Content framework for teaching and learning inorganic qualitative analysis at the high school level

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Abstract

A sound starting point for the teaching and learning of a difficult chemistry topic would be the clarification of the content framework that is required for the topic. Lists of propositional knowledge statements and facts, process skills and metacognitive strategies, as well as concept maps should be drawn up to define the content framework for the topic to help teachers and students know what exactly is required for the topic. In this article, the author describes how he defines the content framework for secondary chemistry qualitative analysis to facilitate the teaching and learning of qualitative analysis.

Introduction

The topic qualitative analysis (QA) is an important component of the General Certificate of Education Ordinary Level (O-level) chemistry practical examinations in Singapore. In QA students (15 to 17 years old) are required to carry out a series of procedures using chemicals, apparatus and appropriate techniques, to observe and record what happens, and to make inferences based on their observations.

In laboratory sessions, students frequently do not think for themselves and seem unaware of what they should be doing (Berry, Mulhall, Gunstone, & Loughran, 1999). However, teachers assume their students do know what to do during experiments, and thus, seldom emphasise or make explicit the purpose of and the theory behind the procedures (Tasker & Freyberg, 1985). Left to themselves, students have "difficulty establishing any meaningful overall purpose [in the experiments, so] their purpose and actions degenerate to simply following instructions" (Tasker & Freyberg, 1985, p. 72); consequently, the tasks of assembling apparatus and making required observations or measurements become the focus of student action. Many students also see no relationship between practical work and theory, and without theory to guide their experiments, it is likely that they will not know what to take note of in the experiments (Hodson, 1992).

These problems are manifested in QA which is shown by research to be a difficult topic for Singapore secondary chemistry students (Tan, Goh, Chia, & Treagust, 2000). This difficulty is likely related to the content of the topic (White, 1994), the lack of appropriate frameworks (Tasker & Freyberg, 1985), the lack of cognitive strategies (Gunstone, 1994), and cognitive overloading (Johnstone & Wham, 1982). In addition, teachers in Singapore frequently complain that their students are not able to properly carry out the procedures in QA experiments and record their observations, as well as make inferences from the results obtained. Unfortunately, many teachers do not spend time helping students develop such procedural skills, and as a result, many students lack mastery of such process skills (Goh, Toh & Chia, 1987). Hodson (1990) succinctly summed up the situation that is applicable to QA practical work in Singapore by stating that "It is not that practical work is necessary in order to provide children with certain laboratory skills. Rather, it is that certain skills are necessary if children are to engage successfully in practical work" (p. 36).

The topic of QA can be made more manageable for students by defining and making explicit what exactly is required to learn QA and carry out QA practical work meaningfully (Tan, Goh, Chia, & Treagust, 2000). This will increase the probability that important concepts, reactions and skills are targets for teaching (Johnson, 2000), and are not overlooked by teachers in the QA lessons. The aim of this paper is to illustrate how a content framework for QA has been developed.

Defining the content framework

To define the content framework of QA, the authors carried out the following five procedures:

1. extract the relevant sections of the O-level pure chemistry syllabus for 1999 (UCLES, 1996) pertaining to QA,
2. develop a concept map on QA,
3. identify the propositional knowledge needed to understand the reactions and procedures involved in QA,
4. relate the propositional knowledge to the concept map,
5. identify the skills required to carry out QA practical work.

Procedures 1 to 4 have been used to define the content knowledge framework for the development of various two-tier multiple choice diagnostic instruments (e.g. Peterson, Treagust & Garnett, 1989; Tan & Treagust, 1999).

O-level syllabus

There is no specific section in the O-level chemistry syllabus (UCLES, 1996), on QA. Under the 'Scheme of Assessment' section in the syllabus it is stated that candidates may be asked to carry out exercises based on tests for oxidising and reducing agents as specified in the syllabus, and to identify the ions and gases as specified in the syllabus (Textbox 1). Students are not required to identify any species not stated in Textbox 1. However, they may be required to deduce the properties of any unstated species, such as whether it is basic or acidic, reducing or oxidizing, based on the reactions with the reagents in the various procedures.

However, the author felt that what was given in Textbox 1 did not adequately describe the scope of QA that secondary students were doing. He further extracted parts of the syllabus that students require to understand what they were doing in QA and these included properties and reactions of metals, acids, bases, salts, oxides, hydrogen, nitrogen, sulfur and alcohols, and periodicity of elements in addition to the content stated in Textbox 1. Even then, there is considerable content not included in the syllabus which the students need to know in order to understand QA. Discussions with four secondary chemistry teachers confirmed that the more comprehensive extract of the syllabus better matched the requirements of O-level QA than that described in Textbox 1.

Textbox 1:
Sections on redox and the identification of ions and gases in the O-level syllabus.

7.3 Redox
- d. Describe the use of aqueous potassium iodide, acidified potassium dichromate(VI) and acidified potassium manganate(VII) in testing for oxidising and reducing agents from the colour changes produced.

8.4 Identification of ions and gases
Candidates should be able to describe and explain the use of the following tests to identify:
- a. Aqueous cations
  Aluminium, ammonium, calcium, copper(II), iron(II), iron(III) and zinc, using aqueous sodium hydroxide and aqueous ammonia, as appropriate. (Formula of complex ions are not required.)
- b. Anions
  Carbonates (by reactions with dilute acid and then limewater), chloride (by reaction, under acidic conditions, with aqueous silver nitrate), iodide (by reaction, under acidic conditions, with aqueous lead(II) nitrate), nitrate (by reduction with aluminium to ammonia) and sulfate (by reaction, under acidic conditions, with aqueous barium ions).
- c. Gases
  Ammonia (using damp red litmus paper), carbon dioxide (using limewater), chlorine (using damp litmus paper), hydrogen (using lighted splint),
  oxygen (using glowing splint) and sulfur dioxide (using acidified potassium dichromate(VI))

Concept map

The concept map (Figure 1) addresses the most essential and inclusive concepts in QA, the reactions which occur across the identification of cations, anions and gases. Examples of such reactions are acid-base, acid-carbonate, double decomposition and redox. Some tests for cations, anions and gases seem different but involve the same type of reaction. For example, the tests for iron(II) ions using aqueous sodium hydroxide, iodide ions using aqueous lead(II) nitrate(V), and carbon dioxide using limewater all involve double decomposition, so these different tests are grouped under 'double decomposition'. A teacher remarked that she had never viewed QA in the way that it was organised as a whole in the concept map.

Propositional knowledge statements

Propositional knowledge statements (Appendix 1) were written for the content and concepts relevant to the topic of QA taught in Singapore schools based on the author's personal teaching experience, a chemistry textbook and two QA manuals. Statements 22 to 26 on redox were either taken directly or adapted from Garnett and Treagust (1922) work on electrochemistry. The list of propositional knowledge statements consists mainly of statements on the reactions which occur in QA and includes other reactions than those specified in the O-level pure chemistry syllabus. Thus, secondary chemistry teachers may not teach some of the propositional knowledge statements. The reasons for inclusion of such reactions are that these reactions occur frequently in the experiments that the students do and many of these reactions are very similar to the ones that the students have learned. The reaction of acids with sulfate(IV) salts, the formation of ammine complexes, and the heating of nitrate(V) and sulfate(IV) salts are included even though they are not stated in the syllabus because they are pertinent to QA. Problems will most likely arise if these reactions are not known to the students. For example, students are expected to test for sulfur dioxide but they are not required to know how the gas is formed. Thus, how will they know when to test for the gas if they do not know when the gas is formed? Similarly, students are expected to test for oxygen but they are not required to know that the heating of certain nitrate(V) compounds will liberate oxygen, and when they add excess aqueous ammonia to copper(II) solutions, they will get a deep blue solution without knowing why. It is undesirable to instruct students to carry out procedures and obtain results without understanding the underlying reactions since this approach may result in the procedures being meaningless to students, producing gaps in their knowledge and understanding.

Linking the propositions with the concept map

To ensure the list of propositional knowledge statements and the concept map were internally consistent, a matching of the propositional knowledge statements to the concept map was carried out.

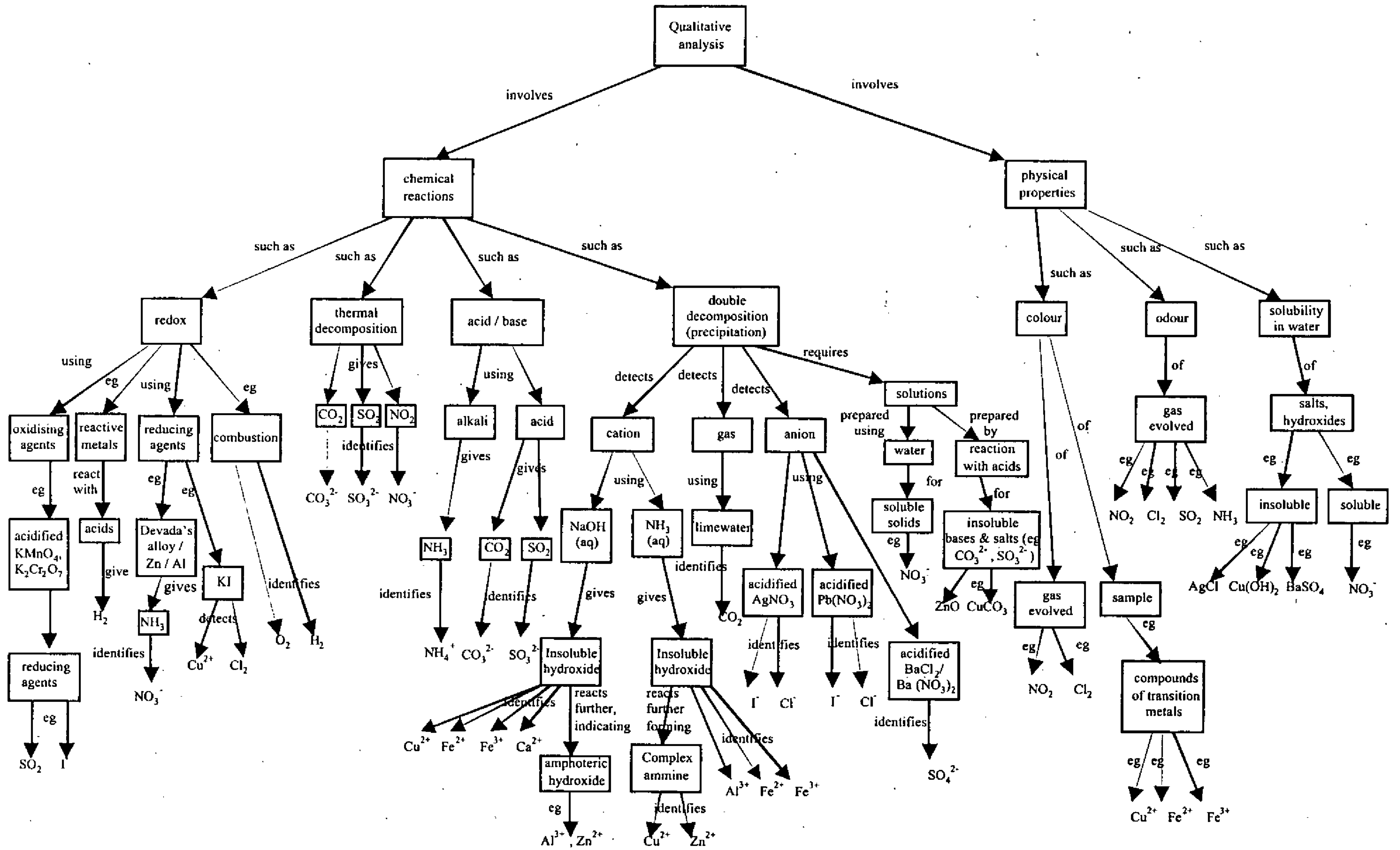

Figure 1: Concept map on qualtative analysis

Skills required for QA practical work

Herron (1996) commented:

> We seldom make deliberate efforts to teach laboratory skills that, much to our chagrin, students have never learned. By teaching, I do not mean telling students what to do or performing a quick demonstration in front of the class. I mean carefully prepared lessons, with clear statements of expectation, feedback to individual students so that they can correct errors, and evaluation at the end of instruction to be sure that the lesson is learned. I am talking about doing what any good coach would do in teaching a psychomotor skill. (p. 20)

In QA, teachers need to explicitly teach students skills such as how to dissolve substances, add reagents, test gases, and heat substances. They also need to ensure that their students practise and master these skills. A list of manipulative skills that students need to identify cations is given in Textbox 2.

Textbox 2:

List of skills required in the identification of cations

1. Adding reagents
   a. how much of the unknown to use
   b. how to add a small amount of reagent
   c. how to add reagent to excess
   d. how to shake/stir after adding reagent
2. Making solutions with soluble salts
   a. how to prepare a saturated solution
   b. how to fold a filter paper
   c. how to filter
3. Making solutions with insoluble salts
   a. how to prepare a saturated solution using acid-salt reactions
4. Determining the colour of a precipitate in coloured liquid eg. the precipitate formed in the reaction between aqueous barium nitrate (V) and aqueous copper (II) sulfate (VI)
   a. how to decant the coloured liquid leaving the precipitate behind
   b. how to filter off the precipitate
5. Heating mixtures containing ammonium ions and aqueous sodium hydroxide
   a. how to heat properly
   b. how to use litmus paper to test for ammonia

In addition, students need to monitor what they are doing when they carry out QA experiments. They need to ask questions such as "What is the purpose of this procedure?", "What reaction can possibly occur when I carry out the procedure?", "What do I have to look out for?", "Have I prepared everything that is necessary for this procedure?" and "Does the result make sense to me?". Being able to predict what would happen in experiments and resolve differences between predictions and actual results would lead to greater understanding of the content involved (Linn & Songer, 1991).

One of the ways to teach students how to monitor and evaluate what they do in QA is for the teachers to show their students the strategies and thinking that they themselves would use. Thomas and McRobbie (1999) believe that teachers should assist students "in becoming more reflective and metacognitive" (p. 667) by teaching them how to plan, monitor, evaluate and regulate their learning processes. The required cognitive processes in QA can be made explicit by the verbalisation, modelling and coaching of appropriate thinking and strategies by the teacher; teachers need to unveil the "experts' normally covert thinking process" (Volet, 1991, p. 321). Firstly, teachers need to show students how to deduce which reactions are involved in the experiments by reading the procedures given in the worksheets. This knowledge is important as the students need to know what to look out for in the reactions, which gases may be liberated, and which reagent and apparatus they need to prepare before carrying out the procedure. Secondly, teachers also need to show their students how they themselves would carry out the experiments by thinking aloud, explaining the steps and precautions they took and the decisions they made. This would show the students the appropriate behaviours required to carry out QA successfully. Students also need to practise these strategies and behaviours, reflect on their thinking and receive feedback on their performances in order to internalise the metacognitive strategies successfully (Volet, 1991). Students believe that practical work requires interaction with equipment but minimal thinking, so teachers need to help students rethink practical work as "a thinking task supported by laboratory equipment" (Berry et al., 1999, p. 31).

Conclusion

It can be seen from this paper that the content framework of QA is rather extensive. By making the content framework explicit, teachers will know what they have to prepare in their lessons to enable their students to learn QA meaningfully. Students can also refer to the framework to get an overall picture of the concepts, proposition and skills required in QA to guide them in the learning of QA. The author believes that specifying the content framework of other difficult topics in chemistry also will be beneficial for teachers and students as it will make the requirements of the topics explicit for all.

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Appendix 1:
List of propositional knowledge statements pertaining to the O-level qualitative analysis

1. When a substance ionises in water to produce hydrogen ions, an acidic solution is formed.
2. Hydrogen ions are responsible for the reactions of acids with metals, and metal oxides, hydroxides, carbonates and sulfate(IV).
3. When a more reactive element is added to a solution of an ionic compound of a less reactive element, a displacement (redox) reaction may occur, forming the less reactive element and the ionic compound of the more reactive element. (Normally reactive metals displace less reactive metals, and reactive non-metals displace less reactive non-metals. However a reactive metal may react with a dilute acid to displace hydrogen and produce the salt of the metal.)
4. An acid will react with a carbonate to produce a salt, carbon dioxide and water.
5. An acid will react with a sulfate(IV) to produce a salt, sulfur dioxide and water.
6. An acid will react with aqueous ammonia or a metal oxide or hydroxide to produce a salt and water only.
7. When an acid reacts with a metal, an insoluble metal oxide, hydroxide, carbonate or sulfate(IV) to form an insoluble salt, the reaction may stop after a while due to the formation of the insoluble salt which coats the solid reactant particles, preventing further reaction with the acid.
8. When an acid and an aqueous barium, silver or lead(II) salt are to be added to an unknown solution, the anion of the acid must be the same as that of the barium, silver or lead(II) reagent respectively. This is to prevent the introduction of an additional anion which may interfere with the reactions.
9. Alkalis are substances which produce hydroxide ions when dissolved in water.
10. Hydroxide ions are responsible for the reactions of alkalis with acids and amphoteric oxides/hydroxides, and for the formation of insoluble hydroxides with certain cations.
11. An alkali will react with an ammonium salt to produce a salt, ammonia and water.
12. An amphoteric oxide/hydroxide is an oxide/hydroxide of a metal which will react with either an acid or an alkali to produce a salt and water.
13. Aqueous ammonia will react with zinc hydroxide, copper(II) hydroxide and silver chloride to produce the respective soluble ammine complexes.
14. A precipitation/double decomposition reaction is a chemical reaction which involves the exchange of ions when two or more aqueous solutions of ionic compounds are added together, and results in the formation of a sparingly soluble ionic compound (which precipitates out of the solution).

15. The solubility of a salt in water determines whether it forms as a precipitate during double decomposition reactions.

16. If a precipitate is formed due to the formation of an insoluble hydroxide, the colour of the precipitate and whether it reacts with excess aqueous sodium hydroxide or aqueous ammonia helps to identify the cation.

17. The ease of decomposition of ionic compounds by heat, and the products formed depend on the cations present in the compounds. Generally sodium and potassium salts are very stable to heat, while those of copper(II) and silver are easily decomposed.

18. Most carbonates (except those of sodium and potassium) decompose on heating to form the oxide and carbon dioxide.

19. Most sulfate (IV) salts (except those of sodium and potassium) decompose on heating to form the oxide and sulfur dioxide.

20. Most nitrate (V) salts decompose on heating to form the oxide, nitrogen dioxide and oxygen. Nitrate (V) salts of sodium and potassium decompose to give the nitrite (III) salts and oxygen while ammonium nitrate (V) decomposes to form dinitrogen oxide and water. Silver nitrate (V) decomposes to form silver, nitrogen dioxide and oxygen.

21. The physical properties of a substance, for example, colour, odour and solubility in water or organic solvents, may help in the identification of the substance.

22. Oxidation can be defined as
    a. the gain of oxygen.
    b. the loss of hydrogen.
    c. the loss of electrons.
    d. an increase in the oxidation state.

23. Reduction can be defined as
    a. the loss of oxygen.
    b. the gain of hydrogen.
    c. the gain of electrons.
    d. a decrease in the oxidation state.

24. An oxidising agent (oxidant)
    a. causes the oxidation of another species.
    b. accepts electrons from the species being oxidised.
    c. is reduced.

25. A reducing agent (reductant)
    a. causes the reduction of another species.
    b. donates electrons to the species being reduced.
    c. is oxidised.

26. Oxidation - reduction (redox) reactions involve simultaneous oxidation and reduction processes.

27. Oxidising agents are identified through the use of specific reducing agents (e. g. aqueous potassium iodide). Colour changes produced in the reactions can indicate the presence of oxidising agents.

28. Reducing agents are identified through the use of specific oxidising agents (e. g. acidified potassium dichromate (VI) or acidified potassium manganate (VII)). Colour changes produced in the reactions can indicate the presence of reducing agents.

29. When a solid solute dissolves in a liquid solvent, a homogeneous mixture of the solute and the solvent is obtained ; the solute can be recovered in its original form simply by removing (e. g. evaporating) the solvent.

30. A solute dissolves in a solvent because of the interaction between the solute and solvent particles. Generally, in a solution, the attraction between the solute-solvent particles is greater than the attraction between the solute-solute or solvent-solvent particles.

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