# TEACHING AND LEARNING DIFFICULT CHEMISTRY TOPICS: THE NEED FOR A CONTENT FRAMEWORK

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**Abstract:** Students have difficulties in learning certain topics in chemistry, for example, bonding, equilibrium, chemical reactions, electrochemistry, mole concept, and qualitative analysis. Possible reasons why students find such topics difficult include the abstract nature and the inter-relatedness of the concepts involved, the need to shift between four representation systems, and the involvement of process skills. A sound starting point for the teaching and learning of a difficult topic would be the clarification of the knowledge base that is required for the topic. Lists of conceptual and 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. This would help teachers and learners to know what exactly is required for the topic. In this paper, the authors describe how they define 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 G.C.E. 'O' level chemistry practical examinations in Singapore during which students are required to carry out a series of procedures using chemicals, apparatus and appropriate techniques, observe and record what happens, and make inferences based on their observations. QA is a difficult topic for secondary chemistry students (Tan, Goh, Chia, & Treagust, 2000), possibly because of the content of the topic (White, 1994), the lack of appropriate frameworks (Tasker & Freyberg, 1985; Duit & Treagust, 1995), the lack of cognitive strategies (Gunstone, 1994), overloading (Johnstone & Wham, 1982) and the lack of mastery of process skills (Goh, Toh & Chia, 1987, 1989).

In the 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, they 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);

the tasks of assembling apparatus and making required observations or measurements become the focus of student action (Gunstone, 1991). Thus, 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.

## 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.

### O-level Syllabus

There is no specific section in the O-level chemistry syllabus (UCLES, 1996), on qualitative analysis. 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. In Figure 1, the requirements for redox reactions, and the cations, anions and gases which students are required to be able to identify, are listed, together with the reagents that they are required to use. Students are not required to identify any species not in the list, but they may be required to deduce its properties based on its reactions with the reagents in the various procedures.

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 sulphate (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 sulphur dioxide (using acidified potassium dichromate (VI))

**Figure 1: Qualitative Analysis in the O-level Syllabus**

However, the authors felt that what was given in Figure 1 did not adequately describe the scope of qualitative analysis that secondary students were doing. The first-named author examined the pure chemistry syllabus (UCLES, 1996) and extracted all parts of the syllabus that he felt were required for students to understand what they were doing in qualitative analysis, for example, sections on 'Reactivity of Metals' and 'Acids, Bases and Salts'. Even then, the authors felt that there was considerable content not included in the syllabus which the students needed to know in order to understand qualitative analysis.

**Concept map**

The concept maps in this study were prepared following the procedure described by Novak and Gowin (1984). The concept map (Figure 2) addresses the most essential and inclusive concepts in qualitative analysis, the reactions which occur across the identification of cations, anions and gases. Examples of such reactions are acid-base, acid-salt, double decomposition and redox.

**Propositional statements**

Propositional statements (Figure 3) were written for the content and concepts relevant to the topic of qualitative analysis. The list of propositional statements consists mainly of statements on the reactions which occur in qualitative analysis 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 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 sulphate (IV) salts, the formation of complex ammines, and the heating of nitrate (V) and sulphate (IV) salts are included even though they are not stated in the syllabus as they are pertinent to qualitative analysis. There will be problems if these reactions are not known to the students. For example, students are expected to test for sulphur 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 evolved? The authors felt that it is undesirable to instruct students to carry out procedures and get results without understanding why they had obtained such results; this approach would result in the procedures being meaningless to students, and produce gaps in their knowledge and understanding.

**Linking the propositions with the concept map**

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

**Skills required for QA practical work**

Teachers frequently complain that students do not know how to carry out the procedures in qualitative analysis experiments properly. Unfortunately, many teachers do not spend time in helping students develop such procedural skills. Hodson (1990) succinctly summed up the situation in qualitative analysis practical work in Singapore by stating that "It is not that practical work is necessary in order to provide children with certain

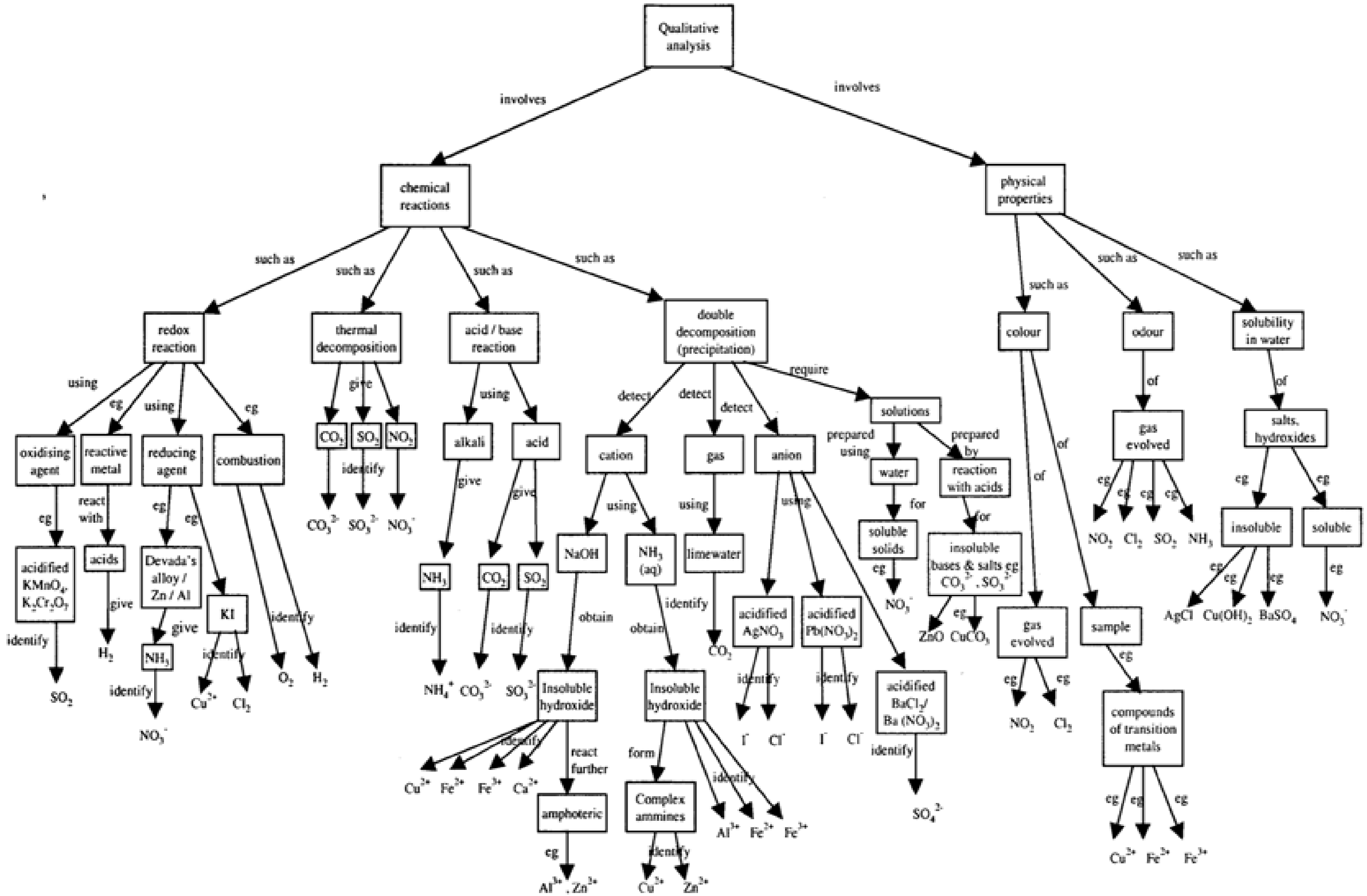


Figure 2: Concept map on qualitative analysis

1. When a substance ionises in water to produce hydrogen ions, an acid is formed.
2. Hydrogen ions are responsible for the reactions of acids.
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 sulphate (IV) to produce a salt, sulphur dioxide and water.
6. An acid will react with a base to produce a salt and water only.
7. When an acid reacts with a metal, an insoluble base, carbonate or sulphate (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. If an acid is to be added before or after the addition of a barium, silver or lead (II) reagent 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.
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 complex ammines.
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 solution).
15. The solubility of a salt in water determines whether it forms 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 identifies the cation.
17. The ease of decomposition of ionic compounds by heat and the types of products formed depend on the reactivity of the metal present in the compound. The greater the reactivity of the metal, the more difficult it is decompose the compound by heating.
18. Most carbonates decompose on heating to form the oxide and carbon dioxide.
19. Most sulphate (IV) salts decompose on heating to form the oxide and sulphur dioxide.
20. Most nitrate (V) salts decompose on heating to form the oxide, nitrogen oxide and oxygen.
21. The physical properties of a substance, for example, colour, odour and solubility, may help in the identification of the substance.
22. Oxidation can be defined as the gain of oxygen, the loss of hydrogen, the loss of electrons or an increase in the oxidation state.
23. Reduction can be defined as the loss of oxygen, the gain of hydrogen, the gain of electrons, or a decrease in the oxidation state.
24. An oxidising agent (oxidant) causes the oxidation of another species, accepts electrons from the species being oxidised, and is reduced.
25. A reducing agent (reductant) causes the reduction of another species, donates electrons to the species being reduced, and is oxidised.
26. Oxidation-reduction (redox) reactions involve simultaneous oxidation and reduction processes.

Figure 3: List of Propositional Statements Pertaining to the O-Level Qualitative Analysis

27. Oxidising agents are identified through the use of specific reducing agents (e.g. aqueous potassium iodide). Colour changes produced in the reducing agents indicate the presence of oxidising agents.
28. Reducing agents are identified through the use of specific oxidising agents (e.g. acidified potassium dichromate (VI)). Colour changes produced in the oxidising agents 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 among 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.

Figure 3 (Continued): List of Propositional Statements Pertaining to the O-Level Qualitative Analysis

laboratory skills. Rather, it is that certain skills are necessary if children are to engage successfully in practical work" (p. 36). In qualitative analysis, 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. Goh et al. (1987, 1989) found that many students lack mastery of process skills in qualitative analysis, so, it would seem that this aspect of qualitative analysis has been neglected. A list of manipulative skills that students need to identify cations is given in Figure 4.

1. Adding reagents
    a. how much 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. 
3. Making solutions with soluble salts
    a. how to prepare a saturated solution
    b. how to fold a filter paper
    c. how to filter

4. Making solutions with insoluble salts
    a. how to prepare a saturated solution using acid-salt reactions

5. 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) sulphate (VI)
    a. how to decant the coloured liquid leaving the precipitate behind
    b. how to filter off the precipitate

5. Heating mixture containing ammonium ions
    a. how to heat properly
    b. how to use litmus to test for ammonia

Figure 4: List of Skills Required in the Identification of Cations

In addition, students need to have tactical control (Pintrich, Marx & Boyle, 1993) to monitor what they are doing when they carry out qualitative analysis 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?", "What results can I expect?" and "Does the result make sense to me?". Being able to predict what would happen in experiments is beneficial; Linn and Songer (1991) found that students who actively predicted outcomes and reconciled results in their experiments had greater understanding of the content involved.

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 in carrying out qualitative analysis. Reif and Larkin (1991) state that students have significant learning difficulties in science because they do not know what kinds of cognitive processes are required in science. The required cognitive processes in qualitative analysis can be made explicit by the verbalisation, modelling and coaching of appropriate thinking and strategies by the teacher (Pintrich et al., 1993; Volet, 1991). Firstly, they 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 qualitative analysis 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 to rethink about 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 authors believe that specifying the content framework of other difficult topics in chemistry will also be beneficial for teachers and students as it will make the requirements of the topics explicit for all.

## References

Berry, A., Mulhall, P., Gunstone, R., & Loughran, J. (1999). Helping students learn from laboratory work. *Australian Science Teachers' Journal, 45*(1), 27-31.

Duit, R., & Treagust, D.F. (1995). Students' conceptions and constructivist teaching approaches. In Fraser, B.J., & Walberg, H.J. (Eds.), *Improving Science Education* (pp. 46-69). Chicago, Illinois: The National Society for the Study of Education.

Goh, N.K., Toh, K.A., & Chia, L.S. (1987). *The Effect of Modified Laboratory Instruction on Students' Achievement in Chemistry Practicals.* Research report, Institute of Education, Singapore.

Goh, N.K., Toh, K.A., & Chia, L.S. (1989). Use of modified laboratory instruction for improving science process skills acquisition. *Journal of Chemical Education, 66*(5), 430-432.

Gunstone, R.F. (1991). Reconstructing theory from practical experience. In Woolnough, B.E. (Ed.). *Practical Science: The Role and Reality of Practical Work in School Science.* (pp. 67-77). Milton Keynes: Open University Press.

Gunstone, R.F. (1994). The importance of specific science content in the enhancement of metacognition. In Fensham, P.J., Gunstone, R.F. & White, R.T. (Eds.), *The Content of Science: A Constructivist Approach to its Teaching and Learning.* (pp. 131-146). London: Falmer Press.

Hodson, D. (1990). A critical look at practical work in school science. *School Science Review, 70*(256), 33-40.

Johnstone, A.H. & Wham, A.J.B. (1982). The demands of practical work. *Education in Chemistry, 19*, 71-73.

Linn, M.C. & Songer, N.B. (1991). Teaching thermodynamics to middle school students: What are appropriate cognitive demands? *Journal of Research in Science Teaching, 28*(10), 885-918.

Novak, J.D. & Gowin, D.B. (1984). *Learning How to Learn.* Chapter 2, 15-40 Cambridge: Cambridge University Press.

Pintrich, P.J., Marx, R.W., & Boyle, R.A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*, 167-200.

Reif, F. & Larkin, J.H. (1991). Cognition in scientific and everyday domains: Comparison and learning implications. *Journal of Research in Science Teaching, 28*(9), 733-760.

Swartz, R.J. (1991). Infusing the teaching of critical thinking into content instruction. In Costa, L.A. (Ed.), *Developing Minds: A Resource Book for Teaching Thinking. Volume 1.* (pp 177-184). Alexandria, Va: Association for Supervision and Curriculum Development.

Tan, K.C.D., Goh, N.K., Chia. L.S., & Treagust, D.F. (2000). *Secondary Four Students' (15-17 Years Old) Perceptions on Learning Qualitative Analysis in Chemistry.* Paper presented at the Australasian Science Education Research Association, Fremantle, WA.

Tasker, R. & Freyberg, P. (1985). Facing the mismatches in the classroom. . In Osborne, R & Freyberg, P. (Eds.), *Learning in Science: The Implications of Children's Science* (pp. 66-80). Auckland, London: Heinemann.

University of Cambridge Local Examinations Syndicate (UCLES). (1996). *Chemistry: Examination Syllabuses for 1999*. Cambridge: Author.

Volet, S.E. (1991). Modelling and coaching of relevant metacognitive strategies for enhancing university students' learning. *Learning and Instruction, 1*, 319-336.

White, R.T. (1994). Dimensions of content. In Fensham, P.J., Gunstone, R.F. & White, R.T. (Eds.), *The Content of Science: A Constructivist Approach to its Teaching and Learning.* (pp. 225-262). London: Falmer Press.