Students' understanding of acid, base and salt reactions in qualitative analysis

Kim-Chwee Daniel Tan, Ngoh-Khang Goh, Lian-Sai Chia and David F. Treagust

Conventional methods of teaching QA do not seem to help students understand the reactions involved. This new instructional package may help.

The topic qualitative analysis (QA) is an important component of the national grade 10 chemistry practical examinations in Singapore. During the practical examinations, grade 10 students (15- to 17-years-old) are required to carry out a series of procedures using chemicals, apparatus and appropriate techniques. They also need to observe and record what happens, and make inferences based on their observations. Teachers in Singapore usually begin teaching QA by reviewing the reactions involved and demonstrating some procedures that the students need to carry out. Using commercially available workbooks or teacher-prepared worksheets, students then do a series of tests for the various cations, anions, gases, oxidising and reducing agents as specified in the syllabus. As students are assessed mainly on their written observations, the main emphasis of QA practical work is getting correct results and writing 'standard' observations. Thus, many students merely follow instructions given in the worksheets, and seldom think about what they are doing (Tan *et al.*, 2001).

ABSTRACT

A two-tier multiple-choice diagnostic instrument was used to determine 915 grade 10 students' (15- to 17-year-olds) understanding of the acid, base and salt reactions involved in basic qualitative analysis. The results showed that many students did not understand the formation of precipitates and complex salts, acid-salt/base reactions and thermal decomposition involved in qualitative analysis. This indicated that the usual method of teaching the topic might be ineffective in fostering its understanding. In response to this, an instructional package which emphasised the three levels of representation of the reactions was developed.

To understand the reactions involved (Figure 1), students mainly need to apply the content knowledge which they have learnt in the topic, 'Acids, bases and salts'. However, studies have found that students have difficulties in understanding the reactions in this topic. For example, Butts and Smith (1987) found that students could not relate the formation of a precipitate in a double decomposition reaction to the low solubility of the salt, and Boo (1994) found that students believed the driving force for a double decomposition reaction was the difference in reactivity between the metallic elements present in the compounds involved. Another alternative conception of double decomposition reactions was that the ions from the reactants had to return the electrons to their original atoms before a new electron transfer occurred to form the precipitate (Taber, 2001). In another study, Schmidt (2000) reported that students believed the reaction between magnesium oxide/hydroxide and hydrochloric acid was a redox reaction because of the oxygen present in the oxide and hydroxide.

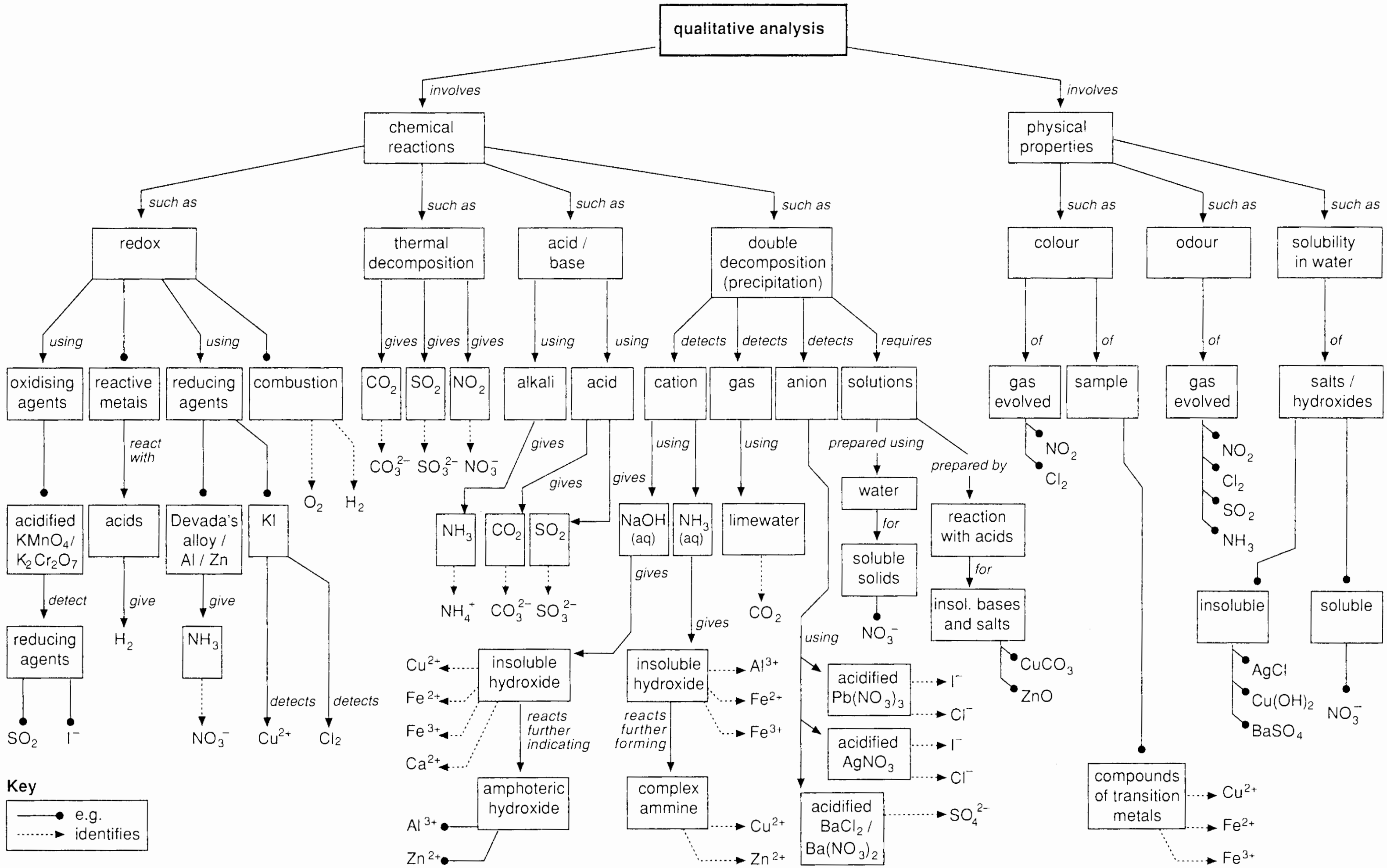

Figure 1 Concept map.

The study

In this study, we used a two-tier multiple-choice diagnostic instrument (Treagust, 1995) to determine 915 grade 10 students' understanding of the reactions involved in QA. The students were from 11 secondary schools and were preparing for a national examination, one of their subjects being chemistry. Sixty per cent were females and forty per cent were males. These students were academically above average and all were studying chemistry as a single subject rather than as part of a combined science subject.

The items in two-tier multiple-choice diagnostic instruments are specifically designed to identify alternative conceptions and misunderstandings in a limited and clearly defined content area. The first part of each item consists of a multiple-choice content question having usually two or three choices. The second part of each item contains a set of four or five possible reasons for the answer to the first part. Incorrect reasons (distracters) are derived from actual student alternative conceptions gathered from the literature, interviews and written tests. Examples of items in the Qualitative Analysis Diagnostic Instrument (QADI) (Tan *et al.*, 2002) that relate to this paper are given on pages 96–97.

Results and discussion

The grade 10 students found the QADI difficult – the average mark was 5.8 out of a maximum of 19, with 87% scoring 9 marks or less. The facility indices indicating the proportion of students obtaining both the correct answer and reason for each item are given in Table 1. It can be seen that complex salt formation and reaction posed the greatest difficulty, followed by acid-salt/base reactions, thermal decomposition of salts and precipitate formation.

Table 1 Students' performance on the items in the QADI.

Facility index	*Item*	*Reaction*
		Precipitates and complex salts
.17	3	complex salt (zincate) + alkali (sodium hydroxide) + acid (nitric(V))
.19	9	complex salt (ammine) + alkali (aqueous ammonia) + acid (nitric(V))
.19	2	complex salt (zincate) formation
.20	8	complex salt (silver ammine) formation
.23	15	complex salt (ammine) + alkali (aqueous ammonia) + acid (sulfuric(VI))
.29	14	complex salt (copper(II) ammine) formation
.38	12	formation of precipitate (barium + sulfate(VI))
.41	1	formation of precipitate (zinc + hydroxide)
.43	5	formation of precipitate (silver + chloride)
.45	13	formation of precipitate (copper(II) + hydroxide)
.48	7	formation of precipitate (silver + chloride)
.48	18	formation of precipitate (lead(II) + iodide)
		Acid-salt/base reactions
.20	17	acid (nitric(V)) + carbonate
.22	4	acid (nitric (V)) + base (zinc hydroxide)
.23	16	acid (sulfuric(VI)) + base (copper(II) hydroxide)
.24	11	acid (nitric(V)) + carbonate
.34	6	acid (nitric(V)) + carbonate
		Thermal decomposition
.29	19	thermal decomposition of salt
.35	10	thermal decomposition of nitrate(V)

Precipitates and complex salts

Unknown cations are identified by reacting them with aqueous sodium hydroxide and/or aqueous ammonia. For example, zinc salt solutions react with aqueous sodium hydroxide to form a white precipitate, zinc hydroxide, which in turn will react with excess aqueous sodium hydroxide to form a colourless solution of sodium zincate, a complex salt. However, in item 1, only 41% of the students knew that the zinc and hydroxide ions combined to form the zinc hydroxide precipitate. Many students (25%) indicated that a displacement reaction resulted in the formation of the precipitate because the sodium ion was more reactive than the zinc ion; this is similar to the finding of Boo (1994) mentioned earlier. This showed that students did not understand that the precipitate was the result of a double decomposition reaction, and that, in a displacement reaction, a more reactive element displaces the ion of a less reactive element rather than a more reactive ion displacing a less reactive ion. Examples of students' alternative conceptions are shown in Table 2.

Students found complex salt formation and reactions difficult. Although they learned that zinc hydroxide was amphoteric and would react with excess aqueous sodium hydroxide to form a complex

Table 2 Examples of students' alternative conceptions of reactions in qualitative analysis.

	Alternative conception	*Choice combination*	*Students with the alternative conception/%*
	Precipitates and complex salts		
1	A more reactive ion displaces a less reactive ion in a double decomposition/precipitation mixture.	Q1 (A3)	25
2	The precipitate dissolves in the excess reagent (instead of reacting with it) because:		
	a more excess reagent means more space/volume for the precipitate to dissolve.	Q2 (A1)	29
	b no further reaction is seen except its disappearance and no new reagent is added.	Q2 (A2)	16
3	When acid is added to a mixture containing excess alkali and a complex salt (e.g. ammine, zincate or aluminate), it removes the solvent (alkali) which dissolved the precipitate in the first instance.	Q3 (A5)	18
	Acid-salt/base reaction		
1	The insoluble base dissolves in the excess acid (instead of reacting with it) because no further reaction is seen except its disappearance and no new reagent is added.	Q4 (A3)	16
2	Carbonate ions cannot be identified if acid is added after the addition of barium nitrate(V).		
	a The acid must be added directly to the unknown.	Q11 (B4)	25
	b Addition of barium nitrate(V) invalidated the test for carbonates.	Q12 (B4)	20
	c The procedure is strictly a test for sulfate(VI).	Q11 (B3)	20
	Thermal decomposition		
1	All gases have to be tested when a substance is heated.	Q10 (A1)	23
2	Oxygen cannot be produced when a substance is heated because it is used up during heating.	Q10 (B3)	27
3	Compounds containing hydrogen and hydroxide ions will liberate hydrogen on heating.	Q19 (A5)	21
4	Ionic compounds have strong bonds and do not decompose on heating.	Q19 (B1)	26

salt (zincate), students indicated in item 2 that the precipitate dissolved in, instead of reacted with, the excess alkali because more alkali added meant more space/volume for the precipitate to dissolve (29%), or that no new reagent was added and no further reaction was seen except for the disappearance of the precipitate (16%). Many students could not relate the disappearance of the precipitate to the formation of the complex salt. They seemed to base their answers on perceptual-dominated thinking (Ebenezer and Erickson, 1996) – if a solid disappeared in a liquid, then it dissolved in the liquid. In addition, Ribeiro, Pereira and Maskill (1990) reported that if students did not see a new substance being formed, they tended not to refer to the change as a reaction. This problem was further compounded by students being taught to write 'white precipitate dissolves in excess aqueous sodium hydroxide to give a colourless solution', a 'standard' answer required in the examinations to describe the disappearance of the precipitate.

If students did not understand or know the zincate formation in item 2, then it was unlikely that they would know that the acid reacted with the complex salt and the excess alkali to reform the zinc hydroxide in item 3 – only 17% chose the correct option. Though another 18% (A5) indicated that the zinc hydroxide was reformed, the reason they gave was that the acid removed the solvent (alkali) which dissolved the solid in the first instance.

Acid-salt/base reactions

Item 4 was a continuation of items 2 and 3, so it was unlikely that students would get it correct if they did not understand the theory involved in items 2 and 3 – 78% got item 4 wrong. Students needed to know that zinc hydroxide was formed in item 3 before they could work out that, since it was a base, it would react with the acid to form a soluble salt and water. The most common alternative conception (A3, 16%), again, was that the precipitate dissolved in excess acid because no further reaction was seen except the disappearance of the precipitate and no new reagent was added.

Students usually identify anions such as carbonate, iodide and sulfate(VI) by adding a barium/silver(I)/lead(II) solution to the unknown followed by a dilute acid, or vice versa. Many students have difficulty understanding the tests for anions as shown by their responses for items 11 and 12. For example, 20% (item 11, B3) of the students believed that the addition of aqueous barium nitrate(V) followed by dilute nitric(V) acid was to test for sulfate(VI) only; another 25% (item 11, B4) believed that to test for a carbonate, acid had to be added directly to the unknown sample. In item 12, 20% (B4) believed that the addition of barium nitrate(V) invalidated the test for carbonates. These responses showed that students did not understand that if a carbonate was present, insoluble barium carbonate would be formed and it would react with the nitric(V) acid to give carbon dioxide gas which could be identified. Sulfate(IV) would give similar results to carbonate, the difference being the formation of sulfur dioxide.

Thermal decomposition

Students were required to heat unknown compounds to determine colour changes and identify gases evolved. For example, the liberation of carbon dioxide could indicate that the unknown was a carbonate, and the presence of oxygen, usually accompanied by brown nitrogen dioxide, showed that a nitrate(V) was present. However, many students did not seem to know or understand the reactions that take place during heating. In item 10, 23% (A1) stated that all gases had to be tested when a substance was heated; the students did not realise that only gases such as oxygen, carbon dioxide or sulfur dioxide could be liberated. The 26% who chose B1 in item 19 believed that all ionic compounds do not decompose on heating; they seemed to have forgotten their experiences with the compounds (for example, carbonates and nitrates(V)) that they heated during their practical work. Other areas of difficulty are shown by B3 (27%) in item 10 and A5 (21%) in item 19. Students would have heated nitrate(V) salts several times in the course of their practical work, and would have obtained positive results for oxygen. On the other hand, as hydrogen was never liberated during heating in grade 10 QA practical work, it was extremely unlikely that they ever obtained a positive test for hydrogen when heating a solid.

Conclusions

The results of this study indicate that the usual way of learning QA (as described in the introduction) did not seem to help students understand the reactions involved. Additional indications were obtained from the interviews with 51 students from three schools involved in the study to determine their perceptions of their learning of QA (Tan *et al.*, 2001). Twenty-six students admitted that they frequently did not have any idea about what they were doing during the QA practical sessions. To illustrate this, 14 students mentioned that when they had to test for a gas, they did not know which gases to test for in a given situation. Hence, they randomly tested for all the gases that were in the syllabus; this could explain the poor performance in items 10 and 19. They complained that they wasted time testing for the 'wrong' gases, and used up all the gas evolved before they could complete all the tests. They did not seem to realize that the procedures and the reagents used could indicate which gases might be evolved during the process. Other comments, for example, that they often had no idea why they were instructed to use a certain reagent, what they were testing for, what reactions occurred or why they obtained a particular result, further highlighted the lack of understanding of QA prevalent among the students.

The instructional package

In response to the findings of this study, the authors have developed an instructional package on QA centred mainly on the studies by Woolnough and Allsop (1985), Driver and Oldham (1986), Goh, Toh and Chia (1987) and Russell *et al.* (1997). The aims of the instructional package are to allow students to:

1 be exposed to the three levels of chemical representation of the main reactions involved in QA;
2 gain tacit knowledge of reagents, apparatus and reactions;
3 gain proficiency in manipulative, observational and inferential skills;
4 learn the thinking/reasoning required in QA, and apply what they have learnt to plan, execute and evaluate experiments to identify unknown samples.

The instructional methods used in the package are illustrated below with reference to the section on precipitate formation.

To help students understand precipitate formation, they experience sodium hydroxide–zinc chloride and sodium hydroxide–iron(III) chloride reactions to observe the formation of precipitates and any further changes in excess aqueous sodium hydroxide. They are required to think about the chemical phenomena and discuss their ideas with their classmates. The students have to listen to the teacher's explanations carefully, compare them with their own ideas, and try to resolve any differences or any areas that they do not understand. They will have previously learned these reactions in the topic 'Acid, bases and salts' but may not know that the reactions are relevant to QA. The inability to relate theory to QA practical work seemed to be the main weakness of many students (Tan *et al.*, 2001). Students also view computer animation sequences depicting precipitate formation at the micro-level. Garnett, Garnett, and Hackling (1995) and Harrison and Treagust (1998) explain that the use of multimedia simulations can provide students with concrete micro-level representations of chemical structures and reactions, and Dechsri, Jones and Heikkinen (1997) noted that images were more easily recalled than words and could act as an '*easily recalled conceptual peg for abstract concepts*' (p. 892). Thus, students will be exposed to three levels of representation of double decomposition and precipitation – the results from the addition of the reagents (macro), the computer animation (micro) and the relevant chemical equation (symbolic) – to help them understand the processes better. A preliminary study has shown that the QA instructional package has the potential to help students understand the reactions involved. Further work on the instructional package is being undertaken.

Summary

The two-tier multiple-choice diagnostic instrument on QA, the QADI, was able to determine students' understanding of important acid, base and salt reactions in grade 10 QA. The results showed that the grade 10 students found many reactions difficult to understand, and several significant alternative conceptions were found. This indicated that the present method of teaching QA was ineffective in fostering understanding of the important reactions involved. We have developed an instructional package which emphasises the three levels of representation of the reactions involved and has the potential to help students understand these reactions better.

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Daniel Tan is an Assistant Professor in the National Institute of Education, Nanyang Technological University, Singapore, where **Ngoh-Khang Goh** and **Lian-Sai Chia** are Associate Professors. **David Treagust** is the Professor of Science Education, National Key Centre for School Science and Mathematics, Curtin University of Technology, Perth, Western Australia.

Examples of items in the QADI

For Questions 1 to 4, refer to Experiment A:

Experiment A

Step	*Test*	*Observations*
a	To a sample of aqueous zinc chloride, add aqueous sodium hydroxide until a change is seen.	A white solid is obtained.
b	Add excess of aqueous sodium hydroxide to the mixture from (a).	White solid disappears in excess reagent to give a colourless solution.
c	Add dilute nitric(v) acid (HNO_3) to the mixture from (b) until no further change is seen.	White solid reappears. When excess acid is added, the solid disappears giving a colourless solution.

1 What happens when aqueous sodium hydroxide is added to aqueous zinc chloride resulting in the white solid?

A Displacement

B Precipitation

C Redox

Reason/Justification

(1) The solution is too concentrated with sodium chloride so the sodium chloride comes out of the solution as a solid.

(2) Sodium hydroxide loses oxygen in forming sodium chloride and zinc chloride gains oxygen in forming zinc hydroxide.

(3) Sodium ion is more reactive than zinc ion.

(4) Zinc ions combine with the hydroxide ions.

2 In step (b), a colourless solution is obtained because the white solid ______ the excess sodium hydroxide.

A dissolves in B reacts with

Reason/Justification

(1) More solvent is added so there is more space for the white solid to dissolve.

(2) No further reaction is seen except for the disappearance of the white solid, and no new reagent is added.

(3) Sodium ion displaces the cation from the white solid.

(4) The white solid forms a new soluble compound with the excess sodium hydroxide.

3 A student concludes that the white solid observed in step (c) is the same as the white solid obtained in step (a). Do you agree with the student's conclusion?

A Yes B No

Reason/Justification

(1) Different reagents were used.

(2) The acid reacts with the excess sodium hydroxide to form sodium nitrate(v) which appears as the white solid.

(3) The acid reacts with the zinc compound to form zinc nitrate(v) which appears as the white solid.

(4) The acid reacts with the mixture to reverse the formation of the soluble compound in step (b).

(5) The acid removes the solvent which dissolves the white solid in step (b), so the white solid reappears.

4 The student also concludes that, in step (c), the white solid dissolves because more solvent (dilute nitric(v) acid) is added. Do you agree with the student's conclusion?

A Yes B No

(Continued)

Reason/Justification

(1) Adding more acid dilutes the solution.

(2) Hydrogen is more reactive than the cation in the white solid, so it displaces the cation from the solid.

(3) No further reaction is seen except for the disappearance of the white solid, and no new reagent is added.

(4) The acid contains hydrogen ions which reduce the white solid.

(5) The acid reacts with the white solid to form a soluble compound.

10 Will you test for oxygen gas when you heat an unknown solid?

A Yes B No

Reason/Justification

(1) All gases must be tested when a substance is heated.

(2) Oxygen gas is produced only when acids react with compounds containing oxygen.

(3) Oxygen gas will not be liberated during heating, instead it would be used up.

(4) Some compounds decompose on heating to give oxygen gas.

11 A student is given a solution which may contain carbonate ions. She decides to add aqueous barium nitrate(v) ($Ba(NO_3)_2$) to the solution first, followed by dilute nitric(v) acid. Is it possible for her to determine whether carbonate ions are present when she carries out the above procedures followed by the identification of the gas involved (if any)?

A Yes B No

Reason/Justification

(1) An insoluble carbonate would be formed leaving no free carbonate in solution to react with the acid.

(2) Dilute nitric(v) acid will react with both a soluble and an insoluble carbonate.

(3) The above procedure is strictly to test for the presence of sulfate(vi) (SO_4^{2-}) only.

(4) The acid must be added directly to the solution to test for the presence of a carbonate.

(5) The unknown compound will only react with the dilute nitric(v) acid and not with the barium nitrate(v).

12 Instead of dilute nitric(v) acid, can the student add dilute sulfuric(vi) acid (H_2SO_4) after the addition of barium nitrate(v) in Question 11?

A Yes B No

Reason/Justification

(1) Any acid can be used as they have similar properties and reactions.

(2) Sulfate(vi) ions from dilute sulfuric(vi) acid will interfere with the test.

(3) Dilute sulfuric(vi) acid will react with the nitrate(v) ions.

(4) The addition of barium nitrate(v) has already invalidated (spoilt) the test for carbonate ions.

19 A student believes that she has to test for hydrogen and carbon dioxide when she heats an unknown ionic compound (in powder form). Do you agree?

A Yes B No

Reason/Justification

(1) Ionic compounds have strong bonds and do not decompose on heating.

(2) Gases are only evolved when covalent compounds are heated.

(3) Some carbonates decompose on heating to give carbon dioxide but hydrogen is never liberated when any ionic compound is heated.

(4) The ionic compound would react with oxygen on heating to give water and/or carbon dioxide.

(5) Those ionic compounds containing carbonate, hydrogen or hydroxide ions will liberate carbon dioxide or hydrogen on heating.