *et al.*, 2008).

The ability to see the connections and move seamlessly between these levels is referred to as representational competence (Kozma and Russell, 1997; Madden et al., 2011). More successful problem solvers are generally found to have stronger and richer representations than their less successful counterparts (Kozma and Russell, 1997; Bodner and Domin, 2000; Madden et al., 2011). As a result, while chemistry instructors are able to move freely between these levels, beginning chemistry students often find this to be a challenge, and are likely to develop misconceptions during instruction (Gabel, 1993).

Methods

Free-response protocol

For the first part of this study, students ($N = 105$) enrolled in a first-semester introductory chemistry class who had previous instruction on solution chemistry (precipitations, acid–base reactions, oxidation-reduction reactions) were asked to write balanced equations for the dissolution of four ionic compounds in water. The ionic compounds were LiCl (a compound with no subscripts), $CaCO_3$ (a compound with a polyatomic subscript), $BaBr_2$ (a compound with a monatomic subscript), and K_2SO_4 (a compound with both types of subscripts). The student-generated equations were analysed and categorized to determine common student errors made in writing these equations.

Interview protocol

In order to corroborate the student misconceptions and errors identified based on the written balanced equations, an additional 37 students were interviewed in groups of one or two using a semi-structured interview protocol (Borg and Gall, 1983); the interviews each lasted about 30 min and focused on students' particulate explanations of their self-generated (symbolic) balanced equations. Conceptual and propositional knowledge statements (Table 1) needed to fully understand the dissolving process were derived by the researchers after reviewing several introductory college chemistry textbooks. These statements were reviewed by two college chemistry professors, and their comments were used to revise the list. The statements represent the scientifically accepted knowledge required for students to fully understand the dissolution process, and a framework for developing the interview protocol and the procedures for data analysis.

The interviews started out with a chemical demonstration of the solubility and conductivity of solid lithium chloride in water. Participants were shown a sample of distilled water and solid LiCl, and the conductivity of each sample was measured. Then a small amount of LiCl was added to a sample of water and the participants were asked if it dissolved and how they knew. Then, the conductivity of the solution was tested. The participants were then asked to explain the conductivity data.

For the second part of the interview, participants were asked to write a balanced equation for the dissolution of LiCl in water, including states of matter, and were then asked to write similar equations for dissolving $CaCO_3$, $BaBr_2$, and K_2SO_4 in water. After writing each balanced equation, the students were asked to explain their thought processes

regarding why they wrote the equations the way that they did. Follow-up questions were asked as needed including questions on charge balance, why water was reacting, why some subscripts did or did not become coefficients, why polyatomic ions did or did not dissociate in solution, etc. A brief summary of the interview protocol and some of the open-ended questions used in the interview process appear in Fig. 1.

Analysis of data

The balanced equations from the first group of students were tabulated for each ionic solid as a list of balanced equations along with the number of students writing each equation. These lists were analysed for errors, which were categorized into themes that represented common student misconceptions. The misconceptions identified from the written responses were used as a guide to analyse the semi-structured interviews. Each interview was digitally recorded, and the student-generated balanced equations were written on the question sheets used during the interview. The interviews were transcribed verbatim by the first author. The misconceptions identified by the free-response equations were either supported or refuted by referring to interview transcriptions. The digital recordings were analysed by two chemical education researchers; any initial disagreements were discussed and resolved by these researchers.

Results and discussion

The most common student-generated equations (provided by 5% or more of the student population) for each ionic solid are listed in Table 2. These responses include correct equations and incorrect equations involving several types of misconceptions described in greater detail below. Many of the student-generated equations had a combination of more than one error, resulting in quite a few unique ($N = 1$) responses. To get a better understanding of the prevalence of these mistakes, the number of students making each kind of error was tabulated for each ionic solid and these results appear in Table 3. Table 4 contains a list of student misconceptions identified from these equations and the subsequent interviews.

Double displacement reactions involving water

Several students wrote balanced equations showing that ionic salts react with water through double displacement to form an acid and the metal oxide or hydroxide when they dissolve (Misconception 1). This response appeared in the top three responses in Table 2 for each ionic solid. It was the most common answer for the interview students (shown by over 40% of these students for each ionic solid), and was even more popular than the correct response. The following interview excerpt provides an example of this misconception:

Participant: (written) $2LiCl(s) + H_2O(l) \rightarrow Li_2O(aq) + 2HCl(aq)$.

Interviewer: From your equation is water reacting?

Participant: It should be a double displacement.

Interviewer: What about states of matter?

Participant: Aqueous.

Interviewer: How do you know it's aqueous?

Participant: You don't see a solid anymore.

188 | *Chem. Educ. Res. Pract.*, 2012, **13**, 186–194

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Table 1   Conceptual and propositional knowledge statements for the dissolution of ionic solids in water

1. Ionic solids contain positively charged ions (cations) and negatively charged ions (anions). The ratio of cations to anions in the solid is determined by the charges of the two ions since the overall charge of the ionic solid must equal zero. Ionic solids are usually solids under normal laboratory conditions. The formula unit of an ionic solid contains the simplest (smallest) ratio needed to maintain neutrality. The cation is listed first and the anion is listed second. If more than one ion is needed in the formula unit, subscripts are used to denote the number of each ion present. If a subscript is needed for a polyatomic ion, parentheses must be placed around the formula of the polyatomic ion with the subscript appearing after the right parenthesis.

2. When an ionic compound dissolves in water, it changes from the solid state to an aqueous state. Ionic compounds do not dissolve in water as neutral ion-pairs. Instead, water-soluble ionic compounds are strong electrolytes in which the individual ions dissociate from one another and move independently throughout the solution.

3. Water does not chemically react with an ionic compound when it dissolves in water. Instead, water molecules hydrate the individual ions, positioning the partially negative oxygen atom in a water molecule toward the cations and a partially positive hydrogen atom in the water molecule toward the anions. Dissolving ionic compounds in water can be viewed as a physical process that can be reversed by evaporating the water.

4. The process of electrical conductivity requires charged particles that have the freedom to move from one electrode to the other. Solid ionic compounds have charged ions in them but these ions do not have the freedom to move from one electrode to the other, so the solid will not conduct electricity. Pure liquid water does not have an appreciable amount of charged particles in it to allow the conduction of electricity. Aqueous solutions of ionic compounds, on the other hand, do conduct electricity because the dissolved cations and anions have the freedom to move from one electrode to the other.

5. Polyatomic ions represent clusters of two or more atoms that have a net electrical charge. Polyatomic ions are held together by strong covalent bonds. These ions tend to be stable in water and do not dissociate but instead remain intact when a solid ionic compound is dissolved in water.

6. When writing balanced equations for dissolving ionic compounds in water: (a) The ionic compound present before dissolving is in the solid state, designated as (s), and the individual ions present after dissolving are in the aqueous state, designated as (aq); (b) Although water is needed for the dissolution process, it is not a involved in a chemical reaction with the ionic solid and is left out of the equation; (c) The cations and anions present after dissolving are written separately to denote that these ions are no longer joined together in the solution; (d) Numbers placed after an atom or group of atoms (subscripts) are used to denote how many of each type of atom or group of atoms are present in a chemical species; (e) Numbers in front of a chemical formula (coefficients) are used to denote how many of these chemical species are present; (f) Polyatomic ions are left intact and any subscripts in the polyatomic ion are still written as subscripts; (g) Any subscripts placed in the formula unit of the ionic solid that are not part of polyatomic ions, used to denote how many of these ions are present in the formula unit, are now written as coefficients in front of the ion it modified.

Demonstration

After seeing a small amount of solid lithium chloride being added to a sample of distilled water:

1. How can you tell whether solid lithium chloride is dissolving?
2. Suppose you could zoom in really close inside the test tube, could you estimate the relative amount of lithium chloride and water?

After the conductivity tests of distilled water, solid lithium chloride, and the aqueous salt solution:

3. How does the salt solution conduct electricity? What part of the salt solution conducts electricity?

Balanced equations

Write the net ionic equation for what happens when these ionic compounds dissolve in water:

4. $LiCl(s) \rightarrow$
5. $CaCO_3(s) \rightarrow$
6. $BaBr_2(s) \rightarrow$
7. $K_2SO_4(s) \rightarrow$

Follow-up questions

The following questions were used as needed in the semi-structured interviews

8. What are the states of matter for the chemicals present before and after dissolving?
9. Why did you write these ions separate from each other?
10. Why did you change this number from a subscript to a coefficient?
11. Why didn't you change this number from a subscript to a coefficient?
12. What is the difference between F_2 and $2F$?
13. Is the equation balanced?
14. Are charges balanced?
15. Why didn't you break the sulfate/carbonate ions apart?

Fig. 1   Interview protocol used for the semi-structured interviews regarding the dissolution process for the four ionic compounds in water.

Interviewer: Before you said there are ions in the mixture, and where are the ions in your written equation?
Participant: It's [a] net ionic [equation].
Interviewer: Though you wrote it in the molecular form, the charges in $Li_2O(aq)$ and $HCl(aq)$ will be?
Participant: Li^+, O^{2-}, H^+, Cl^-. (Misconception 1).

A few students wrote double displacement reactions in which the cation combined with the positively-charged hydrogen atoms from water and the anion combined with the negatively-charged oxygen atoms from water (Misconception 2). For example, four students wrote the equation: $LiCl(s) + H_2O(l) \rightarrow LiH_2(aq) + ClO(aq)$. To a chemist, this reaction appears to be an oxidation-reduction reaction but these students treated this reaction as a simple double displacement between Li, Cl, H_2, and O.

Dissociation into neutral atoms/molecules

Another common student mistake was to write balanced equations in which the ionic salts dissolve as neutral atoms or molecules instead of cations and anions (Misconception 3). This response also appeared in the top two responses in Table 2 for each ionic solid, and was routinely demonstrated by 16–35% of the students. When a pair of students who wrote lithium chloride dissolving as aqueous Li and Cl atoms were asked what in their written equation was causing the salt solution to conduct electricity, they stated it was the lithium atom because metals conduct electricity. The following interview excerpt illustrates the belief that dissolved ionic solids have the same properties as their neutral elements (Misconception 4):

Participant: (written) $LiCl(s) \rightarrow Li(aq) + Cl(aq)$.
Interviewer: Which of those [species] conducts electricity?
Participant: Metal, lithium.
Interviewer: How do you know the state of matter is aqueous?
Participant: Because no solid [is present] and it's dissolved in water. (Misconception 4).

Subscript/coefficient errors

Several students wrote balanced equations showing confusion between the use of subscripts and coefficients. Less than 5% of

Table 2 Student-generated balanced equations for ionic compounds dissolved in water for the free response and interview studies

Equation	Number (per cent) of respondents		Equation errors
	Free-response	Interview	
$LiCl(s) \rightarrow Li^+(aq) + Cl^-(aq)$	44 (42)	9 (24)	None (correct)
$LiCl(s) \rightarrow Li(aq) + Cl(aq)$	18 (17)	7 (19)	Charges missing
$2LiCl(s) + H_2O(l) \rightarrow Li_2O(aq) + 2HCl(aq)$	5 (5)	12 (32)	Water reacting
$LiCl(s) + H_2O(l) \rightarrow LiO(aq) + HCl(aq)$	7 (7)	0 (0)	Water reacting, Atoms not balanced
Other unique responses	31 (30)	9 (24)	Various
$CaCO_3(s) \rightarrow Ca^{2+}(aq) + CO_3^{2-}(aq)$	21 (20)	11 (30)	None (correct)
$CaCO_3(s) \rightarrow Ca(aq) + CO_3(aq)$	17 (16)	5 (14)	Charges missing
$CaCO_3(s) + H_2O(l) \rightarrow CaO(aq) + H_2CO_3(aq)$	7 (7)	14 (38)	Water reacting
$CaCO_3(s) \rightarrow CaCO_3(s)$	7 (7)	0 (0)	Solid does not dissolve
Other unique responses	53 (50)	7 (19)	Various
$BaBr_2(s) + H_2O(l) \rightarrow BaO(aq) + 2HBr(aq)$	10 (10)	12 (32)	Water reacting
$BaBr_2(s) \rightarrow Ba(aq) + Br_2(aq)$	11 (10)	5 (14)	Charges missing, Subscript error
$BaBr_2(s) \rightarrow Ba^{2+}(aq) + 2Br^-(aq)$	11 (10)	5 (14)	None (correct)
$BaBr_2(s) \rightarrow Ba^{2+}(aq) + Br_2^-(aq)$	10 (10)	4 (11)	Charges not balanced, Subscript error
$BaBr_2(s) \rightarrow BaBr_2(s)$	8 (8)	0 (0)	Solid does not dissolve
$BaBr_2(s) \rightarrow Ba(aq) + 2Br(aq)$	7 (7)	1 (4)	Charges missing
$BaBr_2(s) \rightarrow Ba^{2+}(aq) + Br^-(aq)$	7 (7)	0 (0)	Atoms not balanced, Charges not balanced
Other unique responses	41 (39)	11 (30)	Various
$K_2SO_4(s) + H_2O(l) \rightarrow K_2O(aq) + H_2SO_4(aq)$	8 (8)	13 (35)	Water reacting
$K_2SO_4(s) \rightarrow K_2(aq) + SO_4(aq)$	12 (11)	5 (14)	Charges missing, Subscript error
$K_2SO_4(s) \rightarrow 2K^+(aq) + SO_4^{2-}(aq)$	8 (8)	8 (22)	None (correct)
$K_2SO_4(s) \rightarrow K_2^+(aq) + SO_4^{2-}(aq)$	7 (7)	1 (3)	Subscript error, Charges not balanced
Other unique responses	70 (67)	10 (27)	Various

Table 3 Number (per cent) of students making common errors in student-generated equations

Error	LiCl		CaCO$_3$		BaBr$_2$		K$_2$SO$_4$	
	Free-response	Interview	Free-response	Interview	Free-response	Interview	Free-response	Interview
None	44 (42)	9 (24)	21 (20)	11 (30)	11 (10)	4 (11)	8 (8)	8 (22)
Water reacting	27 (26)	16 (43)	17 (16)	16 (43)	25 (24)	16 (43)	24 (23)	15 (41)
Charges missing	27 (26)	8 (22)	28 (27)	6 (16)	26 (25)	6 (16)	37 (35)	8 (22)
Subscript errors	0 (0)	2 (5)	5 (5)	2 (5)	40 (38)	16 (43)	44 (42)	10 (27)
Incorrect charges	8 (8)	2 (5)	26 (25)	2 (5)	25 (24)	7 (19)	32 (30)	3 (8)
Polyatomic ion dissociated	—	—	32 (30)	2 (5)	—	—	8 (8)	1 (3)
Atoms not balanced	17 (16)	2 (5)	27 (26)	0 (0)	28 (27)	0 (0)	32 (30)	2 (5)
Charge not balanced	11 (10)	2 (5)	22 (21)	1 (3)	24 (23)	5 (14)	31 (30)	3 (8)

Table 4 List of misconceptions identified in this study

1. Ionic salts chemically react with water when dissolved *via* double displacement to form an acid and the metal oxide or hydroxide.
2. In double displacement reactions of the ionic salt and water, the hydrogen atoms from water combines with the cation of the salt and the oxygen atoms from water combines with the anion of the salt.
3. Ionic salts dissolve as a combination of neutral atoms or molecules in water.
4. Dissolved ions/ionic compounds have the same properties as their neutral elements.
5. There are no fixed rules for when a subscript or coefficient should be used, and subscripts and coefficients do not convey specific information to chemists.
6. When a subscript is added to a monatomic ion, it also changes the total charge of the ion.
7. Monatomic non-metal ions will bond together because their neutral elements exist as diatomic molecules; monatomic metal ions will not bond together because their neutral atoms do not exist as diatomic molecules.
8. Polyatomic ions dissociate into smaller components when dissolved in water.

students showed subscript/coefficient errors when the ionic solid contained no subscripts (LiCl), or when it only contained a subscript as part of a polyatomic ion (CaCO$_3$). When the ionic solid contained a subscript for monatomic ions (BaBr$_2$ and K$_2$SO$_4$), more of the student-generated equations (27–43%), contained subscript/coefficient errors, and most of these errors involved the monatomic ions (Br$^-$ and K$^+$, respectively). Further probing in the interviews showed that many of these students did not know the scientific rules for using chemical subscripts and coefficients or what the difference between 2F and F$_2$ would be (Misconception 5).

Participant: (written) BaBr$_2$(s) + H$_2$O(l) → BaO(aq) + H$_2$Br$_2$(aq).
Interviewer: Why didn't you write 2HBr instead of H$_2$Br$_2$?
Participant: 2HBr means 2 moles of HBr.
Interviewer: What is the difference between 2F and F$_2$?

Participant: F$_2$ means is balancing the charges in the formula. 2F means to balance the equation. (Misconception 5).

In writing monatomic ions with subscripts, it was common for students to write the "ion-pair" with the charge of a single ion (*i.e.*, H$_2^+$, Br$_2^-$, K$_2^+$, *etc.*). It became clear that many of these students believed that the subscript placed at the bottom of the atom symbol not only modifies the total number of atoms present but also the total charge of the ion (Misconception 6). In other words, they believed that writing Br$_2^-$ was the same as writing (Br$^-$)$_2$ which would be properly written as Br$_2^{2-}$.

One pair of students wrote equations showing that BaBr$_2$ dissolved in water to make the Br$_2^-$ ion but that K$_2$SO$_4$ dissolved in water to make 2 K$^+$ ions. Subsequent questioning showed that they understood the difference between coefficients and subscripts. The students explained that ions of non-metal anions would bond together as a diatomic unit because their neutral elements do, but ions made of metals would not because their neutral elements do not (Misconception 7). This is an extension of Misconception 4 applied to monatomic ions.

Participant: (written) BaBr$_2$(s) → Ba^{2+}(aq) + Br$_2^-$(aq); K$_2$SO$_4$(s) → 2 K$^+$(aq) + SO$_4^{2-}$(aq).

Interviewer: In K$_2$SO$_4$(s), 2 is a subscript but you wrote 2 K$^+$, why is that?

Participant: When they are diatomic, they can't exist by themselves.

Interviewer: What is F$_2$?

Participant: Stuck together.

Interviewer: What is 2F?

Participant: Separate.

Interviewer: Why does Br bond together and K$_2$ doesn't?

Participant: Elements like O$_2$, Br$_2$ are stuck together. They just can't exist alone. (Misconception 7).

Dissociating polyatomic ions

For the dissolution of CaCO$_3$ and K$_2$SO$_4$, some students wrote balanced equations showing the polyatomic ions dissociating into smaller particles (Misconception 8). This error was more common among the students in the free-response group, and was much more common for the carbonate ion than the sulfate ion. One reason why students may be more comfortable breaking up the carbonate ion is that chemistry instructors often show demonstrations of carbonate salts reacting (and breaking into CO$_2$ and "O^{2-}") in the presence of acids. Another reason may be that they recognize O$_3$ as ozone but do not recognize O$_4$ as a known substance.

Participant: (written) CaCO$_3$(s) → Ca(s) + C(s) + O$_3$(g).

Interviewer: You said O$_3$ is a gas and Ca and C are solids. How did you figure that out?

Participant: Something that I know from class, but for Ca and C as solid, I am not sure. (Misconception 8).

Other errors

Several students wrote equations with incorrect charges for some of the ions (*e.g.*, Li^{2+}, Cl^{2-}, Ca$^+$, CO$_3^-$, Ba$^+$, Br^{2-}, K$^-$, SO$_4^{2+}$, *etc.*). It is difficult to determine whether these represent incorrect conceptions or simply a lack of propositional knowledge regarding the common charges of these ions. Similarly, it is difficult to be sure that students writing correct charges have

a mature understanding why these charges are the stable ones. Several students also wrote equations that were not atom-balanced or charge-balanced (both ranging from 0–30% of the population for the four ionic solids). These errors were more common for the students in the free-response group than the interview group. Since the free-response group participated in this study when the topic of dissolving ionic compounds in water was first introduced in class but the second group of students were interviewed later in the semester, this could simply be a matter of familiarity and practice in writing balanced equations.

Conclusions

This study identified four major student misconceptions in writing balanced equations for ionic compounds dissolved in water. These misconceptions included the idea that ionic compounds react with water in a double displacement reaction when dissolved, the idea that ionic compounds dissociate into neutral atoms or molecules in water, a general confusion regarding the proper use of subscripts and coefficients, and the idea that polyatomic ions dissociate into smaller components when dissolved in water. It should be noted that these misconceptions could appear as a result of simple student mistakes, memory lapses on the part of the student (especially for those students predicting incorrect charges for the ions), or the fact that students and researchers may have assigned different meaning to terms used in discussing students' ideas (Klaassen and Lijnse, 1996).

Possible sources of student misconceptions

The misconception that water reacts with the dissolved ionic salts is not new. Ebenezer and Erickson (1996) found that many students considered dissolving to be a chemical reaction, in which sugar or sodium chloride react with water to form new compounds with entirely different physical and chemical properties. Tien *et al*. (2007) and Smith and Nakhleh (2011) reported that some college students gave responses suggesting that dissolved NaCl forms chemical bonds with water, but both groups failed to indicate if students thought that new compounds would form as a result. It is possible that our demonstration, which showed that solid lithium chloride and liquid water did not conduct electricity but the combination of chemicals did, could have convinced students that water was important to the process and therefore part of the reaction. In American textbooks, the concept of dissolving ionic compounds in water is immediately followed by the discussion of double displacement reactions including acid/base and precipitation reactions. This proximity could lead to misconceptions where students confuse double displacement acid/base or precipitation reactions with the process of dissolving ionic compounds in water.

The misconception that ionic compounds dissolve as neutral atoms/molecules in water is inconsistent with the conductivity demonstration performed as part of the interviews. Some of these students explained this discrepancy by saying that it is the metals in solution that are conducting electricity because (solid) metals always conduct electricity. This misconception that dissolved ions in water have the same properties as their neutral elements is common and dates back to 1883, in which

members of the doctoral committee of Svante Arrhenius were reported to have discounted the idea that sodium chloride would dissociate into ions in water because these solutions had none of the properties of elemental sodium or chlorine (Jaffe, 1976; Chemical Heritage Foundation, 2010). Computer animations depicting ions and ionic compounds without labeled charges on the ions could also support this misconception (Tasker, 1998). Perhaps showing students the conductivity of ionic compounds that do not contain metals ions (like hydrochloric acid or ammonium nitrate) would help some of these students relinquish this misconception.

Students' confusion regarding the use of subscripts or coefficients has also been previously reported (Yarroch, 1985; Al-Kunifed *et al.*, 1993; Sanger, 2005; Nyachwaya *et al.*, 2011). Some of these students did not understand the chemical conventions regarding subscripts or coefficients and did not understand the difference between the formulas 2F and F_2, or that the formulas Br_2^- and $(Br^-)_2$ are not the same. However, other students who did understand the rules for subscripts and coefficients still wrote formulas showing two cations or two anions bonded together (*i.e.*, K_2^+ or Br_2^-), especially if they appeared that way in their neutral ionic salts (K_2SO_4 or $BaBr_2$). As a result, students exhibited more subscript/coefficient errors when the ionic compounds contained subscripts for monatomic ions (K_2SO_4 or $BaBr_2$) than when the ionic compounds did not (LiCl or $CaCO_3$).

The misconception that polyatomic ions dissociate into smaller components when dissolved in water most likely represents a lack of understanding of the nature of polyatomic ions. Although there are some notable exceptions (such as when carbonate ions are mixed with acids), polyatomic ions tend to stay together as a single object when dissolved in water and are often treated as a single entity by chemists. Nyachwaya *et al.* (2011) showed particulate drawings from a student who drew "molecules" of $CaCO_3$ in which the Ca atom was in the middle with one C and the three O atoms bound to it, indicating that this student did not understand the structure of a polyatomic ion like carbonate. Smith and Metz (1996) showed similar student-generated particulate drawings with hydroxide groups broken into H and O atoms.

Although we identified several the misconceptions in this study, there was another misconception that we had expected to see but did not. The dissolution of ionic compounds to form neutral ion pairs (*i.e.*, solid LiCl dissolving in water as neutral LiCl molecules) has been well documented in the chemical education literature (Butts and Smith, 1987; Boo, 1998; Tasker, 1998; Liu and Lesniak, 2006; Kelly and Jones, 2007; Tien *et al.*, 2007; Kelly and Jones, 2008; Smith and Nakhleh, 2011; Nyachwaya *et al.*, 2011; Rosenthal and Sanger, 2011). Taber (Taber, 1994; Taber, 1997; Barke *et al.*, 2009) also noted that many students believed individual ion pairs exist in solid ionic salts, even though the cations and anions in the solid were surrounded by several ions of the opposite charge. However, only one student out of the 142 students in both studies demonstrated this misconception in his or her balanced equations. We are not sure why this common misconception was not more popular among our students.

This study was performed using students in first-semester introductory chemistry courses where the concept of dissolving ionic compounds in water is first introduced. We had originally interviewed 20 students in a second-semester introductory chemistry course (after they had studied equilibrium solubility of ionic compounds in water including K_{sp} calculations) to corroborate or refute the misconceptions identified in the first part of this study. However, all of these students were able to write the correct equations for the solubility of the four compounds used in this study. It is encouraging to see that after studying the solubility of ionic compounds in two different chemistry courses, these students demonstrated a solid understanding of writing balanced equations for the dissolution process.

Future studies

This study has identified several misconceptions exhibited by students when writing balanced equations for dissolving ionic compounds in water. These results may be useful to instructors, textbook authors, or instructional designers trying to develop strategies to improve students' conceptual understanding about the dissolving process. Research involving instruction that incorporates the conceptual change approach (Posner *et al.*, 1982), in which the instructor elicits and then actively confronts student misconceptions, may help some students relinquish some of the misconceptions identified in this study.

Most research involving the use of computer animations of chemical reactions at the particulate level have focused on instructional interventions to improve students' conceptual understanding of these chemical processes (Williamson and Abraham, 1995; Sanger *et al.* 2000; Kelly and Jones, 2008; Gregorius *et al.*, 2010a, b). Few have used these animations a part of the assessment process (Sanger *et al.*, 2007; Rosenthal and Sanger, 2011). Nyachwaya *et al.* (2011) compared students' abilities to balance chemical equations at the symbolic level to their abilities to create particulate drawings of these chemical reactions, and found that students were adept at balancing chemical equations but could not translate these formulas into the particulate level. The authors of the present study have created particulate animations depicting the dissolving process of four ionic compounds in the form of multiple-choice questions with four distractors based on the misconceptions identified in this study (the correct process, one showing a reaction with water, one showing neutral ion pairs/molecules, and one involving a confusion of subscripts and coefficients). Students in a future research study will be asked to answer questions for the same four ionic compounds dissolving in water, posed at the particulate and symbolic levels. This study will allow the authors to determine whether students' choices from the symbolic equations and the particulate animations are consistent, which may imply a more robust conception (whether right or wrong). It may also allow the researchers to further probe whether students understand the chemical conventions used for subscripts and coefficients in the symbolic-level balanced equations at the particulate level.

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194 | *Chem. Educ. Res. Pract.*, 2012, **13**, 186–194

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